STUDY OF SELECT ISSUES OF RESILIENT SUPPLY CHAINS

A Thesis submitted

in partial fulfilment for the Degree of

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by

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Don't judge each day by the harvest you reap, but by the seeds that you plant: ***Robert Louis Stevenson***

CERTIFICATE

This is to certify that the thesis entitled **Study of select issues of resilient supply chains** submitted by **Rajesh R.** to the Indian Institute of Space Science and Technology, Thiruvananthapuram, in partial fulfilment for the award of the degree of **Doctor of Philosophy** is a *bona fide* record of research work carried out by him under my supervision. The contents of this thesis, in full or in parts, have not been submitted to any other Institution or University for the award of any degree or diploma.

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DECLARATION

I declare that this thesis entitled **Study of select issues of resilient supply chains** submitted in partial fulfilment of the degree of **Doctor of Philosophy** is a record of original work carried out by me under the supervision of **Dr. V. Ravi.**, and has not formed the basis for the award of any other degree or diploma, in this or any other Institution or University. In keeping with the ethical practice in reporting scientific information, due acknowledgements have been made wherever the findings of others have been cited.

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ABSTRACT

Supply chain risk management and supply chain resilience are getting reasonable attention during the recent past. The research was conducted to address some of the critical problems in the domain of supply chain risk management and supply chain resilience. The related issues were considered in an Indian context by taking representative case studies. *Five* problems were addressed in this research and suitable methodologies were developed for addressing the same. *First* problem was to effectively quantify supply chain risk management strategies based on their net influences. A methodology using a combination of grey theory and digraph- matrix methodologies were employed to address the same. The results of the study and the managerial implications were remarked.

Second and *third* problems are complementary problems of interest to practitioners. These problems were addressed to fill the gap from the effective implementation of supply chain risk management practices towards achieving supply chain resilience. In effect, there are critical entangled cause- effect relations existing among the drivers of risks as well as among the enablers of risk mitigation. These cause- effect relations were quantified to identify the critical causal driver of supply chain risk as well as to identify the most influential enablers of risk mitigation. A representative case evaluation was conducted and the solutions were obtained using a combined methodology using grey theory and DEMATEL methodologies. The results and related discussions of the paired research problems of interest are elaborated and the implications in practice were stated.

Fourth problem is in consideration of the upstream supply chain as most of the critical disruptions in past are supply related. A resilient supply chain selection problem was formulated and solved for a representative case supply chain. Also, the results and the managerial implications related to this are presented and discussed. *Fifth* problem is to study the strategic level objectives of supply chains and the periodical shifts in their focus. Major objective is to identify the sequence of evolution of supply chains and to devise the exact location of positioning of partition line in a network to achieve complementary strategic objectives in the same supply network. A concept of sustainable-resilient supply network is proposed and the positioning of partition line to achieve sustainability and resilience together in a network was studied. A model case analysis was conducted and the results were also discussed.

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CHAPTER 1

INTRODUCTION

Supply chains are regarded as the network of organizations involved through upstream and downstream linkages to perform different activities that creates value to the end consumers in the form of products and services. Contemporary supply chains are designed to deliver goods in the *right quantities*, to the *right places*, at the *right time*, in a most *efficient manner*. One thing essentially need to understand is that supply chains are not simple linear chains or processes but are complex networks. Supply chain management is integrative and is cross functional so supply chain vulnerability is also a concern for practitioners in other streams like business continuity management and corporate risk management. Supply chains of today can be categorized on basis of their objective focus into *(i) efficient supply chains (ii) risk- hedging supply chains (iii) responsive supply chain (iv) agile supply chains* (Lee, 2002).

Supply chains comprise of a couple of organizations and are guided under institutional pressures. *Three* types of institutional pressure generally guide organizations are *(i) coercive pressure (ii) normative pressure and (iii) mimetic pressure. Coercive pressure* arises from force, persuasions and invitations to participate with external environment. Coercive pressures often appear as laws and government regulations. *Normative pressure* appear as cultural expectations from where the norms of the operating environment are formed. Organizational choices are often influenced by values and norms under normative pressure.

Mimetic pressure operates from the desire to mimic structure, practices and outputs of other organizations. Organizations model themselves to appear successful by following practices of successful competitors. Even then, supply chains are operating under high levels of risks and uncertainty which is detailed in the following sub- section. Risk and uncertainty are related notions, but there are differences in the perception and management of both (Peck, 2005).

1.1. Supply Chain Risk and Uncertainty

Competitive environments and the increasing resource requirements offer significant challenges in customer service levels, anticipated costs and the estimated level of profitability. When a risky alternative is considered whose outcomes are often good, human subjects appear to be risk averse but when the situations are changed and if the outcomes of a risky alternative are generally poor, human subjects tend to be risk seeking. Risk is defined using the relationships among range of possible negative outcomes including its severity and the negative impacts and the distribution of probabilities corresponding to each outcomes (Paul, 2015). Risks are often interpreted as unreliable and uncertain resources creating supply chain interruptions while uncertainties are related to supply and demand mismatches in supply chain processes. Outcome of the risk and expectation of its sources are the key determinants of it. If the outcome of an event is not sure and the worst cases are known, it is a risk and even the worst cases are not known it becomes uncertainty

Supply chain risk is defined by the underlying components of it, the potential loses and the likelihood of these loses. Supply chain risk can be regarded as perceptions of the particular set of unwanted and undesirable outcomes occurring that affect the ability of the supply chain to deliver values to the customer effectively and efficiently. Supply chain risk occur at *three* dimensions *(i) likelihood of occurrences of an event or outcome (ii) consequences of the event or occurrence of outcome and (iii) sources and causal pathways of the event.* Risks to the supply chain can be classified as *(i) internal to the firm such as, process risks and control risks (ii) external to firm and internal to supply network such as, demand risks and supply risks (iii) external to the network such as, environmental risks. Processes* constitutes a sequence of value adding managerial activities of the firm and their execution is likely to be immediately dependent on internally owned or managed assets on a functioning infrastructure.

Controls are assumptions of systems and procedures that determine how an organization governs their processes. The control may be in the form of order quantities, batch sizes, safety stock policies along with the policies that govern asset and transportation management. *Demand* risks consolidate the potential or actual disturbances to the flow of a product, information that includes cash emanating from within the network considering the focal firm and the market. *Supply* risks represents the upstream equivalent of the above representing the potential or actual disturbances to the flow of products or information from within the network upstream of the firm. *Environmental* risk consolidates the risks associated with the operating environment where the supply chain executes its operations.

Risk is generally calculated as the product of the probability of the event and the severity or negative impact if the event happens. In general, supply chain risks fall into four major categories such as; *(i) supply risks (ii) operational risk (iii) demand risks and (iv) security risks*. *Supply risks* relates to any adverse event in the inbound supply causing failures from suppliers or the supply market resulting in the inability of the focal firm to meet the demand within the anticipated costs or time. *Operations risks* account for the possibility of any adverse event affecting the internal ability of the firm to produce goods and services, maintain quality and timelines of production or the profitability of the company. Operations risks are the distribution of outcomes related to adverse events within the firm affecting the internal capability of the firm to produce goods and services and to increase profitability.

Risks in supply chains appear as a complex phenomenon that can be divided into the sources and types of risks. Risk sources can be classified in clusters as; *(i) material flow risks (ii) financial flow risks and (iii) information flow risks*. *Material flow risks* involve the risk related to the physical flow of supply chain elements. A vast majority of supply risks, process risks and demand risks are material flow risks.

Financial flow risks often arise from the inability to settle payments or other improper investments. Exchange rate risks, price and cost risks, financial status of the partners fall under these categories. Risks related to information flows on demand, inventory, order status, design changes and capacity status trigger the value added activities in supply chains. Information accuracy, security, intellectual property and information outsourcing risks fall under the category of *information flow risks* (Tang & Musa, 2011).

Another classification of risks is as follows; *(i) macroeconomic risks (ii) policy risks (iii) competitive risks and (iv) resource risks*. *Macroeconomic risks* are risks related to significant shifts in wage rates, exchange rates and prices. *Policy risks* related to the changes or new actions implemented by governments. *Competitive risks* relate the competitors' actions and the related uncertainty in associated markets. Unanticipated fluctuations in the resource requirements constitute *resource risks*. The sources reside inside the firm and may result in the breakdown of core operations, inadequate manufacturing or processing capabilities, process variations, changes in technologies making current facilities obsolete and changes in the operating exposures.

Demand risk is the likelihood of occurrence of any adverse event in the outbound flows affecting the number of customer orders, variances in the volume and assortment of product levels by the customers. Sources of demand risks may vary from delayed or inappropriate new product introductions, variations in demand and chaos in the system. *Information security risks* often occur from a third party member who wishes to steal proprietary data or knowledge and to upset operations of the firm. The sources include individuals within the firm leaking information to competitors, system hackers and improper firewalls of the supply chain (Manuj & Mentzer, 2008). Risks in operational supply chains can be of the following wide varieties; *(i) supply interruption risks (ii) demand, supply planning risks (iii) integration risks (iv) purchase price risks (iv) inventory and obsolescence risks (v)* *regulatory and compliance risks (vi) information privacy and security risks (vii) customer satisfaction and service risks (viii) contract compliance and legal risks (ix) process inefficiency risks (x) employee and third party fraud risks (xi) product introduction and cycle time risks (xii) human resources skills and capabilities risks (xiv) project management risks (xv) corporate culture and management of change risks and (xvi) information integrity and availability risks* (Asbjørnslett, 2009).

An excursion event is attributed to an unpredictable event that effectively hinder or having a large negative impact on the performance of atleast one member of a system for a relatively long period of time. As supply chains are transforming to complex supply networks, failure of any element in it could bring disastrous damage to the whole supply network. Vulnerability is highest when the likelihood of disruption and its potential impacts are high. Resilience increases the efficiency of the system and its processes starts functioning easily and quickly from a disrupted state. Risks are often interrelated and this is the reason for the cascade failures of systems (Baud-Lavigne, et al., 2012). Although the shape and nature of risk management process vary depending on the situation, it is rather regarded as a proactive approach to a reactive one (Ritchie & Brindley, 2007). Disruptions are inter-organizational involving a minimum of two firms involved or affected by it.

Risk management is the consolidation of the range of activities to avoid the happening of an undesirable event or to reduce, modify or to eliminate the consequences should the event occur. For an adverse event to generate organizational response, firms must develop a motivational act that aid in noticing the event and analyze its importance with respect to its goals. Uncertainty offered from the environment makes a firm unable to plan and perform its operations deterministically. Uncertainty is often associated with lack of control and power over the environment and not due to lack of information. Hence uncertainties arising from dependence relations need to be managed. Too much information can also be dangerous as either the firms must increase their capability to process information or to reduce the amount of information based on their relative importance.

Market and technology turbulence are common *endogenous* uncertainties. *Exogenous* uncertainty lies outside supply chain and are of discrete events and continuous risks. Terrorist attacks, strikes etc. account for discrete events and inflation, consumer price index etc. account for continuous risks. Exogenous uncertainty is difficult to reduce, however proper structuring of the supply chain can improve resiliency. Unpredictable technological as well as market changes could create turbulence and results in the inability to forecast accurately. When the composition of customers and their preferences in the market changes, market turbulence arises. The degree of technological changes and its aftereffects in an industry constitutes technological turbulence. When there is *technological turbulence*, firms must be capable of quicker information sharing rather to when the technology is more predictable.

Supply chains also have to deal with several other environmental disruptions like natural disasters or human centered issues like labor strikes, fraud or a malfunction. Considering exogenous uncertainty, continuous risks are classified as events where the cost of potential changes are continuous and are relatively easy to predict whereas discrete event category consists of low likelihood, high impact risks. In an agile supply chain, supplier flexibility and their responsiveness to market turbulence are important. Alternatively in a lean supply chain, reliability and low variations in lead times are important. Practically, a combination these two can effectively manage vulnerabilities. It is imperative for companies to identify how much risk a company is willing to take and how far could it be mitigated (Tummala & Schoenherr, 2011).

Risks are associated to events leading to negative outcomes where uncertainty can have both positive and negative outcomes. Uncertainty could be managed through *two* broad set of strategies, *(i) reduce uncertainty*: enable the organizations to detect its source and manage accordingly and *(ii) coping with uncertainty*: enable the organizations to act and tries to find ways to adapt and minimize the resultants of uncertainty. Supply chain redesign for resilience should consider the following; *(i) chain configuration (ii) chain control (iii) chain information systems and (iv) chain organization and governance*. To reduce uncertainties associated with innovative products those are having short product lifecycles and variety, responsive stock replenishments could be utilized where the planning period is shorted than forecast horizon. *Contingency theory* stresses on the realization that the appropriate approach to management strategy depends on a set of contingency factors including the uncertainties of the environment. According to *alignment theory*, an organization should develop a strategy that aligns with strategic sources and environmental requirements to improve business performances. Performance is strongly related to the alignment between sources of uncertainty and the choice of uncertainty management strategies (Tang, 2006).

1.2. Supply Chain Risk Management (SCRM)

SCRM can be defined as the identification and management of risks within and outside the supply chain through a coordinated approach among the members of supply chain to reduce the overall vulnerabilities. The tools and practices of SCRM is applicable to one or many of the three supply chain activities, *supply chain planning, supply chain operations management and supply chain change management*. Supply chains are expected to be most vulnerable during periods of change. There are no commonly accepted definitions of supply chain risks or vulnerability within the supply chains in an industrial context. It is the competitive commercial interest of the organizations that deter them in sharing risk management data. Risk management is the process of identifying and evaluating the consequent risks in supply chains and to implement suitable strategies through coordination among partners to reduce one or many of the following, *a loss, probability, speed of event and loses, time of detection, frequency and exposure to loses*.

The risk chain analysis (RCA) focus on the *risk identification, risk measurement and risk prioritization* constitutes the tactical cycle. The operational cycle focus on the activities of *risk analysis, risk reduction and risk control.* It is essential that supply chain risk analysis be conducted before any changes in business strategy are implemented (Jüttner, et al., 2003). Operations managers must manage several risks in today's competitive environments to buffer against uncertainties to optimize operational performances. *Technological changes* are important parameters determining the intensity and extend of risk management practices. Suppliers who provide items of high security requirements need extensive risk management practices when compared to other suppliers.

Suppliers providing *high volume, value and critical* items require intense risk management practices when compared to other suppliers. Also suppliers with a less history of purchase need more extensive risk management practices when compared to others (Giunipero & Eltantawy, 2004). A disruption event occurring anywhere in the supply chain impacts a firm's ability to continue operations, provide finished goods to markets or providing critical services to customers. A key component in an effective SCRM is the real time sharing of right information from every single node in a supply chain to improve responsiveness and flexibility and making it able to withstand potential disruptions. Before defining SCRM, *four* aspects and constructs need to be identified such as: *SC risk sources, risk consequences, risk drivers and risk mitigation strategies* (Jüttner & Maklan, 2011).

Considering disruption management philosophy, the areas identified as critical for successfully managing disruption are *(i) disruption discovery (ii) disruption recovery and (iii) supply chain redesign*. Considering *disruption discovery*; the visibility, capacity and predictive analysis play a vital role. It is essential to build more comprehensive models of risks as well as practicing more dynamic and real time measures. Considering *disruption recovery*, real time supply chain reconfigurations and reachability analysis are to be implemented. In a real time environment, supply chain reconfiguration needs to be performed quickly to avoid looming disruptive events. Apart from that, once a disruption occurs, the firm needs to quickly determine the aftereffects or impacts in the supply chains. For *supply chain redesign*, understanding global supply chain cost tradeoffs along with flexible and robust optimization tools are essential (Blackhurst, et al., 2005).

Considering a risk assessment and management framework, the following are to be considered *(i) diversification could reduce risk (ii) robustness to disruption is determined by the weakest link (iii) loss avoidance and prevention is better (iv) too much leaning and focus on efficiency increases vulnerability (v) backup systems, contingency plans and maintaining reasonable slack can increase the readiness level of risk management (vi) collaborative information sharing and best practices among supply chain partners are essential to curb vulnerability (v) modularity of product and process designs and other elements of flexibility and agility can leverage risk reduction (vi) six sigma and reduction in process variances achieve higher supply chain security and reduced chances of supply disruptions.*

Disruption risk management must be designed to provide incentive alignment and collaboration for risk avoidance and risk reduction considering the supply chain partners. *Risk avoidance* must precede *risk reduction* in any supply chains. Tradeoff between *robustness* and overall *efficiency* are to be maintained to reduce risks and loses from potential disruptions. Applying reliability theory and process improvements can improve SC robustness. Cross functional implementation of *cooperation, coordination and collaboration* across the partners could improve visibilities. Quantification of risk is also essential to have good case for mitigation. *Flexibility* and *mobility of resources* to reduce risks increases the responsiveness towards contingencies (Christopher, 2004).

Organizations that might have managed risks through strategies often have overlooked the critical risk exposures of their supply chains. For designing a global supply chain network, some major issues are to be considered like *(i) network* *configuration (ii) product assignment (iii) customer assignment (iv) product planning and (v) transportation planning.* When the resources are fungible and there are delayed differentiations, *mobility and flexibility* promotes resilience. Firms have realized the importance of supply management as suppliers enable the firm to focus on their core competence and to reduce costs, product development cycle time and increase product quality simultaneously. Depending upon the types of contracts, length of contracts, type of information exchange, pricing schemes and delivery schedules, supplier relationships can be classified into *four* types, *(i) vendor (ii) preferred supplier (iii) exclusive supplier and (iv) partner.*

Companies with higher brand value are more concerned about security breakdowns and corporate reputations. *Risk specification, risk assessment and risk mitigation* are considered as the distinct phases of risk management. Risk assessment focusses on the consequence or impact of specific risks. Major strategies like *multiple suppliers, strategic stocking, flexible transportation and postponement of product differentiation* could reduce the impending vulnerabilities of supply chains. Robustness can also be built through several strategies such as *product design standardization, supply contract flexibility, spot marketing and contracting flexible capacities*. Flexible supply chains running in highly risky environments are likely to adopt postponement strategies.

Supply chain risks can be further consolidated into *six* categories, *(i) supply risks (ii) process risks (iii) demand risks (iv) intellectual property risks (v) behavioral risks and (vi) policy/ social risks.* The common strategies to deal with risks are *(i) to reduce the likelihood of occurrences of undesirable events and to (ii) reduce its negative impacts.* Aligning the interest of the supply chain partners can reduce the associated supply chain risks. Also, adapting itself according to market dynamics can reduce supply chain risks. Short term demand and supply variations could be managed through agility. Supply side risks could be managed through flexible supply either through *(i) multiple suppliers or through (ii) flexible supply contracts.*

Having multiple suppliers enable the firm to shift order quantities across suppliers and through flexible supply contracts, it is possible to shift order quantities across time. Demand risks could be better handled by having *(i) flexible products through postponements and through (ii) flexible pricing through responsive pricing.* Postponements help in shifting the production quantities across different products and responsive pricing help in shifting the demand across different products. Process risks could be managed through having *flexible processes* through adopting flexible manufacturing processes. This aids in shifting the production quantities across several internal resources (Tang & Tomlin, 2008).

Supply chain risks involve the probabilistic measure of the occurrence of critical events along with the measure of the consequence of these events. When the complexity of the supply chain is high, the effects of risk mitigation strategies over particular risks will reduce. It is often seen that most firms develop plans to protect against frequent low impact risks but avoid low probable high impact risks. *Risk assessments* involve the estimation of the likelihoods and consequences of related risks, by employing frequency of data or on expert opinions and subjective probabilities. Risk management strategies are developed based on the interaction of *risk assessment* and *risk perception* for reducing the probabilities of negative events or/and its consequences. When the related uncertainties are high, there are chances that the managers may underestimate the importance of an issue.

Risk aversion has played a critical role in understanding economic problems varying from *insurance, contracting and portfolio selection*. Outcomes having a low probability of occurrence are often ignored apart from the consideration for the level of significance. A disaster risk management strategy should determine the exact level of *risk avoidance, risk mitigation and contingency planning.* A disaster management process should involve the following steps; *(i) planning (ii) mitigation (iii) detection (iv) response and (v) recovery.* A frequent revisit on planning is recommended. This frequency depends on *(i) periodicity at which new data is available (ii) types of risks* *involved and (iii) any changes to supply chain structure including mergers, acquisitions or formation of a new supply chain* (Knemeyer, et al., 2009).

SCRM may not be effective by adopting a number of practices, it is a philosophy supposed to be deep rooted with the company and its supply chain. Management of crisis often needs flexibilities, improvisations, redundancies and above all breaking of rules. As the direct and indirect suppliers operate in different markets, there is variation in the level of market turbulences and hence the force influencing supplier also varies. Hence certain supplier strategy might be acceptable in a turbulent environment can be detrimental in a non-turbulent one. Considering the *contingency theory* that states there is no single best way of organizing an organizational style that is universally effective, we could infer that there is no common optimal choice suitable for all businesses. The roots of uncertainty can be of *two* types *(i) endogenous and (ii) exogenous. Endogenous* uncertainty lies within the supply chain that lead to changing relationships between firm and suppliers and *exogenous* uncertainty lies outside the supply chain.

SCRM consists of *four* major management aspects as, *(i) assessing the risk sources of supply chains (ii) defining the adverse consequences (iii) identifying risk drivers and (iv) mitigating risks for the supply chain.* Sustainable competitive advantage of a firm is its ability to quickly sense and adapt to changing environments. A global supply chain would be beneficial if it could accommodate operational flexibility. Flexibility should allow it to reap benefits out of exchange- rate arbitrages. Innovations in product market that could affect production or its processes are considerable threats as it can change the patters of competition and coordination among firms. Operating uncertainties fall into *three* major categories, *(i) labor uncertainty (ii) input supply uncertainty and (iii) production uncertainty* (Rao & Goldsby, 2009). Risk management often lacks ability to characterize *low probability* and *high probability* events. The performance of supply chain will increase when there is a proper balance between *capabilities* and *vulnerabilities*.

Major vulnerabilities in the supply chain can be classified into *(i) turbulence (ii) deliberate threats (iii) external pressures (iv) resource limits (v) sensitivity (vi) connectivity and (vii) supplier/ customer disruptions.* Major capabilities of the supply chains to counteract these vulnerabilities are *(i) sourcing flexibility (ii) inventory flexibility (iii) capacity (iv) efficiency (v) visibility (vi) adaptability (vii) anticipation (viii) recovery (ix) dispersion (x) collaboration (xi) organization (xii) market position (xiii) security and (xiv) financial strength* (Pettit, 2010).

An interesting commonality among *crisis* and *disaster* is the high level of uncertainty existing with the nature and potential consequence of the threat. Disturbance even it is small will propagate rapidly through supply networks, making it tough to understand the source and the way of its propagation in the network. When the level of *trust* is a prominent and distinguished, *coordination* slowly follows it (Azevedo, et al., 2010). Due to the increasing difficulties in classifying, identifying and finding analogous cases for mitigation process and strategies, supply chain managers are facing difficulties to choose amongst a variety of security measures. *Cost effectiveness* is a primary concern of mitigation measures. Resilient supply chain strategies are often developed through learning from several disruptions. Several management strategies to alleviate vulnerabilities are as follows; (i) *introducing risk management cycle (ii) management training and education (iii) hedge strategies (iv) flexible strategies (v) risk sharing and contracts (vi) implementing TQM practices (vii) knowledge and process backups (viii) burden shifting (ix) increasing safety stocks (x) substitution (xi) decentralization of operations (xii) increasing level of collaboration (xiii) consulting chief security officer* (Faisal, et al., 2007).

Companies are habitual to build buffers regardless of the extent of perceived supply chain risks and exchange of information often take place between companies and not within entire supply chain. *Strategic partnerships* aids in boosting corporate learning, innovation, communication and common risk management. Risks are perceived mutual if there are asymmetrical relations. SCRM concepts are built on collaboration with partners and generally distribute the risks and divide them based on dimensions of severity. Having an integrated and general SCRM could enable the actors to work under a common platform of risk management system and afterwards there exist general standards, definitions, structures and processes ensuing (Pfohl, et al., 2010).

As the impact of disruptions on the focal firm increases, the need for *buffering* and *bridging* by the firm also increases. *Buffering* is external to a relationship and it reduces the exposure of the firm to an exchange partner and the detrimental consequences for the relationship arising from disturbances. *Bridging* is internal to a relationship and it seeks managing resource dependencies through enhancing influence of the firm over it. Buffering will be more practiced when the level of dependence on exchange partner is moderate rather than at *low* or *high* levels of dependence. When the level of dependence over the exchange partner is high, bridging is more desirable option. At lower levels of trust among relationships and lower prior experiences of partners, the influence of supply chain disruption and the pursuit for bridging and buffering will be weaker (Wagner & Neshat, 2010).

For achieving *efficient, effective and robust* supply chains, the critical factor is being able to design and redesign the supply chain in a changing environment (Christopher & Holweg, 2011). Considering organizational culture for this, *two* basic dimensions of cultural typology are deliberated, *grid* and *group*. *Grid* defines the level of rigidity of influence of rules and traditions on risk taking and decision making whereas *group* defines the level of tightness of interpersonal and professional ties perceived as frequency and transparency of communications and group solidarity. Mis-aligned culture is dangerous and has been always over looked since there is low level of *visibility* and *tangibility*. It is the habit of people and enterprises to handle and mange those assets and characteristics that are tangible and quantifiable while ignoring the remaining things that are either not visible or not tangible (Das, 2011).

Different companies have different maturity levels to manage risks based on clear structure and processes to prevent, monitor and manage risks. Responsiveness towards supply chain risks can be either of responses to *operational risks* or towards *catastrophic risks*. *Initial step* towards risk management is the identification of risks and related uncertainties. *Second step* is the assessment of risks including the likelihood and impact. *Third step* in SCRM is related to the process of mitigation. This includes the reduction of likelihood of risk occurrence or/ and its potential impacts. *Fourth step* in implementing SCRM is the response to an actual risk event or disturbances to reduce its potential impacts and to accelerate recovery (Sodhi, et al., 2012). The unpredictable business environments, varying consumer demands, competitive market dynamics and continuous improvement of firms imply that supply chains never reaches a stable steady state. The ability of supply chains to execute proper functions over a variety of future scenarios could attribute to the robustness of supply chains whereas the proactive, structured and integrated exploration of capabilities of the supply chain to respond to mishaps attributes to the resilience of supply chains.

Robustness and *resilience* should be built it supply chains to handle impending vulnerabilities. Risk management process could be more effective if incorporated along with *four* basic approaches as; *(i) supply management (ii) demand management (iii) product management and (iv) information management.* SCRM consists of *five* major components; *(i) risk drivers (ii) risk management influencers (iii) decision makers characteristics (iv) risk management responses and (v) performance outcomes.* Mitigation capabilities include the routines that enhance the abilities of supply chains to recover expediently from a manifested disruption and to create awareness of a future disruptions and realization of its expected losses. A proactive approach intend to avoid risks, enhances the preparedness to respond to risks once they occur (Blome & Schoenherr, 2011). Even though there are positive risks, most of the risk management context defines risks are events leading to negative consequences.

Considering the type of uncertainties in supply chains, *basic uncertainty* is one that could be managed through objective measures whereas a *knightian uncertainty* refers to immeasurable risks that cannot be evaluated. *Substantive uncertainty* arises from the incompleteness of information sets which is attributed to the lack of information about environmental events and other information necessary to make certain outcomes. *Procedure uncertainty* arises from the inability of the agents to identify and interpret relevant information even when it is available, due to competence gaps in problem solving and cognitive and computational limitations of their capabilities. *Probabilistic uncertainties* define a situation where the structure of future events is known in terms of its objective probabilities considering the likelihood and potential impact of its occurrences. Also, there exist the *parametric uncertainty* where the structure of future events is known but the probability parameters are not known. This includes the subjective belief of the future events and its outcomes. *Radical uncertainty* refers to situations in a hypothetical world of total uncertainties discussing the chaotic behaviors. Risk management is rather proactive since risk avoidance precedes risk reduction. SCRM and analysis are impossible since the knowledge of uncertainty and the elements for decision making are incomplete that even do not allow for the formation of subjective belief about future events (Vilko, et al., 2014).

1.3. Supply Chain Security

The inherent complexities associated with the supply chains as well as the large quantity and diversity of actors in the international supply chain processes and the need of efficient security measures have initiated research in supply chain security management (SCSM). The way of interaction of the security measures to the company employees in sustainable norms and expectations is critical to the implementation of *supply chain security* (Marley, et al., 2014). Visibility is a critical component of security as it is a prerequisite to develop comprehensive monitoring activities and to detect and isolate an out of control problem on time (Holweg, et al., 2011).

Supply chain security involves the whole set of *policies, practices and technologies* to safeguard supply chain assets from *theft, damage or terrorism* or to prevent appearance of *unauthorized contraband, people or weapons for mass destruction* of the supply chain. Also, supply chain security covers all process, technologies and resources used in a systematic way to detect and recover from a threat or crime in the fastest possible time. The primary step towards creating supply chain security is to understand the types of relationships with suppliers. Competitors in a business environment will create policies and practices that everyone in the environment adopt them to remain competitive. Environmental scanning can be said effective for organizations to include practices of competitors. Institutional pressures such as *customers, government, competitors and society* act as drivers for securing supply chains can be explained through institutional theory as coercive, normative and mimetic pressures (Wieczorek, 2012).

Safety refers to the state of being safe for person or a unit against a distinct threat. The common trends affecting the degree of risk are *(i) globalization (ii) outsourcing (iii) centralization (iv) lean processes (v) complex product and service (vi) IT- dependence (vii) dearth of information.* Product safety is related to the reduction in probability that the product use results in illness, death or negative consequences to people, property or facilities. Product security is related to the product delivery, which is uncompromised by international contamination, damage or diversions within the supply chain. The common challenging areas where global supply chains face difficulty are *(i) regulation and standards (ii) product lifecycle management (iii) traceability and recalls and (iv) supplier relationships* (Barlas & Gunduz, 2011).

1.4. Supply Chain Agility

Agility can be enhanced with the presence of agile partners in the upstream and downstream. Key components of agility are *(a) visibility*: visibility is referred to as the clear view of inventories, demand and supply conditions, production and purchasing schedules across the supply chain. Bullwhips and functional silos act as hindrances to visibility and lead to second guesses in supply chains. *(b) velocity*: velocity as a general notion refers to distance over time. SC velocity can be improved through reducing the end to end pipeline times of transactions (vi) developing a risk management culture: it is essential to develop a culture of SCRM into the core supply chain operations to cross boundaries of *corporate risk management* and *business continuity management* to become *supply chain continuity management* (Christopher & Ryals, 2014).

Supply chain risk management is becoming more important as the related issues are more frequently atop the minds of end consumers forcing the members of the supply chain to have a new look at security measures. The focus of SCM is changing putting greater emphasis on design and management of change. Supply chains are often characterized by *arm length* and *adversarial relationships*. Too long time for recovery from supply disruptions or changes in the response times of supply chains has put organizations under risk. *Visibility*, the determinative element of agility is based upon close collaboration with customers and suppliers. *Velocity* alone may not be another determinant of agility, but is the *acceleration*.

Flexibility can withstand significant disruptions and also better respond to demand fluctuations. Flexibility can be imparted through several strategies such as, *(i) adopting standardized processes (ii) use of concurrent instead of sequential processes (iii) plan to postpone (iv) aligning procurement strategies with supplier relationships*. Having simultaneous rather than sequential processes accelerates the recovery phase after a disruption and provides collateral benefits. The sources or drivers of supply chain risks are identified at *four* levels, *(i) value stream/ product or process (ii) assets and infrastructure dependencies (iii) organizations and inter-organizational networks and (iv) the environment* (Peck, 2005). The responsive capability of supply chain is having *three* major components, *(i) agile capability (ii) adaptive capability and (iii) innovative capability.*

Agile supply chains are capable of responding quickly to short term changes in demand and supply to smoothly handle external disturbances. *Adaptable* supply chains are capable of adjusting its design to meet structural shifts in markets and to modify related strategies, products and technologies. *Aligned* supply chains are able to create incentives for improved performances. A supply chain creates its environment as well as reacts to it. Supply chains often react to the changing environments by adjusting strategic goals and by supporting competences. A proper balance between *stability* and *instability* for learning and innovation is needed for attaining system adaptability (Waters, 2011). Within the existing supply chain design, *dynamic flexibility* allows the firm to manage shifts in demand and technology. *Structural flexibility* is the ability of the supply chains to adapt with fundamental changes in the business environment. Structural flexibility is generally achieved through the following strategies; *(i) dual sourcing (ii) asset sharing (iii) separating base and surge demand (iv) postponement (v) flexible labor (vi) rapid manufacturing (vii) outsourcin*g. Higher degrees of centralization increases the lead times and reduces the agility and responsiveness of the supply chains. Investments in flexibility will show positive returns by rigorously challenging the assumptions under which decisions are made. *Volatility* in business environment is likely to continue for the foreseeing future, increases the uncertainties of supply chain landscape (Christopher & Holweg, 2011).

Use of interchangeable product assemblies and relying on identical plant designs avail flexibility to the firm by reallocating the resources when the demand is higher. Tightly coupled lean supply chains operated under minimum levels of time and material buffers makes them vulnerable to disruptions affecting negatively on cost, quality, flexibility and reliability traits. *Agile and resilient* supply chain management emphasizes on the following principles; *(i) market sensitivity (ii) customer satisfaction (iii) quality improvement (iv) delivery speed (v) data accuracy (vi) new product management (vii) collaborative planning (viii) process integration (ix) use of IT tools (x) lead time reduction (xi) service level improvement (xii) cost* *minimization (xiii) uncertainty minimization (xiv) trust development and (xv) control the exposure to uncertainty.*

In order to cope with external turbulences, structural flexibility of supply chains is needed which can build flexible options into the design phase itself. Issues in inter-organization domains could be abridged using enhanced information sharing practices as in collaboration. *Network configuration* in supply chains refers to *density, connectivity and hierarchy* and how these properties influence *level of contact, accessibility, resource exchanges and flexibility*. Appropriate organization is a structural dimension for achieving resilience where organizations created for one purpose are able to provide resources for achieving other through collaboration. Shared codes as mutual rules, values and goals facilitate communication, understanding and support collaborative interfaces and are considered in the *cognitive dimensions* for resilience. *Trust* among partners along with confidence in competence, reliability and openness could be considered under the relational dimensions for resilience. Effective communication of codified and tacit knowledge enable the identification of viable alternatives (flexibility) for improving the level of understanding for knowing status of network partners (visibility) and facilitating a rapid response (velocity). Considering incident responses, *visibility, flexibility and collaboration* contributes towards *velocity* (Caridi, et al., 2010).

1.5. Supply Chain Resilience

Supply networks become more vulnerable when the supply chain transforms to longer and leaner. Often *robustness* is interpreted as *resilience*. A robust process is expected to produce reasonably consistent results with more or less variation in outputs. *Resilience* is the property to return to an original state or even better after the disturbances. *Efficiency* vs *redundancy* tradeoffs are usually revisited to find those pinch points where capacity and inventory can be effectively utilized for creating resilience. Increasing the level of collaborative working environments significantly helps in building resilience. The ultimate aim of tradeoffs is to enhance the visibility of supply chain and thus creating supply chain intelligence. Also, agility creates resilience by timely responses to unpredictable fluctuations in demand and supply. Robustness may not always impart resilience. Hence firms have to select processes that are *robust* and are indeed *resilient* (Carvalho, et al., 2012). Efficiency of the supply chain may or may not be directly related to its security, but increasing transparency to improve efficiency definitely will improve SC security. Some security enhancement programs ensure fault tolerance and resilience of a system. The risks can be classified at *five* levels of sub networks in each supply chain detailed as, *(i) physical:* risks related to the actual movements or flows *(ii) financial:* risks related to the flow of cash between organizations, processes and systems *(iii) informational:* risks related to processes and electronic systems, market intelligence and use of data and information systems *(iv) relational:* risks in the linkage between suppliers, organization and its customers *(v) innovational:* risks in the process and linkages in discovering and bringing new product, service and process opportunities (Cavinato, 2004).

Agile supply chains are so designed to respond rapidly and cost effectively to unpredictable and volatile markets as well as increasing levels of environmental turbulences considering volume and variety. *Redundancy* and *flexibility* can be considered as the building blocks of supply chain resilience. Creating redundancies across the supply chain may impart resilience to its supply chain. This enables the firm to hold extra inventory, maintain low capacity utilizations and to have many suppliers. Although building redundancy is a temporary and very expensive measure, it provides a breathing room for operations to continue after a disruption. Keep employees aware of the strategic goals, tactical policies and day to day focus of businesses. Delegation of power empowers employees to take decision of their own in related matters. Companies are to cultivate a sense of greater good with their employees. Considering small and operational level disruptions, flexibility enable the firm to condition or adapt with them.

Disruptions can even create shortages of higher intensities when compared to supply/ demand mismatches. Resilient supply chains can also enhance competitiveness in supply chains (Sheffi & Rice Jr, 2005). Considering a proper management of disruption risks; first and foremost the sources of risks and vulnerabilities need to be identified. These sources fall under the categories of *(i) operational contingencies (ii) natural hazards such as earth quakes, hurricanes, tsunami and storms (iii) terrorism and political instabilities.*

The concepts of *robustness, responsiveness and resilience* are often confusing. *Robustness* is the quality of the supply chain to remain effective in all conceivable futures. *Responsiveness* is the capability to positively respond to all variations and business changes. *Resilience* is the capability to avoid disruptions or to quickly recover from them. High impact extreme events should not be assigned with the same priority as low impact usual business events. Robustness can be regarded as the measure of useful flexibility of the system in a decision to leave many options or choices in the future. Responsive policies often provide adequate responses to supply capacity and demand variations and provide hedge against randomness and hazards to increase the expected value of the network. Resilience is directly related to the structure of the supply chain network and the resources hence to the first stage of design variables. Strategies for resilience should aim at obtaining a network structure for reducing risks and providing capabilities to efficient implementation of various policies for responsiveness (Klibi & Martel, 2012). Relational contracts may well increase the need for *risk sharing, accountability and transparency* by enabling *trust, mutual interest and a willingness* to do according to situations.

Resilience in one dimension can be defined as the ability to manage risks to better position than competitors to deal with and even gain advantages out of disruptions. For managing the consequences of a disruption, firms must have *(i) robustness or capability to continue operations (ii) resourcefulness or capability to* *manage complexity of anticipated events (iii) infrastructure responsiveness for efficient recovery and (iv) organizational learning process* to learn lessons from incidents and to recommend corrective actions. The need of collaborative patch up is driven by the projected needs of impact area, presence of inbound supply chains for the needs and the strategic importance of impacted nodes within the supply network. When the critical infrastructure capabilities are improved there is a positive influence in the resilience capabilities. *Adaptive resilience* is to enhance the inherent resilience of a firm by leveraging the ability to put extra effort to creatively increase inputs compensating the loss during disaster.

Resilience could often be perceived at three levels, *(i) microeconomic (ii) mesoeconomic and (iii) macroeconomic.* By increasing the access to resources, supply chain resilience could influence the capability of communities to manage the consequences of disasters to restore economic social networks (Talluri, et al., 2013). There is little recourse during disruption events for strategic events such as facility location and network design (Zsidisin & Ritchie, 2008). In order to reduce risks, event readiness should be incorporated in supply chains that could provide an *efficient* and *effective* response to potential disruptions. Systems have two distinct properties, *(i) resilience and (ii) stability*. *Resilience* determines the ability of the system to absorb fluctuations and *stability* corresponds to the property of the system to return to an equilibrium state after a temporary disturbance. Also, resilience measures the degree manner and pace of restoration of the system after a disruption.

Resilience is based on the basic assumption that not all the risks can be prevented. Resilience has certain components, *(i) elasticity:* Rapidity of restoration *(ii) amplitude:* the zone of deformation *(iii) hysteresis:* the extend to the path of degradation *(iv) malleability:-* degree of difference of steady state from original and *(v) damping:* degree, manner and alterations to the pace of restoration. Resilience can attributed to *three* major elements, *(i) control:* direction, regulation and coordination of activities *(ii) coherence:* understanding of the worst times and processes needed to reduce uncertainty *(iii) connectedness:* behavior to bend together rather to break at a point. The effective way to deal with supply chain risk is to increase confidence in supply chain. Resilience in a better way defined as the adaptive capability to prepare for unexpected events, respond to disruptions and recover from them through achieving desired level of connectedness and control over structure and functions to maintain continuity of operations.

Increasing the level of dynamic integration may increase supply chain resilience. When the resilience capabilities of the firm are high, the better it maintains control, coherence and connectedness across logistics capabilities when disruption occurs. The level of risk sharing has a positive influence on firm's resilience and also its sustainable competitive advantages (Ponomarov & Holcomb, 2009). A risk neutral decision maker have the propensity to rely on central tendency measures but while considering strategic level issues, most of the decision makers are risk averse. Institutional theory helps to understand how environmental pressures affect managerial actions and shape organizational structure and actions. Organizations operate as social networks where practices are influenced by social rules and rule of thumb. Social reality is created by the environment where it operates. Supply chain resilience management is rather proactive and could complement traditional risk management and business continuity planning.

Conceptualization of resilience and the formative elements of SCRM are consistent with the dualism of abilities to absorb shocks and to adapt to changes. Shorter lead times and quick responsiveness could offset brittleness in supply chains, however increased complexities and constraints makes disruptions disastrous. Disruptions have a direct effect on the ability of organizations to bring finished goods into markets and providing critical services to customers. *Four* important traits of resilience can be identified as *(i) flexibility (ii) motivation (iii) perseverance and (iv) optimism*. Resilience is a trans-disciplinary concept defined in *physical systems, ecological systems, social systems, psychological systems, disaster management* *systems, organizational systems, engineering systems* as well as in *supply chain systems*. The focus on resilience on a system perspective is perceived as the persistence and ability to absorb disturbances and maintain the same relationships among system entities. Resilience involves both individual and organizational responses towards turbulences and discontinuities including the *ability to withstand* and the *capability to adapt*.

Trust building is a chief step towards the introduction of flexibility without which the suppliers and customers may be reluctant to share information and resources for achieving flexibility. The response capabilities of the system relates to the *ability of the system to adjust to a disturbance, moderate the effects, taking advantage of available opportunities and ability to cope with consequences of system transformations*. Adaptive capability of the system refers to the ability to *respond to changes in external environment and to recover from damage of internal structures* within the system affecting the capability to achieve its purpose. Resilience is a function of vulnerability and the adaptive capabilities of the system. Major system characteristics contributing to resilience are, *(i) diversity (ii) efficiency (iii) adaptability and (iv) cohesion* (Wu, et al., 2015). The formative elements of supply chain resilience define how *event readiness, response and recovery* can be secured and why it is relevant from a management perspective.

The level of confidence in supply chains is indicated by the visibility of the supply chain that aids to prevent *over reactions, unnecessary interventions and ineffective decisions* during risk situations. *Collaboration* includes the willingness of the parties to share even sensitive risk and risk event related information and is often related to visibility. Supply chain resilience decreases the negative consequences of risk events by ensuring a fast return to original or improved situations and decreases supply chain vulnerability in case of a manifest risk event. Risk sharing has a positive influence over *flexibility, visibility and collaborative capabilities* of supply chains. Joint business continuity plans aids in improving the willingness to share consequences from the volatility of systems and to restrict opportunistic behaviors. Strategic outsourcing agreements act as measures to build flexibility into a reconfigured supply chain and allow for the absorption of disturbances through joint efforts. Visibility acts as a key driver of effective timing of intervening actions throughout a risk event. Risk events of high impacts and low probabilities are often tolerated as the sources appear to be too manifold and the ability to control them are very limited (Jüttner & Maklan, 2011).

Resilience limen is defined as the required amount of stimulus needed to produce a sensation or a level that can be perceived different from the other. Resilient supply chain management prevents the shift towards undesirable states and certain modes were failures are most prone to occur. Improving visibility in the upstream and downstream enable companies to anticipate, perceive and effectively manage consequences of potential disruptions (Carvalho, et al., 2012). Considerable efforts in resources, negotiating, monitoring and enforcing inflexible contracts needs to be spend without collaboration of suppliers and customers. Risk mitigation is possible through *avoidance, control cooperation and flexibility*. Vulnerabilities can be mitigated through *awareness, planning, independent backup systems* and having alternate procedures for critical applications (Lee, 2004).

Resilient supply chains may not be always cost effective but are robust to change and are able to cope with the uncertainties in business environment. Increasing the resilience capabilities of supply networks reduces the risks of interruptions in networks through *improving the elasticity of the network, ensuring rapid recovery of supply capacity and to initiate measures against risks of interruptions of the critical nodes*. A disruption risk model should be designed in a way to protect the selected appropriate nodes of the supply network thereby enhancing the reliability of the existing supply chain system (Carvalho, et al., 2012). Robust strategies enhances the capability of the firm to sustain its operations during a major disruptive event by preventing the risks to execute its negative impacts enabling resistance to change without adapting initial stable configuration. Supply chain resilience through preparedness should be focused on process of planning through *knowledge management, collaboration and agility* rather than on the plan itself. High levels of capabilities for collaboration are needed while *implementing disaster management plans, evaluating its direction and control and ensuring communication*.

Planning team has the responsibility to ensure risk and resilience management by resuming operations to the desired level of robustness though supply chain re-engineering and maintaining employee support. Mitigation processes are antecedents of supply chain resilience that enable the execution of necessary processes during preparedness, response and recovery and for managing inventory (Sodhi & Tang, 2012). In case of *vendor managed inventory* (VMI), there is a delegation of decision from retailers to manufacturer. There is an increased visibility and level of information sharing between the partners in those cases. Collaboration has been enhanced by the *voluntary inter industry commerce standards* (VICS) as an initiative called the *collaborative planning, forecasting and replenishments* (CPFR). Resilience acts as a link between dynamically integrated capabilities and the sustainable competitive advantage of the firm.

A robust strategy for mitigating supply chain disruptions should have two specific properties in common, *efficiency* and *resiliency*. Being *efficient* makes the firm able to manage operational risks efficiently regardless of the occurrence of major disruptions. Being *resilient* enable the firm to sustain its operations during a major disruptive event and to recover quickly from it (Giunipero & Eltantawy, 2004). Formative resilience capabilities span over the various functional areas as it is based on integration and coordination of resources. Cooperative schemes for supply chain coordination include *vendor managed inventory (VMI) and co- managed inventory (CMI), efficient consumer response (ECR), quick response (QR), just in time (JIT), collaborative planning, forecasting and replenishment (CPFR) and collaborative* *transportation management (CTM).* Some major strategies can be employed to reduce the effects of risk pooling that are (i) postponement (ii) built- to order (iii) product variability reduction and (iv) centralized inventory management (Lavastre, et al., 2012).

1.6. Supply Chain Complexity

Complexity of the supply chain is a critical task to be managed through virtues of *visibility, velocity and control*. A supply chain at the lowest degree of complexity consists of a company, a supplier and a customer directly involved in the upstream and downstream flow of products, services, finances and information. Supply chain risk sources are inextricably linked to its supply chain structure (Gong, et al., 2014). Supply chain design characteristics have a direct influence on supply chain disruptions. *Density, complexity and criticality* of supply chains are the *three* major considerations while designing a supply network. Supply chain density is the relative geographical spacing of nodes and is inversely proportional to the spacing distance. The supply chain disruptions become severe when the supply chain density is more.

Exact determination of the appropriate practices for risk mitigation is context specific and is dependent on the need of the supply chain towards operational excellence. A disruption event can cause major impacts to a dense supply chain rather than hitting a less dense supply chain. Supply chain complexity also contributes to the vulnerability towards disruptions. Complexity is determined as the sum of *two* components, the sum of nodes and the total of backward, forward and within tier material flows within the supply chain. A more complex supply chain would have considerably large number of nodes when compared to a less complex supply chain. Supply chain complexity is also positively related to the severity of supply chain disruptions.

Considering the complex fragments of the supply network, it is regarded as the disruption event hitting more complex portions of the supply networks can be more severe when compared to a less complex region. Node criticality is regarded as the relative importance of a typical node within the supply chain. A node comprising a critical component would be more important compared to that comprising a less critical component. A node responsible for integrating many equally valued components is more critical compared to that integrates a fewer number of components.

Similarly, a node that distributes materials to many other nodes is more critical when compared to that distributes materials to few other nodes. The importance of a node is relative to other nodes and is context specific. A disruption event has more severe impacts if it is hitting the critical nodes of the supply chain rather than hitting the less critical nodes in the network. Recovery capability of the supply chain and the coordination of resources to return to normal product flow allow interventions to be designed and implemented to overcome the hindrances to planned product flow within supply chain.

An unplanned event hitting the supply chain with proactive and reactive capabilities to respond quickly and effectively is less likely to be severe than the supply chain disruption affecting a supply chain with little capability to recover. A warning capability should be defined towards the interaction and coordination of supply chain resources to detect realized disruptions and to disseminate exact information of relevant entities in the supply chain. A disruption event hitting the supply chain have the capability of quickly detecting and disseminating information related to disruptions is less severe compared to the supply chain with little warning capabilities. Considering all these, the following can be concluded; the severity of a disruption event hitting a supply chain that is *dense, complex and having many critical nodes* can be reduced if the supply chain is capable of quicker responding to disruptions and are able to proactively or reactively correct a disruption event (Hearnshaw & Wilson, 2013).

Many factors decide the complexity of the supply networks like *(i) nature of industry and decoupling points (ii) multinational or global coverage of supply networks (iii) long term impact of the design decisions and (iv) complexity and uncertainty of the systems as the systems are more dynamic than static*. Sources of vulnerability can also be classified into *(i) endogenous assets (ii) supply chain assets and (iii) exogenous geographical factors*. Supply network threats are rather difficult to predict and have serious catastrophic consequences that follow Pareto's principle that a small fraction of the events contribute to a vast majority of the disruptive events. Complexity of supply chains is a measure of the *structure, type and volume* of interdependent activities, transactions and processes in supply chains. For effectively managing supply chain risks and impending vulnerabilities, supply chain design models should take into consideration of the uncertainties and complexities in supply chains, developing structured and systematic tools for risk identification and assessments considering the dynamic interactions of *risk sources, enablers and among partners* in supply chains.

The severity of disruptions hitting a complex supply chain would be more compared to a less complex supply chain. Node centrality relates to the *degree, closeness and betweenness* of the positioning of nodes in a network. Proper judgment of the relative importance of a node is essential while designing supply networks. If *betweenness centrality* of a node is higher, there is more than one shortest path throughout the network. Complex network theory aids in determining the vulnerability of nodes, finding the risk managing ability of network and to optimize the network topology by improving ability to resist risks that can be realized through protecting critical nodes and by temporarily separating them. Network non-connectivity leading to the interruption of supply networks are the major risks of supply chain disruptions from a complex network perspective. According to complex network perspective, the shortest is the path through the node, the more important the node position is; hence the node plays a critical role in the connectivity of whole network.

1.7. Postponement in Supply Chains

Quick response systems make the supply chain more brittle by increasing connectivity requirements and reducing buffers. Postponement decisions for processes helps to keep products in semi- finished forms that help in the movement of products from surplus to deficit areas. If a company relies on a small group of key suppliers, company can better maintain deep and collaborative relationship among them. Such suppliers become vital as the failure of one hem could create major impacts in the supply chain. Having a large supplier network may enable the firm to distribute the risk once a problem occurs. The corporate culture of the company is a major determinant that helps companies to recover quickly and even profitably. When the environment is dynamic and rugged, the margins of supply chains are to be changed by including or excluding elements and by changing the mode of interactions among them.

Creating such a culture need to keep the following traits in mind *(i) continuous communication among informed employees (ii) distributed power to make empowered employees (iii) passion to work in organization (iv) conditioning for small disruptions*. Considering the major demand management strategies considering postponements, the following are important, *(i) shifting demand across time (ii) shifting demand across markets and (iii) shifting demand across products*. *Shifting demand across time* enable the firm to increase the generated profits considering fixed supply capacity by procuring customers from different segments who are willing to pay different prices for their services benefitted at different times.

Considering *shifting demand across markets*, firms are considering product rollover strategies in different markets generally for shorter lifecycle products. This includes phasing out old products and introducing new products. A solo-rollover strategy aids in selling new products in different markets with non-overlapping selling seasons. Considering *shifting demand across products*, various pricing and promotion strategies are employed to entice customers to switch between brands and products. Retailers can avail higher benefits by adjusting assortment of products to offer right products for customers. Selling products with similar features increases substitutability of products. Apart from that, a firm can increase the sales by developing bundles. Bundling of products increases demand and have the advantage of selling together. Postponement delays the distribution activities until exact customer information is available. When the number of offshore components increases, postponement become more valuable. Postponement is often seen in association with strategies with *high risk exposure and practices like JIT*.

Postponement is used an effective tool against supply disruptions. Managers are generally less concerned about outbound flows than inbound flows in supply disruptions. Keeping track on signals indicating disruptions in inbound and outbound help companies to prepare, prevent, control and mitigate supply disruptions. Overall supply chain performance could be improved by reducing complexity to streamline their processes. Increasing the number of elements or the level of coupling among different elements shall influence the level of complexity of supply chains. Postponement provides opportunity to alter the configuration of a product in cases of supply disruptions. Postponement often shifts the risk towards the most appropriate player in the supply chain to reduce overall vulnerabilities.

Delaying activities in time aid companies to learn from the demand and other environmental behaviors. Postponement in turn could be considered as a sequencing strategy where high risk activities are postponed up to which exact market information is available. *High interactive complexity, tight coupling* and other modern supply chain practices amplify the probabilities for disruption considering the principles of *normal accident theory* (NAT). *Coupling* refers to the level of available buffer in the supply network whereas interactive complexities refer to the ways in which parts within a system are connected and interact. Reducing *tight coupling* while increasing *complexities* or by reducing *complexities* while having *tight coupling* help to mitigate several disruptions. Less number of components and options in components reduces the level of interaction. When the interactive complexity is high, even small independent failures can interact in unexpected ways and could lead to potential disruptions.

Product proliferations are the primary elements increasing complexities that are better managed through postponements by seeking undifferentiated status by delaying volume, weight, value adding operations or final customizations. Modular productions enable the process of delaying points where product variations are expected to happen and help in postponements. Excess resources in a loose coupling system are also dangerous as it generates a feeling of false security in supply chain systems. Companies are advised to check the level of complexity of their supply chain prior to take decision on adding flexibility or increasing redundancies in their supply chains (Yang & Yang, 2010).

1.8. Background of the Study

A robust supply chain is defined as the one reduces cost and improve customer relations and satisfaction under normal SC operations. SC resilience is compartmentalized to distinct stages as, *preparation to guard against disruptions, occurrence of the disruption, immediate and first response to disruptive events, the initial impact of the disruption, escalation of risk until its full impact, preparations for recovery and final recovery to normal operations*. Generally disruption risks are underestimated as it is difficult to quantify them and making it further difficult to justify preventive investments in robustness and security (Sodhi & Tang, 2012).

Supply chain management for disaster relief is to coordinate suppliers, equipment, manpower and organizations to facilitate quick and efficient responses to situations of crisis. *Supply chain disruption management* (SCDM) focus on business continuity by minimizing impact of disruptions in supply and demand (Khan & Burnes, 2007). As said earlier, supply chain constitutes a complex network with several interactions and interdependencies among process, assets and organizations.

Increasing complexities as well as the lack of proper prediction mechanisms hinder the proper control and management of vulnerabilities. Complexity can be referred to as difference between the information needed to perform a task and the information actually processed. Complexity consists of both *static* and *dynamic* types. *Static complexity* refers to how the elements interact with each other and how they are varied. *Dynamic complexity* is related to unpredictable variations and emerging behavior of supply chains over time periods.

A short term focus on risk management generally suggests a lower importance for managing risks. In uncertain and volatile markets, a flexible supply chain can exercise its options faster when compared to its competitors. Flexibility in brief can be mentioned as the ability to change or react with little penalty in *time, cost and performances*. Flexibility plays a pivotal role in coordination and provides the ability to manage high levels of environmental and operating uncertainties that are inherent to most supply networks.

Major risk management strategies are *postponement, speculation, hedging, control/ share/ transfer, security and avoidance of related risk outcomes*. *Postponement* is a type of flexibility by delaying the actual commitment of resources to delay the incurring costs. *Speculation* or selective risk taking is the counter objective strategy of postponement that holds the principle that changes should be made in the form and forward inventories at the earliest stage to reduce the costs in the marketing systems. *Hedging* is a risk management strategy at the supply side undertaken by globally dispersed portfolio of suppliers. Since there is a need for creating multiple options for decision variables, hedging is regarded as an expensive strategy.

Vertical integrations, contracts and agreements aid in the *control, share and transfer* of risks. Vertical integration increases the capability to control processes, systems and methods for every member in the supply chain. Vertical integration can be applied to both demand side and supply side by forward and backward integrations. Vertical integration serves the purpose of reducing vulnerabilities but it changes variable costs into fixed costs. *Security* strategy aims at triggering the unusual moving elements in the supply chain. Security strategies also enable close working with government and other agencies to proactively comply with regulations. *Avoidance* is another strategy to deal with risks. There are *two* types of avoidance strategies, avoidance strategy *type 1* is used while operating in a geographical market or a given product or working with certain suppliers or customers considered as unacceptable.

Avoidance is applied through divestment of specialized assets, delay entry into markets or participating in low uncertainty markets. Avoidance strategy of the *type 1* assumes the overall probability of risk events to zero by making sure that the risk does not exist. Avoidance strategy of *type 2* aids in preempting adverse events. The focus of avoidance strategy of *type 2* is to reduce the probability and frequency of risk events. It is entailed when managers are to enter into high uncertainty demand and supply markets without having any other option. Inter organizational leaning strengthens the effects of risk mitigation strategies over typical supply chain risks. Supply chain managers must understand the degree of complexity of their supply chains and the ability of their organizations to reduce it by enhancing inter-organizational learning processes (Manuj & Mentzer, 2008).

Considering the gaps in literature, *five* major problems related to supply chain risk management and resilience has been considered for the present study. For identifying the research gaps, many quantitative and qualitative works in literature have been reviewed for the study that is discussed in the coming chapters. It is seen that supply chain resilience is a growing area of interest for researchers and practitioners for the past decade. Quantification of supply chain resilience is a major problem and was addressed in Pettit (2010), Soni et al. (2014). But for quantifying resilience and vulnerability, many of the limitations are to be considered. In general, attributes of resilience are hard to measure on a tangible scale and most of the attributes have serious interrelationships among themselves. So the effect of risk mitigation strategy over individual risks need to be studied. This was the *first* objective of research. A research problem was formulated in the context of electronic supply chains considering *twelve* major risks and *twenty one* risk mitigation strategies. For the effective quantification of effects, a methodology using grey theory and digraph matrix was proposed and is discussed in chapter 2.

The *second* and *third* objectives are of complementary nature and are intended to address the gaps from the effective implementation of supply chain risk management practices to the formation of resilient supply chains. For that two major particulars need to be understood, one is the level of vulnerability of the supply chain and the other is the level of resilience needed. So the potential risks and the practices of risk mitigation in supply chain need to identified. Risk management should be more proactive than reactive. Hence, it is important to identify major risk drivers contributing towards these risks. Similarly, the practices of risk mitigation become effective only when the enablers of risk mitigation are identified and implemented properly.

But, it is perceived that the drivers of risks as well as the enablers of risk mitigation have serious interrelationships among themselves. Hence, for effectively reducing vulnerability, it is essential to prioritize the drivers of risks and to identify the root causal drivers of risks. The above said is also true for the enablers of risk mitigation. So a methodology appropriate for studying the cause effect relations is to be employed. A combination of grey theory and DEMATEL methodologies were employed for addressing this. The results expose those most important drivers of supply chain risks as well as the most important enablers of supply chain risk mitigation. Together, this leads to reduced vulnerabilities and enhanced risk management capabilities and in effect reduces the gap from the implementation of risk management practices to the creation of resilient supply chains.

The *fourth* problem is to select appropriate suppliers for a resilient supply chain. As major disruptions in the past are mostly supply related, resilience need to be built even from the process of selection of suppliers. The upstream supply chain is more vulnerable and the level of vulnerability is often hard to measure as suppliers are the vital sources of external risks. A supplier selection problem for a resilient supply chain is addressed and a methodology incorporating grey relational analysis has been employed for the study. The suppliers to be selected are in the context are named as resilient suppliers and the critical attributes of selection were formulated. The same was implemented for a practical case and results were compared with classical supplier selection methods as elaborated in chapter 5.

The *fifth* problem is to appropriately position decoupling point in a resilient supply chain. Decoupling point generally separates the supply chains based on its objective focusses into fragment networks. There are contradictory strategic objectives in supply chains as the present day supply chains transforms to supply networks, the positioning of decoupling point becomes a difficult task. The paradigm shift in the objective focus of various categories of supply chains in literature were studied and the positioning of decoupling point is referred to *eight* sample cases as proposed in chapter 6. The research was also extended to gain the benefits of sustainable supply chains and resilient supply chains together. This is possible by suitably fixing the partition line in the network and is discussed in detail in the chapter. The concept of a sustainable- resilient supply chain is proposed in this chapter.

The details of the *five* problems addressed, related literatures, methodology and the case evaluations are briefly discussed in chapters 2, 3, 4, 5 and 6. Also, meticulous analysis of the findings and the related discussions for the problems are completed. This is followed by the concluding remarks, delimitations and scope of future works for each of the *five* problems as elaborated in chapter 7. The niceties are elaborated in the subsequent chapters.

CHAPTER 2

SELECTION OF RISK MITIGATION STRATEGY USING GREY THEORY AND DIGRAPH- MATRIX APPROACHES

2.1. Framework of Risks and Mitigation Strategies

Quantification of supply chain risks and mitigation approaches can be seen in literature. However, risk mitigation approaches can have *positive* as well as *negative* influences over individual supply chain risks. A study in this direction was not conducted till date and the problem is to categorize risk mitigation strategies based on their net influence over individual supply chain risks. A combination of grey theory and digraph matrix approaches were used to answer the present problem. Thus, the risk mitigation strategies are ordered based on their net positive influence values (NPIV), as proposed in this research. Considering the literature, Jüttner et al. (2003) pointed on the importance of the concepts of supply chain vulnerability and its managerial counterpart, supply chain risk management. Later, Christopher & Peck (2004), Sheffi (2005) delineated the concept of supply chain resilience and elaborated the strategies for constructing a resilient supply chain through redundancy and flexibility. Manuj & Mentzer (2008) particularized concepts of global supply chain risk management with focus on the challenges faced by global supply chains. Ponomarov & Holcomb (2009) coagulated the concept of supply chain resilience for disruption management, through multi-disciplinary literature studies.

Tang & Musa (2011) investigated on research developments in supply chain risk management by identifying risk elements and potential mitigation strategies. Chopra & Sodhi (2012) revisited the types of risks in practical supply chains and concluded that, by continually stress testing the supply chains, managers will be in a position to protect against many types of supply-chain risks. Manuj (2013) related academic research with industry practice in the area of global sourcing risk management and recommended directions for future research in global sourcing risk management.

Chen et al. (2013) scrutinized three types of risks, namely supply risk, demand risk and process risk in relation to three types of collaboration, namely supplier collaboration, customer collaboration and internal collaboration, as a mechanism to mitigate those risks. Talluri et al. (2013) proposed a simulation methodology with data envelopment analysis and nonparametric statistical methods to analyze and rank alternative mitigation strategies. Marley et al. (2014) considered alternative strategies of risk mitigation for examining current supply chain processes by using normal accident theory and its constructs. Vilko et al. (2014) analyzed levels and nature of uncertainty in supply chains for efficient and effective implementation of supply chain risk management. Monroe et al. (2014) examined literature on supply chain disruptions for the past *ten* years to develop a clearer understanding of supply chain risks and risk mitigation strategies to deal with.

Supply chain risks predominantly focusing on electronic supply chains can be classified into several groups. Classification of risks and the mitigation approaches can be seen in literature, of which those significant in an electronic supply chain have been identified and framed for the study. A framework showing the risk categories and relevant literatures is shown in Table 2.1. Several risk mitigation strategies can be adopted to alleviate the effects of risks or to reduce the impacts of risks. The detailed framework of mitigation strategies and the literature dealt with are shown in Table 2.2.

Table 2.1: Categories of supply chain risks and their relevant literature

Sl No.	SC risk categories	Relevant literature	Remarks
1	**Supply chain design**	(Klibi, et al., 2010)	Manufacturer fails to incorporate design changes
2	**Forecast**	(Manuj & Mentzer, 2008)	Inaccurate forecasts due to longer lead times, seasonality etc.
3	**Procurement**	(Azevedo, et al., 2010)	Unanticipated increase in acquisition costs due to exchange rate fluctuations, single sourcing etc.
4	**Technology**	(Chopra & Sodhi, 2012)	Use of obsolete technologies or failure to adapt with new technological changes
5	**Capacity**	(Tang & Musa, 2011)	Underutilization and overutilization of capacities or capacity inflexibilities
6	**Inventory**	(Tang & Tomlin, 2008)	Too high or too low levels of inventories
7	**Transportation**	(Tuncel & Alpan, 2010)	Risks with movement of materials including infrastructure, vehicles etc.
8	**Disruptions**	(Tang & Musa, 2011)	Rare but severe events like natural disaster, labor disputes, war and terrorism etc.
9	**Delays**	(Giannakis & Louis, 2011)	High capacity utilizations, inflexibilities or poor yield of the suppliers
10	**System**	(Khan & Burnes, 2007)	Inappropriate e- commerce applications, excessive networking, system integration etc.
11	**Receivables**	(Hendricks & Singhal, 2005)	Delayed receivables from the customers
12	**IPR**	(Holweg, et al., 2011)	Increased vertical integration, amplified global outsourcing and having world-wide markets

Table 2.2: Robust strategies for supply chain risk mitigation

Sl No.	SC risk mitigation strategies	Relevant Literature	Remarks
1	**Adjust supply chain design**	(Qi, et al., 2010)	- Making parallel paths - Reducing the length of supply chains
2	**Flexible supply base**	(Asbjørnslett, 2009)	- Have redundant suppliers - Shift order quantities across suppliers
3	**Flexible supply contracts**	(Cheng, et al., 2011)	- Introducing binding contracts with clearly stated obligations - Shift order quantities across time
4	**Dynamic assortment planning**	(Sauré & Zeevi, 2013)	- Increases control of product demand - Better capability to manage demand - Rapid influence over demands of different products
5	**Aggregate or pool demand**	(Purvis, et al., 2014)	- Reduces capacity risks - Reduces inventory risks
6	**Adding capacity**	(Chen, et al., 2013)	- Adding real or virtual capacity - Quick responses towards large fluctuations in demand - Reduced delays and risk of procurement
7	**Standardization**	(Baud-Lavigne, et al., 2012)	- Interchangeable product assemblies - Reduction in inventory level
8	**Increase agility**	(Gligor & Holcomb, 2012)	- Favor cost over responsiveness for commodity products - Favor responsiveness over cost for shorter lifecycle products
9	**Concurrent processes**	(Liao, et al., 2010)	- Flexible process adaptation through flexible manufacturing systems - Tasks can be performed parallel rather sequential
10	**Increase collaboration**	(Caridi, et al., 2010)	- Increase trust among partners - Risk hedging opportunities
11	**Reducing bullwhips**	(Barlas & Gunduz, 2011)	- Increase visibility of capacity and inventory - Reduce information distortions - Reduce exaggeration of demand in times of product shortage
12	**Cross-trained employees**	(Closs, et al., 2011)	- Employees for one job are trained to perform other functions - Able to perform most tenacious job any time
13	**Postponement**	(Choi, et al., 2012)	- Increases product flexibility - Increases capability to manage supply - Speedier incorporation of product configuration changes
14	**Rationalize product range**	(de Leeuw, et al., 2013)	- Reduce risks by adjusting choice of products - Improves product availability

Sl No.	SC risk mitigation strategies	Relevant Literature	Remarks
15	**Strategic Stocking**	(Schmitt & Singh, 2012)	- Not-to-stock decisions for high risk products - Better supply management capabilities - Quick response over market demand under disruptions
16	**Flexible transportation**	(Azevedo, et al., 2010)	- Increases transportation availability - Reduces logistic costs
17	**Revenue management**	(Tang, 2006)	- Increases control of product demand - Enhances capability of managing demand
18	**Silent product rollover**	(Billington, et al., 2012)	- Increases control over product exposure - Better capability of managing supply and demand
19	**Have more customer accounts**	(Hofmann & Kotzab, 2010)	- Reduces receivable risks - Increases options for delayed differentiation
20	**Responsive pricing strategies**	(Choi, et al., 2012)	- Swing production quantities across different products - Swing demand across different products
21	**Using insurance**	(Dong & Tomlin, 2012)	- Offers compensation when processes go wrong - Dealing with risk in such a way by trying to avoid its effects

Literature review reveals that efforts have been made related to modeling of supply chain risks, drivers of various supply chain risks, and potential mitigation strategies against supply chain risks. Faisal et al. (2007) provided a conceptual framework for SCRM and modeled various variables associated with risk mitigation environment along with their interdependencies using graph theory and matrix methods. Wagner & Neshat (2010) developed an approach based on graph theory to quantify and mitigate supply chain vulnerability and compared the effectiveness of different risk mitigation strategies. Till date, a quantitative model showing the true (positive and negative) effects of supply chain risk mitigation strategies over risks has not been found in literature. This has provided the motivation for the present research.

2.2. Methodology

In this research, we have used a combination of grey theory and digraph-matrix methodologies for effectively identifying and quantifying the supply chain risk mitigation strategies. Deng (1982) proposed the concept of grey theory from grey sets by combining principles of system theory, space theory and control theory. It can be effectively used to solve uncertainty problems in cases of discrete data and incomplete information (Deng, 1989). A major advantage of grey system theory is that it is credible to generate satisfactory outcomes using a relatively small amount of data or with great variability in factors (Li, et al., 2007). Grey theory has been widely used by researchers to handle ambiguity generated from human judgments.

Grey theory can be potentially incorporated with any decision-making process to improve the accuracy of judgments (Tseng, 2009). Like fuzzy set theory, grey theory is an effective tool for resolving uncertain and indeterminate problems (Liu, et al., 2012). Also, grey theory has been successfully applied in many multi-criteria decision making problems (Xie, 2013; Kose, et al., 2013). The advantage of grey theory over fuzzy theory is that grey theory considers the condition of fuzziness and flexibility in dealing with inconsistent information in group-decision making situations. By using graph theory, the interactions among variables can be analyzed and readily be converted into mathematical equations (Christofides, 1975). This could enable the top management to understand the contributions of each mitigation strategies towards risks (Rao, 2007).

The *step* by *step* methodology in brief can be explained in the following way as; initially, the importance relations among risks and the positive and negative influence of risk mitigation strategies were recorded from analysts in linguistic scales. These matrices of linguistic labels were converted into grey matrices represented by grey numbers and the average grey relation matrices were obtained using grey averaging operators. The average grey relation matrices for positive and negative influence of risk mitigation strategies over risks were converted into crisp relation matrices using the method of grey number whitenization. These crisp relation matrices were modified to strategy selection matrices by replacing the diagonal elements of the importance relation matrices with values representing positive or negative influence of risk mitigation strategies over particular risks.

Thus, we have positive and negative strategy selection matrices and the permanent function of these matrices will give the actual positive or negative influences of risk mitigation strategies over entire risks. The difference between the same gives a representation of the net influence of a risk mitigation strategy, which can be used to effectively rank them. A flow chart representation of the proposed methodology, a combination of grey theory and digraph-matrix approaches is shown in Figure 2.1. The detailed *step* by *step* procedure of the proposed method is elaborated as follows:

Notations

$\otimes x_{ij}^{k}$	Grey matrices of importance ratings	$\otimes y_{pq}^{k}$	Grey matrices of positive influence ratings
$\otimes z_{pq}^{k}$	Grey matrices of negative influence ratings	$\otimes \tilde{x}_{ij}$	Average grey matrices of importance ratings
$\otimes \tilde{y}_{pq}$	Average grey matrices of positive influence ratings	$\otimes \tilde{z}_{pq}$	Average grey matrices of negative influence ratings
$\otimes \dot{x}_{ij}$	Normalized grey matrices of importance ratings	$\otimes \dot{y}_{ij}$	Normalized grey matrices of positive influence ratings
$\otimes \dot{z}_{ij}$	Normalized grey matrices of negative influence ratings	*A, B*	Strategy selection matrices

Step1: Compute the initial relation matrices

Let the number of supply chain risks be *'n'*, the identified supply chain mitigation strategies to be *'m'* and the respondents chosen for rating the supply chain risks and supply chain mitigation strategies to be *L*. Each respondent '*k'* is given the task of evaluating the importance of risk *i* over risk *j* on a linguistic scale varying from *EL, VL, L, M, H, VH, EH* representing *"extremely low importance", "very low importance", "low importance", medium importance", "high importance"*, *"very high importance,* and "*extremely high importance"* respectively. Similarly, the matrices of positive influences (*ELP- EHP*) and negative influences (*ELN- EHN*) were tabulated. Thus $3 \times L$ initial relation matrices were developed based on the importance ratings and influence ratings.

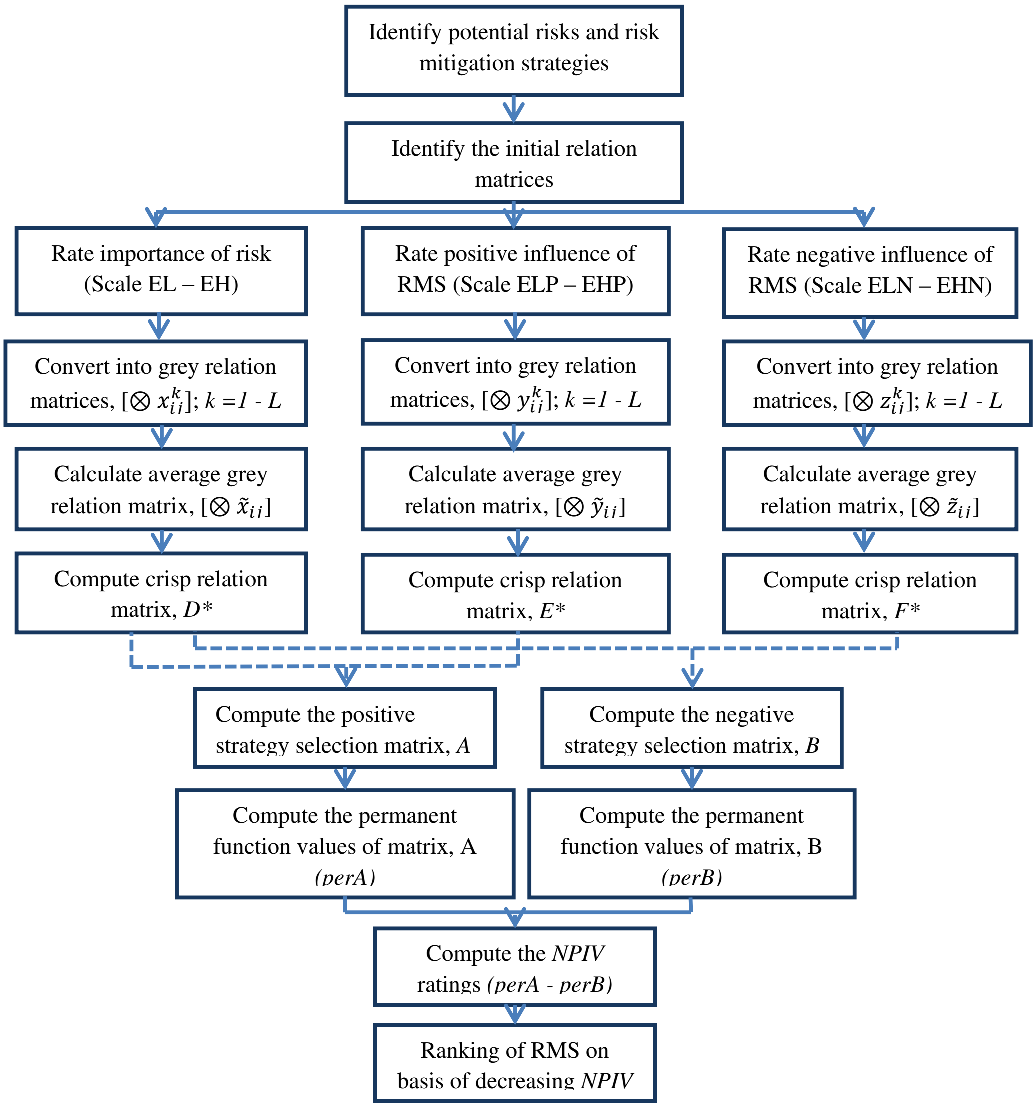


Figure 2.1: Flowchart representation of the proposed methodology

Step2: Compute the grey relation matrices

The linguistic ratings representing importance among risks, positive influence of mitigation strategies over risks and negative influence of mitigation strategies over risks can be converted into associated grey scales specifying an upper range and a lower range of values, i. e.

$$\otimes x_{ij}^{k} = \left(\underline{\otimes}\, x_{ij}^{k},\ \ \overline{\otimes}\, x_{ij}^{k}\right) \tag{2.1}$$

$$\otimes y_{pq}^{k} = \left(\underline{\otimes}\, y_{pq}^{k},\ \ \overline{\otimes}\, y_{pq}^{k}\right) \tag{2.2}$$

$$\otimes z_{pq}^{k} = \left(\underline{\otimes}\, z_{pq}^{k},\ \ \overline{\otimes}\, z_{pq}^{k}\right) \tag{2.3}$$

respectively, where $1 \leq k \leq L;\ 1 \leq i \leq n;\ 1 \leq j \leq n;\ 1 \leq p \leq m;\ 1 \leq q \leq n$

The initial relation matrices are converted into grey relation matrices based on the obtained grey values, $i.e.\ [\otimes x_{ij}^{1}], [\otimes x_{ij}^{2}], [\otimes x_{ij}^{3}], \ldots, [\otimes x_{ij}^{L}];\ [\otimes y_{pq}^{1}], [\otimes y_{pq}^{2}], [\otimes y_{pq}^{3}], \ldots, [\otimes y_{pq}^{L}];\ [\otimes z_{pq}^{1}], [\otimes z_{pq}^{2}], [\otimes z_{pq}^{3}], \ldots, [\otimes z_{pq}^{L}]$

Step3: Compute the average grey relation matrices

The average grey relation matrices $[\otimes \tilde{x}_{ij}], [\otimes \tilde{y}_{pq}]\ and\ [\otimes \tilde{z}_{pq}]$ can be constructed (Liu, et al., 2012; Kose, et al., 2013; Xie, 2013) from 3×L grey relation matrices, $[\otimes x_{ij}^{k}], [\otimes y_{pq}^{k}], [\otimes z_{pq}^{k}]$; $k = 1 - L$ as,

$$\otimes \tilde{x}_{ij} = \left(\frac{\sum_k \underline{\otimes} x_{ij}^{k}}{L}, \frac{\sum_k \overline{\otimes} x_{ij}^{k}}{L}\right) \tag{2.4}$$

$$\otimes \tilde{y}_{pq} = \left(\frac{\sum_k \underline{\otimes} y_{pq}^{k}}{L}, \frac{\sum_k \overline{\otimes} y_{pq}^{k}}{L}\right) \tag{2.5}$$

$$\otimes \tilde{z}_{pq} = \left(\frac{\sum_k \underline{\otimes} z_{pq}^{k}}{L}, \frac{\sum_k \overline{\otimes} z_{pq}^{k}}{L}\right) \tag{2.6}$$

Step4: Compute the crisp relation matrices from the average grey relation matrices

Grey values are converted into crisp values by modified- CFCS method, as shown;

(i) Normalization of the grey values

$$\underline{\otimes}\, \dot{x}_{ij} = \left(\underline{\otimes}\, \tilde{x}_{ij} - {}^{min}_{\ \ j}\underline{\otimes}\, \tilde{x}_{ij}\right) / \Delta_{min}^{max} \tag{2.7}$$

$$\underline{\otimes}\,\dot{y}_{pq} = \left(\underline{\otimes}\,\tilde{y}_{pq} - {}^{min}_{q}\underline{\otimes}\,\tilde{y}_{pq}\right)/\theta^{max}_{min} \quad (2.8)$$

$$\underline{\otimes}\,\dot{z}_{pq} = \left(\underline{\otimes}\,\tilde{z}_{pq} - {}^{min}_{q}\underline{\otimes}\,\tilde{z}_{pq}\right)/\beta^{max}_{min} \quad (2.9)$$

where, $\underline{\otimes}\,\dot{x}_{ij}$ represents the normalized lower limit value of the grey number $\otimes\,\tilde{x}_{ij}$, $\underline{\otimes}\,\dot{y}_{pq}$ represents the normalized lower limit value of the grey number $\otimes\,\tilde{y}_{pq}$ and $\underline{\otimes}\,\dot{z}_{pq}$ represents the normalized lower limit value of the grey number $\otimes\,\tilde{z}_{pq}$

$$\overline{\otimes}\,\dot{x}_{ij} = \left(\overline{\otimes}\,\tilde{x}_{ij} - {}^{min}_{j}\,\overline{\otimes}\,\tilde{x}_{ij}\right)/\Delta^{max}_{min} \quad (2.10)$$

$$\overline{\otimes}\,\dot{y}_{pq} = \left(\overline{\otimes}\,\tilde{y}_{pq} - {}^{min}_{q}\,\overline{\otimes}\,\tilde{y}_{pq}\right)/\theta^{max}_{min} \quad (2.11)$$

$$\overline{\otimes}\,\dot{z}_{pq} = \left(\overline{\otimes}\,\tilde{z}_{pq} - {}^{min}_{q}\,\overline{\otimes}\,\tilde{z}_{pq}\right)/\beta^{max}_{min} \quad (2.12)$$

where $\overline{\otimes}\,\dot{x}_{ij}$ represents the normalized upper limit value of the grey number $\otimes\,\tilde{x}_{ij}$, $\overline{\otimes}\,\dot{y}_{pq}$ represents the normalized upper limit value of the grey number $\otimes\,\tilde{y}_{pq}$, and $\overline{\otimes}\,\dot{z}_{pq}$ represents the normalized upper limit value of the grey number $\otimes\,\tilde{z}_{pq}$.

$$\Delta^{max}_{min} = {}^{max}_{j}\,\overline{\otimes}\,\tilde{x}_{ij} - {}^{min}_{j}\underline{\otimes}\,\tilde{x}_{ij} \quad (2.13)$$

$$\theta^{max}_{min} = {}^{max}_{q}\,\overline{\otimes}\,\tilde{y}_{pq} - {}^{min}_{q}\underline{\otimes}\,\tilde{y}_{pq} \quad (2.14)$$

$$\beta^{max}_{min} = {}^{max}_{q}\,\overline{\otimes}\,\tilde{z}_{pq} - {}^{min}_{q}\underline{\otimes}\,\tilde{z}_{pq} \quad (2.15)$$

(ii) Calculating total normalized crisp values

$$a_{ij} = \left(\frac{\left(\underline{\otimes}\dot{x}_{ij}(1-\underline{\otimes}\dot{x}_{ij})\right)+(\overline{\otimes}\dot{x}_{ij}\times\overline{\otimes}\dot{x}_{ij})}{(1-\underline{\otimes}\dot{x}_{ij}+\overline{\otimes}\dot{x}_{ij})}\right) \quad (2.16)$$

$$b_{pq} = \left(\frac{\left(\underline{\otimes}\dot{y}_{pq}(1-\underline{\otimes}\dot{y}_{pq})\right)+(\overline{\otimes}\dot{y}_{pq}\times\overline{\otimes}\dot{y}_{pq})}{(1-\underline{\otimes}\dot{y}_{pq}+\overline{\otimes}\dot{y}_{pq})}\right) \quad (2.17)$$

$$c_{pq} = \left(\frac{\left(\underline{\otimes}\dot{z}_{pq}(1-\underline{\otimes}\dot{z}_{pq})\right)+(\overline{\otimes}\dot{z}_{pq}\times\overline{\otimes}\dot{z}_{pq})}{(1-\underline{\otimes}\dot{z}_{pq}+\overline{\otimes}\dot{z}_{pq})}\right) \quad (2.18)$$

(iii) Computing the final crisp values

$$d_{ij} = \left(min \underline{\otimes}\, \tilde{x}_{ij} + \left(a_{ij} \times \Delta_{min}^{max}\right)\right) \quad (2.19)$$

$$e_{pq} = \left(min \underline{\otimes}\, \tilde{y}_{pq} + \left(b_{pq} \times \theta_{min}^{max}\right)\right) \quad (2.20)$$

$$f_{pq} = \left(min \underline{\otimes}\, \tilde{z}_{pq} + \left(c_{pq} \times \beta_{min}^{max}\right)\right) \quad (2.21)$$

$$D^* = \left[d_{ij}\right] \quad (2.22)$$

$$E^* = \left[e_{pq}\right] \quad (2.23)$$

and, $F^* = \left[f_{pq}\right]$ (2.24)

Step5: Compute the strategy selection matrices from the crisp relation matrices

The mitigation strategy selection is done by forming strategy selection matrices for positive and negative effects of mitigation strategies over different types of risks. The positive strategy selection matrix consists of values, E_i on diagonals representing the positive effect of mitigation strategies over risks *(1 ≤ i ≤ n)* and e_{ij} values on rows representing the importance of risk *i* over *j*. This matrix is represented as matrix *A*, the permanent of the matrix gives the positive influence of mitigation strategies over risks. Similarly, the negative strategy selection matrix consists of values, F_i on diagonals representing the negative influence of mitigation strategies over risks *(1 ≤ i ≤ n)* and f_{ij} values on rows representing the importance of risk *i* over *j*. This matrix is represented as *B*; the permanent of the matrix gives the negative effects of mitigation strategies over risks. i. e.,

$$A = \begin{bmatrix} E_1 & e_{12} & \cdots & e_{1n} \\ e_{21} & E_2 & \cdots & e_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ e_{n1} & e_{n2} & \cdots & E_n \end{bmatrix} \quad (2.25)$$

$$B = \begin{bmatrix} F_1 & f_{12} & \cdots & f_{1n} \\ f_{21} & F_2 & \cdots & f_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ f_{n1} & f_{n2} & \cdots & F_n \end{bmatrix} \tag{2.26}$$

Step6: Compute the permanent functions of the selection matrices

The permanent of a matrix is a standard function used in combinatorial optimization (Jurkat & Ryser, 1966; Nijenhuis, 1976). The permanent function of a matrix *J*, representing *M* criteria has *M!* (Factorial *M*) terms arranged in *M+1* groups and these groups represent measures of influence criteria and relative importance loops. The *first* group represents the influences of *M* criteria. The *second* group represents the self-loop relations and will be absent if there are no self-loops. The *third* group contains *two* criteria relative importance loops and influences of *M-2* criteria. The *fourth* group represents a set of *three* criteria relative importance loop or its pair and measures of influence of *M-3* criteria. The *fifth* group comprises of *two* sub groups; first of which is a set of *two* criteria relative importance loops with influence measures of *M-4* criteria and the next is a set of *four* attribute relative importance loop or its pair with influence measures of *M-4* criteria. The *sixth* group also contains two sub-groups; of which the *first* one represents a set of three criteria relative importance loop or its pair and *two* criteria importance loop with influence measures of *M-5* criteria and the next is a set of *five* attribute relative importance loop or its pair with influence measures of *M-5* criteria. Similarly other terms are defined. So, the permanent function comprises of all possible combinations of influence of criteria and the relative importance among them.

$$\text{Assume, } J = \begin{bmatrix} A_1 & a_{12} & \cdots & a_{1M} \\ a_{21} & A_2 & \cdots & a_{2M} \\ \vdots & \vdots & \ddots & \vdots \\ a_{M1} & a_{M2} & \cdots & A_M \end{bmatrix} \tag{2.27}$$

The expression for permanent function of matrix *J (M×M)* can be found in section 2.3 of Rao (2007), which is nothing but the determinant expansion of a matrix considering all the terms to be positive. Similarly, permanent function of the matrices *A* and *B* can be calculated for 'm' mitigation criteria.

Step7: Ranking of the mitigation strategies

The permanent function values for 'm' mitigation strategies were calculated for *A* and *B* matrices, where $per\ (A)$ represents the positive impact of the mitigation strategy 'p' over risks and the value $per\ (B)$ typifies the negative impact of the mitigation strategy over risks. The value *NPIV* is calculated, representing the net positive influence of mitigation strategy 'p' over the total risk profile. i. e.,

$$NPIV = per(A) - per(B) \tag{2.28}$$

The mitigation strategies are ranked based upon its effectiveness, in the descending order of values of *NPIV*.

$$
per(A)=\left(\begin{aligned}
&\prod_{i=1}^{12}E_i+\sum_{i=1}^{11}\sum_{j=i+1}^{12}\sum_{k=1}^{3}\sum_{l=k+1}^{4}\sum_{m=l+1}^{5}\sum_{n=m+1}^{6}\sum_{p=n+1}^{7}\sum_{q=p+1}^{8}\sum_{r=q+1}^{9}\sum_{s=r+1}^{10}\sum_{t=s+1}^{11}\sum_{u=t+1}^{12}\left(e_{ij}e_{ji}\right)E_kE_lE_mE_nE_pE_qE_rE_sE_tE_u+\\
&\sum_{i=1}^{10}\sum_{j=i+1}^{11}\sum_{k=j+1}^{12}\sum_{l=1}^{11}\sum_{m=l+1}^{12}\sum_{n=m+1}^{6}\sum_{p=n+1}^{7}\sum_{q=p+1}^{8}\sum_{r=q+1}^{9}\sum_{s=r+1}^{10}\sum_{t=s+1}^{11}\sum_{u=t+1}^{12}\left(e_{ij}e_{jk}e_{ki}+e_{ik}e_{kj}e_{ji}\right)\left(e_{ml}e_{lm}\right)E_nE_pE_qE_rE_sE_tE_u+\\
&\sum_{i=1}^{8}\sum_{j=i+1}^{11}\sum_{k=i+1}^{12}\sum_{l=i+1}^{12}\sum_{m=j+1}^{12}\sum_{n=m+1}^{6}\sum_{p=n+1}^{7}\sum_{q=p+1}^{8}\sum_{r=q+1}^{9}\sum_{s=r+1}^{10}\sum_{t=s+1}^{11}\sum_{u=t+1}^{12}\left(e_{ij}e_{jk}e_{kl}e_{lm}e_{mi}+e_{im}e_{ml}e_{lk}e_{kj}e_{ji}\right)E_nE_pE_qE_rE_sE_tE_u+\\
&\sum_{i=1}^{9}\sum_{j=i+1}^{11}\sum_{k=i+1}^{12}\sum_{l=1}^{11}\sum_{m=l+1}^{12}\sum_{n=m+1}^{6}\sum_{p=n+1}^{7}\sum_{q=p+1}^{8}\sum_{r=q+1}^{9}\sum_{s=r+1}^{10}\sum_{t=s+1}^{11}\sum_{u=t+1}^{12}\left(e_{ij}e_{jk}e_{kl}e_{li}+e_{ik}e_{lk}e_{kj}e_{li}\right)\left(e_{mn}e_{nm}\right)E_pE_qE_rE_sE_tE_u+\\
&\sum_{i=1}^{7}\sum_{j=i+1}^{11}\sum_{k=i+1}^{12}\sum_{l=1}^{10}\sum_{m=l+1}^{11}\sum_{n=m+1}^{12}\sum_{p=n+1}^{7}\sum_{q=p+1}^{8}\sum_{r=q+1}^{9}\sum_{s=r+1}^{10}\sum_{t=s+1}^{11}\sum_{u=t+1}^{12}\left(e_{ij}e_{jk}e_{ki}+e_{ik}e_{kj}e_{ji}\right)\left(e_{lm}e_{mn}e_{nl}+e_{ln}e_{nm}e_{ml}\right)E_pE_qE_rE_sE_tE_u+\\
&\sum_{i=1}^{7}\sum_{j=i+1}^{12}\sum_{k=i+1}^{9}\sum_{l=i+2}^{12}\sum_{m=k+1}^{11}\sum_{n=k+2}^{12}\sum_{p=n+1}^{7}\sum_{q=p+1}^{8}\sum_{r=q+1}^{9}\sum_{s=r+1}^{10}\sum_{t=s+1}^{11}\sum_{u=t+1}^{12}\left(e_{ij}e_{ji}\right)\left(e_{kl}e_{lk}\right)\left(e_{mn}e_{nm}\right)E_pE_qE_rE_sE_tE_u+\\
&\sum_{i=1}^{7}\sum_{j=i+1}^{11}\sum_{k=i+1}^{12}\sum_{l=i+1}^{12}\sum_{m=i+1}^{12}\sum_{n=j+1}^{12}\sum_{p=n+1}^{7}\sum_{q=p+1}^{8}\sum_{r=q+1}^{9}\sum_{s=r+1}^{10}\sum_{t=s+1}^{11}\sum_{u=t+1}^{12}\left(e_{ij}e_{jk}e_{kl}e_{lm}e_{mn}e_{ni}+e_{in}e_{nm}e_{ml}e_{lk}e_{kj}e_{ji}\right)E_pE_qE_rE_sE_tE_u+\ldots\ldots
\end{aligned}\right)
$$

$k.l,m,n,\ldots,u\neq pus$

$$
per(B)=\left(\begin{aligned}
&\prod_{i=1}^{12}F_i+\sum_{i=1}^{11}\sum_{j=i+1}^{12}\sum_{k=1}^{3}\sum_{l=k+1}^{4}\sum_{m=l+1}^{5}\sum_{n=m+1}^{6}\sum_{p=n+1}^{7}\sum_{q=p+1}^{8}\sum_{r=q+1}^{9}\sum_{s=r+1}^{10}\sum_{t=s+1}^{11}\sum_{u=t+1}^{12}\left(f_{ij}f_{ji}\right)F_kF_lF_mF_nF_pF_qF_rF_sF_tF_u+\\
&\sum_{i=1}^{10}\sum_{j=i+1}^{11}\sum_{k=j+1}^{12}\sum_{l=1}^{11}\sum_{m=l+1}^{12}\sum_{n=m+1}^{6}\sum_{p=n+1}^{7}\sum_{q=p+1}^{8}\sum_{r=q+1}^{9}\sum_{s=r+1}^{10}\sum_{t=s+1}^{11}\sum_{u=t+1}^{12}\left(f_{ij}f_{jk}f_{ki}+f_{ik}f_{kj}f_{ji}\right)\left(f_{ml}f_{lm}\right)F_nF_pF_qF_rF_sF_tF_u+\\
&\sum_{i=1}^{8}\sum_{j=i+1}^{11}\sum_{k=i+1}^{12}\sum_{l=i+1}^{12}\sum_{m=j+1}^{12}\sum_{n=m+1}^{6}\sum_{p=n+1}^{7}\sum_{q=p+1}^{8}\sum_{r=q+1}^{9}\sum_{s=r+1}^{10}\sum_{t=s+1}^{11}\sum_{u=t+1}^{12}\left(f_{ij}f_{jk}f_{kl}f_{lm}f_{mi}+f_{im}f_{ml}f_{lk}f_{kj}f_{ji}\right)F_nF_pF_qF_rF_sF_tF_u+\\
&\sum_{i=1}^{9}\sum_{j=i+1}^{11}\sum_{k=i+1}^{12}\sum_{l=1}^{11}\sum_{m=l+1}^{12}\sum_{n=m+1}^{6}\sum_{p=n+1}^{7}\sum_{q=p+1}^{8}\sum_{r=q+1}^{9}\sum_{s=r+1}^{10}\sum_{t=s+1}^{11}\sum_{u=t+1}^{12}\left(f_{ij}f_{jk}f_{kl}f_{li}+f_{ik}f_{lk}f_{kj}f_{li}\right)\left(f_{mn}f_{nm}\right)F_pF_qF_rF_sF_tF_u+\\
&\sum_{i=1}^{7}\sum_{j=i+1}^{11}\sum_{k=i+1}^{12}\sum_{l=1}^{10}\sum_{m=l+1}^{11}\sum_{n=m+1}^{12}\sum_{p=n+1}^{7}\sum_{q=p+1}^{8}\sum_{r=q+1}^{9}\sum_{s=r+1}^{10}\sum_{t=s+1}^{11}\sum_{u=t+1}^{12}\left(f_{ij}f_{jk}f_{ki}+f_{ik}f_{kj}f_{ji}\right)\left(f_{lm}f_{mn}f_{nl}+f_{ln}f_{nm}f_{ml}\right)F_pF_qF_rF_sF_tF_u+\\
&\sum_{i=1}^{7}\sum_{j=i+1}^{12}\sum_{k=i+1}^{9}\sum_{l=i+2}^{12}\sum_{m=k+1}^{11}\sum_{n=k+2}^{12}\sum_{p=n+1}^{7}\sum_{q=p+1}^{8}\sum_{r=q+1}^{9}\sum_{s=r+1}^{10}\sum_{t=s+1}^{11}\sum_{u=t+1}^{12}\left(f_{ij}f_{ji}\right)\left(f_{kl}f_{lk}\right)\left(f_{mn}f_{nm}\right)F_pF_qF_rF_sF_tF_u+\\
&\sum_{i=1}^{7}\sum_{j=i+1}^{11}\sum_{k=i+1}^{12}\sum_{l=i+1}^{12}\sum_{m=i+1}^{12}\sum_{n=j+1}^{12}\sum_{p=n+1}^{7}\sum_{q=p+1}^{8}\sum_{r=q+1}^{9}\sum_{s=r+1}^{10}\sum_{t=s+1}^{11}\sum_{u=t+1}^{12}\left(f_{ij}f_{jk}f_{kl}f_{lm}f_{mn}f_{ni}+f_{in}f_{nm}f_{ml}f_{lk}f_{kj}f_{ji}\right)F_pF_qF_rF_sF_tF_u+\ldots\ldots
\end{aligned}\right)
$$

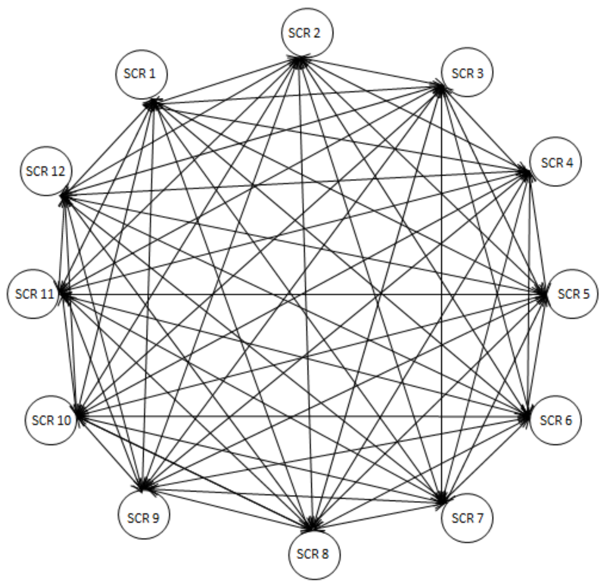
$k.l,m,n,\ldots,u\neq pus$

(2.29)

2.3. Case Study

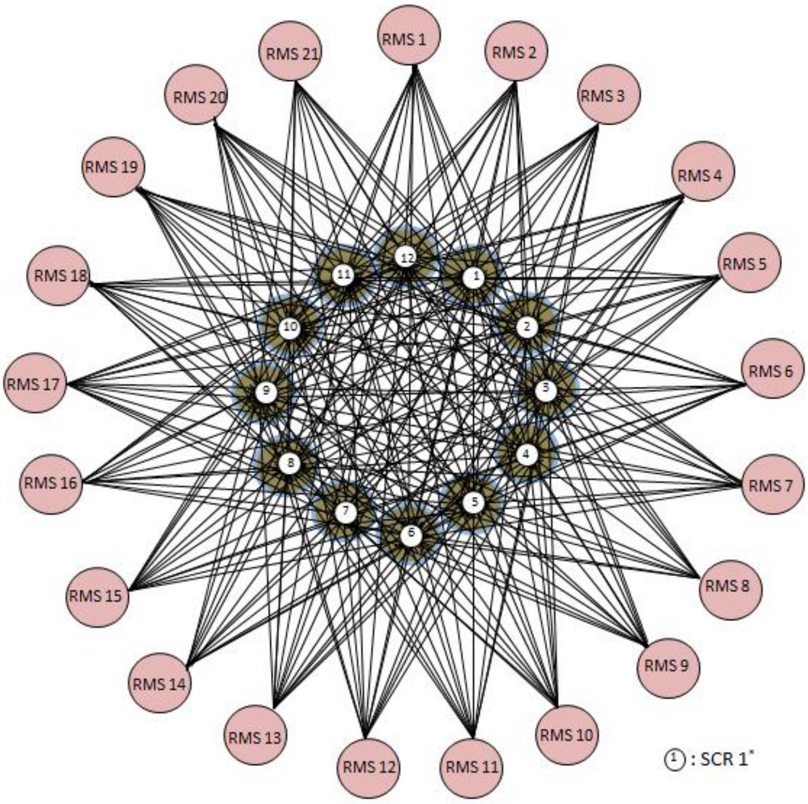
The proposed methodology in this research was evaluated in an electronic manufacturing company *'XYZ'* in India. The case electronic company is chosen to be a representative case for testing the impact of mitigation strategies. *XYZ'*s global supply chain has raw material extraction and processing on its one end and component manufacturing and final product assembly at the other. In-house manufacturing is more desired by *XYZ*, ensuing strict social and environmental standards. Having a global manufacturing network intensifies the risks and chances of vulnerability of its supply chain. *XYZ*'s supply chain was currently facing a critical shortage of a particular component due to problems with indirect suppliers. A particular component supplier relied on single sourcing for his component manufacturing was identified as the prime cause of the shortage. Subsequently, *XYZ* planned to take some proactive steps in its supply chain risk mitigation strategies. Evaluation of the mitigation strategies and assessment of risks is critical to the supply chain of *XYZ.* Hence implementation of effective mitigation strategies to tackle supply chain risks assumes great significance for the company in this context.

In this research, a combination of grey theory and digraph matrix approaches has been used to rank the mitigation strategies based on its effectiveness. The procedure in brief, involves the calculation of positive and negative influences of supply chain risk mitigation strategies over different supply chain risks by calculating the permanent functions. The importance relation among supply chain risks, positive and negative influences of risk mitigation strategies on supply chain risks are represented as digraphs shown in Figures 2.2 and 2.3, respectively.



* 'SCR 1' represents the supply chain risk '*supply chain design risk*', as in Table 1. Similarly all other elements can be read

Figure 2.2: Digraph showing the importance relations among supply chain risks



* 'SCR 1' represents the supply chain risk '*supply chain design risk*', as in Table 1 and 'RMS 1' represents the risk mitigation strategy '*adjust supply chain design*', as in Table 2. Similarly all other elements can be read.

Figure 2.3: Digraph representing the positive and negative influences of risk mitigation strategies on supply chain risks

The case study enables us to understand the implications and limitations of this research from a practical setting. A sample of the calculations has been added in Annexure 1. The *step* by *step* procedure is elaborated as follows:

Step1: A group of *three* supply chain analysts of the case company *XYZ* was given the task of rating the influence of risk mitigation strategies on risks. The supply chain analysts were specialists in the field of supply chain and logistics management having a work experience of over *ten* years in this field. *Twelve* major categories of risks and *twenty one* of the risk mitigation strategies were identified for the case supply chain. The supply chain analysts rated the importance among risks, positive influences of mitigation strategies on risks and negative influences of mitigation strategies on risks separately on a *seven* point scale as shown in Table 3.3. For uniformity of comparison of ratings, we have assumed the same grey scales for importance relations and for the influence relations.

Table 2.3: Linguistic assessment and the associated grey values

Relative importance of supply chain risks	
Linguistic assessment	**Associated grey values**
Extremely low importance (EL)	[0.0, 0.2]
Very low importance (VL)	[0.1, 0.3]
Low importance (L)	[0.3, 0.5]
Medium importance (M)	[0.4, 0.6]
High importance (H)	[0.6, 0.8]
Very high importance (VH)	[0.7, 0.9]
Extremely high importance (EH)	[0.9, 1.0]
Level of positive influence of mitigation strategies on supply chain risks	
Linguistic assessment	**Associated grey values**
Extremely low influence (ELP)	[0.0, 0.2]
Very low influence (VLP)	[0.1, 0.3]
Low influence (LP)	[0.3, 0.5]
Medium influence (MP)	[0.4, 0.6]
High influence (HP)	[0.6, 0.8]
Very high influence (VHP)	[0.7, 0.9]
Extremely high influence (EHP)	[0.9, 1.0]
Level of negative influence of mitigation strategies on supply chain risks	
Linguistic assessment	**Associated grey values**
Extremely low influence (ELN)	[0.0, 0.2]
Very low influence (VLN)	[0.1, 0.3]
Low influence (LN)	[0.3, 0.5]
Medium influence (MN)	[0.4, 0.6]
High influence (HN)	[0.6, 0.8]
Very high influence (VHN)	[0.7, 0.9]
Extremely high influence (EHN)	[0.9, 1.0]

Step2: The linguistic ratings representing importance among risks, positive influence of mitigation strategies over risks and negative influence of mitigation strategies over risks were converted into grey values using equations (2.1), (2.2), and (2.3). *Three* of the initial *12×12* grey relation matrices representing importance among risks and *six* initial relation matrices representing influence of mitigation strategies over risks were framed.

Step3: The average relation matrices $[\otimes \tilde{x}_{ij}]$, $[\otimes \tilde{y}_{pq}]$ and $[\otimes \tilde{z}_{pq}]$ were constructed from *nine* of the initial grey relation matrices, using equations (2.4), (2.5), and (2.6).

Step4: The grey values were converted into crisp values by using equations (2.7) to (2.24). Final crisp values were obtained from the rated grey values. The matrices representing each were shown in tables (2.4), (2.5), and (2.6) respectively.

Table 2.4: Crisp relation matrix of relative importance of supply chain risks

	SCR1	**SCR2**	**SCR3**	**SCR4**	**SCR5**	**SCR6**	**SCR7**	**SCR8**	**SCR9**	**SCR10**	**SCR11**	**SCR12**
SCR1	0	0.795	0.83	0.516	0.52	0.516	0.864	0.479	0.733	0.314	0.991	0.4
SCR2	0.205	0	0.512	0.516	0.76	0.795	0.824	0.14	0.733	0.512	0.733	0.319
SCR3	0.17	0.488	0	0.795	0.76	0.795	0.746	0.437	0.733	0.512	0.655	0.4
SCR4	0.484	0.484	0.205	0	0.4	0.397	0.746	0.096	0.733	0.592	0.5	0.439
SCR5	0.48	0.24	0.24	0.6	0	0.397	0.746	0.351	0.812	0.75	0.85	0.361
SCR6	0.484	0.205	0.205	0.603	0.603	0	0.509	0.096	0.733	0.592	0.772	0.121
SCR7	0.136	0.176	0.254	0.254	0.254	0.491	0	0.054	0.655	0.394	0.5	0.079
SCR8	0.521	0.86	0.563	0.904	0.649	0.904	0.946	0	0.991	0.83	0.947	0.76
SCR9	0.267	0.267	0.267	0.267	0.188	0.267	0.345	0.009	0	0.394	0.655	0.16
SCR10	0.686	0.488	0.488	0.408	0.25	0.408	0.606	0.17	0.606	0	0.733	0.481
SCR11	0.009	0.267	0.345	0.5	0.15	0.228	0.5	0.053	0.345	0.267	0	0.16
SCR12	0.6	0.681	0.6	0.561	0.639	0.879	0.921	0.24	0.84	0.519	0.84	0

* SCR1 indicates the associated supply chain risk, '*Supply chain design risk*', as in Table 2.1. Similarly, the other elements of table can be read. The level of importance of supply chain risk *i* over supply chain risk *j* is represented as crisp values d_{ij}.

Table 2.5: Crisp relation matrix showing positive influences of risk mitigation strategies on supply chain risks

	SCR1	SCR2	SCR3	SCR4	SCR5	SCR6	SCR7	SCR8	SCR9	SCR10	SCR11	SCR12
RMS1	0	0.864	0.5	0.079	0.509	0.427	0	0	0.47	0	0	0
RMS2	0.04	0.509	0.991	0.04	0.509	0.506	0.033	0	0.746	0	0	0.4
RMS3	0.04	0.311	0.85	0.04	0.036	0.506	0	0.4	0.47	0.033	0	0.4
RMS4	0.04	0.864	0.991	0.079	0.509	0.506	0	0	0.589	0	0	0
RMS5	0.04	0.036	0	0.04	0.864	0.908	0.6	0	0.509	0.033	0	0
RMS6	0.04	0.036	0.9	0.04	0	0.035	0.067	0.6	0.864	0	0	0
RMS7	0.04	0.036	0.033	0.16	0.391	0.741	0	0.033	0.746	0	0	0
RMS8	0.04	0.509	0.5	0.601	0.509	0.78	0.3	0.1	0.746	0	0.467	0
RMS9	0.04	0.036	0.033	0.601	0.746	0.506	0	0.367	0.509	0.033	0	0
RMS10	0.04	0.036	0.85	0.04	0.746	0.741	0.4	0.367	0.589	0	0	0
RMS11	0	0.864	0.85	0.079	0.864	0.82	0.4	0.4	0.509	0.74	0.4	0.1
RMS12	0.04	0.036	0.033	0.04	0.509	0.035	0	0.6	0.509	0	0.033	0
RMS13	0.52	0.154	0.85	0.199	0.036	0.741	0	0	0.509	0	0	0.033
RMS14	0.76	0.785	0.033	0.04	0.036	0.585	0.033	0	0	0	0	0
RMS15	0.04	0.036	0.85	0.76	0.509	0	0.033	0.7	0.746	0.033	0	0
RMS16	0.52	0.036	0.072	0.079	0.076	0.035	0.811	0.033	0.864	0	0	0
RMS17	0.76	0.746	0.5	0.559	0.036	0.506	0	0.4	0.036	0.4	0.4	0.4
RMS18	0.04	0.036	0.733	0	0.036	0.741	0.033	0	0.036	0	0	0
RMS19	0.04	0.036	0.033	0.04	0.036	0.035	0	0.067	0.036	0	0.811	0
RMS20	0	0	0.812	0.04	0.666	0.741	0	0.467	0.509	0	0	0
RMS21	0.04	0.036	0.655	0.76	0.589	0.506	0.3	0.777	0.036	0.6	0.533	0.7

* SCR1 indicates the associated supply chain risk, '*Supply chain design risk*' and RMS1 indicates the risk mitigation strategy, '*Adjust supply chain design*' as in Table 2.1 and Table 2.2, respectively. Similarly, the other elements of the table can be read. The level of positive influence of mitigation strategy p over the supply chain risk q is represented as crisp value e_{pq}.

Table 2.6: Crisp relation matrix showing negative influences of risk mitigation strategies on supply chain risks

	SCR1	SCR2	SCR3	SCR4	SCR5	SCR6	SCR7	SCR8	SCR9	SCR10	SCR11	SCR12
RMS1	0.951	0	0	0	0	0	0	0	0	0	0	0
RMS2	0	0	0	0	0	0	0	0	0	0	0	0
RMS3	0	0	0	0	0	0	0	0	0	0	0	0
RMS4	0	0	0	0	0	0	0	0	0	0	0	0
RMS5	0	0	0.795	0	0	0	0	0	0	0	0	0
RMS6	0	0	0	0	0.991	0	0	0	0	0	0	0
RMS7	0	0	0	0	0	0	0	0	0	0	0	0
RMS8	0	0	0	0	0	0	0	0	0	0	0	0
RMS9	0	0	0	0	0	0	0	0	0	0	0	0
RMS10	0	0	0	0	0	0	0	0	0	0	0	0
RMS11	0.855	0	0	0	0	0	0	0	0	0	0	0
RMS12	0	0	0	0	0	0	0	0	0	0	0	0
RMS13	0	0	0	0	0	0	0	0	0	0	0	0
RMS14	0	0	0	0	0	0	0	0	0.76	0	0	0
RMS15	0	0	0	0	0	0.83	0	0	0	0	0	0
RMS16	0	0	0	0	0	0	0	0	0	0	0	0
RMS17	0	0	0	0	0	0	0	0	0	0	0	0
RMS18	0	0	0	0.621	0	0	0	0	0	0	0	0
RMS19	0	0	0	0	0	0	0	0	0	0	0	0
RMS20	0.464	0.76	0	0	0	0	0	0	0	0	0	0
RMS21	0	0	0	0	0	0	0	0	0	0	0	0

* SCR1 indicates the associated supply chain risk, '*Supply chain design risk*' and RMS1 indicates the risk mitigation strategy, '*Adjust supply chain design*' as in Table 2.1 and Table 2.2, respectively. Similarly, the other elements of the table can be read. The level of negative influence of mitigation strategy p over the supply chain risk q is represented as crisp value f_{pq}.

Step5: The mitigation strategy selection matrices were constructed for positive and negative effects of mitigation strategies over different types of risks using equations (2.25) and (2.26). The A and B matrices shown in Tables 2.7 and 2.8 signify the positive strategy selection matrix and the negative strategy selection matrix, respectively.

Table 2.7: Permanent function matrix of positive influences of RMS

***A*=**

E_1	0.795	0.83	0.516	0.52	0.516	0.864	0.479	0.733	0.314	0.991	0.4
0.205	E_2	0.512	0.516	0.76	0.795	0.824	0.14	0.733	0.512	0.733	0.319
0.17	0.488	E_3	0.795	0.76	0.795	0.746	0.437	0.733	0.512	0.655	0.4
0.484	0.484	0.205	E_4	0.4	0.397	0.746	0.096	0.733	0.592	0.5	0.439
0.48	0.24	0.24	0.6	E_5	0.397	0.746	0.351	0.812	0.75	0.85	0.361
0.484	0.205	0.205	0.603	0.603	E_6	0.509	0.096	0.733	0.592	0.772	0.121
0.136	0.176	0.254	0.254	0.254	0.491	E_7	0.054	0.655	0.394	0.5	0.079
0.521	0.86	0.563	0.904	0.649	0.904	0.946	E_8	0.991	0.83	0.947	0.76
0.267	0.267	0.267	0.267	0.188	0.267	0.345	0.009	E_9	0.394	0.655	0.16
0.686	0.488	0.488	0.408	0.25	0.408	0.606	0.17	0.606	E_{10}	0.733	0.481
0.009	0.267	0.345	0.5	0.15	0.228	0.5	0.053	0.345	0.267	E_{11}	0.16
0.6	0.681	0.6	0.561	0.639	0.879	0.921	0.24	0.84	0.519	0.84	E_{12}

Table 2.8: Permanent function matrix of negative influences of RMS

***B*=**

F_1	0.795	0.83	0.516	0.52	0.516	0.864	0.479	0.733	0.314	0.991	0.4
0.205	F_2	0.512	0.516	0.76	0.795	0.824	0.14	0.733	0.512	0.733	0.319
0.17	0.488	F_3	0.795	0.76	0.795	0.746	0.437	0.733	0.512	0.655	0.4
0.484	0.484	0.205	F_4	0.4	0.397	0.746	0.096	0.733	0.592	0.5	0.439
0.48	0.24	0.24	0.6	F_5	0.397	0.746	0.351	0.812	0.75	0.85	0.361
0.484	0.205	0.205	0.603	0.603	F_6	0.509	0.096	0.733	0.592	0.772	0.121
0.136	0.176	0.254	0.254	0.254	0.491	F_7	0.054	0.655	0.394	0.5	0.079
0.521	0.86	0.563	0.904	0.649	0.904	0.946	F_8	0.991	0.83	0.947	0.76
0.267	0.267	0.267	0.267	0.188	0.267	0.345	0.009	F_9	0.394	0.655	0.16
0.686	0.488	0.488	0.408	0.25	0.408	0.606	0.17	0.606	F_{10}	0.733	0.481
0.009	0.267	0.345	0.5	0.15	0.228	0.5	0.053	0.345	0.267	F_{11}	0.16
0.6	0.681	0.6	0.561	0.639	0.879	0.921	0.24	0.84	0.519	0.84	F_{12}

Step6: The permanent expressions for matrices *A* and *B* (*per (A)* and *per (B)*) were constructed similar to that of the permanent of matrix *J*, shown in equation (2.28).

Step7: The permanent function values based on positive and negative strategy selection matrices (*A* and *B*) for *twenty one* risk mitigation strategies were calculated. Permanent function values were calculated using Matlab®2013b. The value *NPIV*, the net positive influence of mitigation strategy *'p'* over the total risk profile is calculated based on equation (2.27). The risk mitigation strategies were ranked upon the descending order of the net positive influence, *NPIV*.

2.4. Analysis of Findings

To address this problem, we have identified *twelve* major risks and *twenty one* of the practical mitigation strategies with specific focus to electronic manufacturing supply chains. The positive and negative influences of risk mitigation strategies over risks were calculated using a combination of grey theory and digraph-matrix approaches. The net positive influence (*NPIV*) values were calculated, which directly indicates the effectiveness of the strategy in mitigating risks. The mitigation strategies were ranked in the descending order of *NPIV* values which is shown in Table 2.9.

Table 2.9: Ranking of risk mitigation strategies on net positive influence over risks

Ranking order	Strategy	Permanent A values (*per (A)*)	Permanent B values (*per (B)*)	Net positive influence (*NPIV*)
1	**RMS 11**	32360	12370	19990
2	**RMS 21**	30666	10871	19795
3	**RMS 17**	25501	10871	14630
4	**RMS 08**	24890	10871	14019
5	**RMS 10**	21859	10871	10988
6	**RMS 02**	20809	10871	9938
7	**RMS 15**	21666	12454	9212
8	**RMS 04**	19773	10871	8902
9	**RMS 03**	19365	10871	8494
10	**RMS 09**	18417	10871	7546
11	**RMS 13**	18059	10871	7188
12	**RMS 16**	17474	10871	6603
13	**RMS 05**	18617	12208	6409
14	**RMS 20**	19637	13272	6365
15	**RMS 06**	18023	12634	5389
16	**RMS 07**	16017	10871	5146
17	**RMS 01**	17650	12539	5111

Ranking order	Strategy	Permanent A values (*per (A)*)	Permanent B values (*per (B)*)	Net positive influence (*NPIV*)
18	**RMS 12**	15963	10871	5092
19	**RMS 14**	15779	12617	3162
20	**RMS 19**	13618	10871	2747
21	**RMS 18**	14162	11957	2205

From the values of *NPIV*, it is evident that case supply chain should adopt and practice risk mitigation strategies *reducing bullwhips* (RMS11) and *using insurance* (RMS21) for reducing their total risk impacts and *silent product rollover* (RMS18) and *having more customer accounts* (RMS19) are risk mitigation strategies that have comparably less effects in reducing the total risk impacts of the supply chain. The most *five* effective mitigation strategies ranks as *RMS11 > RMS21 > RMS17 > RMS8 > RMS10* (*reducing bullwhips*, *using insurance*, *revenue management*, *increase agility*, and *increase collaboration*, respectively). How far the ranking order varies with the variations in weightages given for supply chain analysts? Do there exist any personal bias in the ranking of mitigation strategies for the case supply chain? In an effort to find answers to the following questions, we conducted sensitivity analysis by giving highest weightings to the importance ratings and influence ratings given by supply chain analysts (*analyst 1*, *analyst 2* and *analyst 3*) separately, keeping equal weightages for the others.

Permanent function values were calculated for *3×2×21* (*126*) of the positive and negative strategy selection matrices and *NPIV* values are tabulated. The results from sensitivity analysis agree with the same ranking order, for best and worst mitigation strategies, accepting negligible order discrepancies. Still, mitigation strategies *RMS11* and *RMS21* stand best and mitigation strategies *RMS18* and *RMS19* come out to be the least effective mitigation strategies. The results of sensitivity analysis and the order of ranking for the best and least effective mitigation strategies were shown in Table 2.10.

Table 2.10: Sensitivity analysis for ranking priorities of risk mitigation strategies based on net positive influence on risks

	Sensitivity ana1ysis 1		Sensitivity analysis 2		Sensitivity analysis 3	
Ranking order	**Strategies**	***NPIV* Values**	**Strategies**	***NPIV* Values**	**Strategies**	***NPIV* Values**
1	**RMS 21**	18905	**RMS 11**	21268	**RMS 11**	19944
2	**RMS 11**	18815	**RMS 21**	21235	**RMS 21**	19278
3	**RMS 17**	13569	**RMS 17**	15288	**RMS 17**	15085
4	**RMS 08**	12827	**RMS 08**	14732	**RMS 08**	14544
5	**RMS 10**	10314	**RMS 10**	11288	**RMS 10**	11361
6	**RMS 02**	9216	**RMS 02**	10620	**RMS 02**	10021
7	**RMS 15**	8591	**RMS 15**	9697	**RMS 15**	9385
8	**RMS 04**	8161	**RMS 03**	8955	**RMS 04**	9217
9	**RMS 03**	8094	**RMS 04**	8955	**RMS 20**	8940
10	**RMS 09**	7057	**RMS 09**	7623	**RMS 03**	8451
11	**RMS 13**	6545	**RMS 13**	7512	**RMS 09**	7968
12	**RMS 20**	6045	**RMS 16**	7157	**RMS 13**	7549
13	**RMS 05**	5966	**RMS 05**	6837	**RMS 16**	6795
14	**RMS 16**	5915	**RMS 20**	6454	**RMS 05**	6450
15	**RMS 07**	4927	**RMS 06**	5661	**RMS 06**	5610
16	**RMS 06**	4905	**RMS 07**	5392	**RMS 12**	5258
17	**RMS 12**	4816	**RMS 01**	5317	**RMS 01**	5247
18	**RMS 01**	4790	**RMS 12**	5210	**RMS 07**	5135
19	**RMS 14**	2770	**RMS 14**	3491	**RMS 14**	3255
20	**RMS 19**	2487	**RMS 19**	2963	**RMS 19**	2810
21	**RMS 18**	2068	**RMS 18**	2244	**RMS 18**	2303

In order to exactly quantify the risk mitigation environment, it is essential to detangle the causal and effect relations existing among the attributes in a risk mitigation environment. It is seen that that the drivers of the risk and the enablers of risk mitigation have serious influential relations existing among themselves. These cause- effect relations are in detail studied in chapters 3 and 4, respectively.

CHAPTER 3

CAUSE- EFFECT RELATIONS AMONG DRIVERS OF SUPPLY CHAIN RISKS USING GREY THEORY AND DEMATEL APPROACHES

3.1. Framework of Risk Categories and Risk Drivers

The effect of risk mitigation strategies over various supply chain risks were studied in the previous chapter. However, these effects cannot be clearly perceived in a supply network. The key reason behind this is the existence of cascading effects among supply chain risks. For tackling this, the drivers of supply chain risks are to be identified and addressed. In doing so, we could perceive that one driver can initiate the effects of many other drivers and this is the key reason behind the cascade failure of the system. So a research problem needs to be addressed in this direction to classify the primary causes and effects among risk drivers, which is not seen in literature.

Identifying the predominant drivers of supply chain risks enable the firm to concentrate on reducing associated vulnerabilities whereas, assorting and isolating the most influential enablers of risk mitigation assist the firm to prioritize their SCRM practices. The former research problem is addressed in this research and the latter is at present addressed in the subsequent chapter. Also, this reduces the gaps from the effective implementation of SCRM practices towards the establishment of resilient supply chains as depicted in Figure 3.1. A combination of grey theory and decision making trial and evaluation (DEMATEL) methodologies were employed for this study.

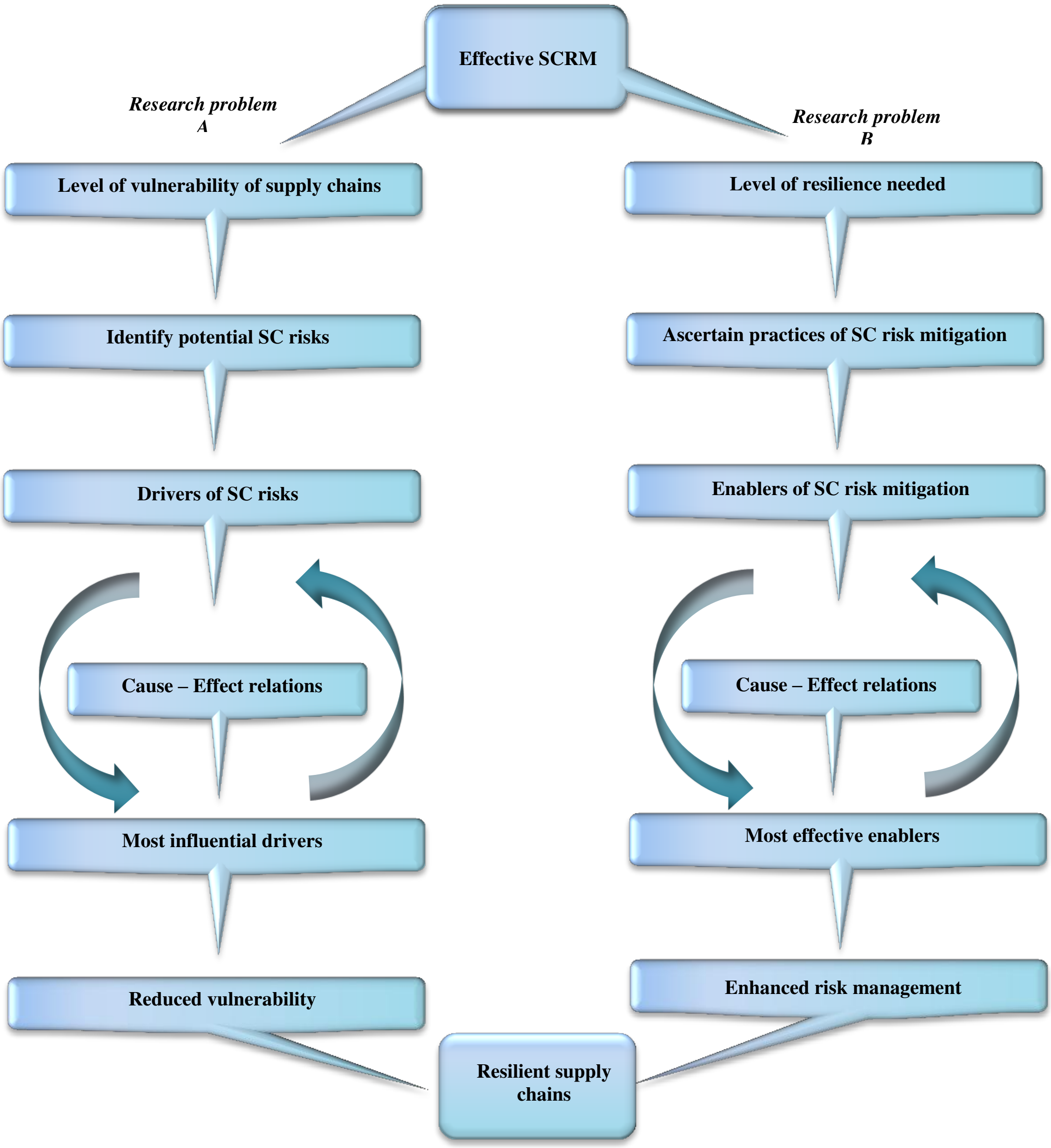


Figure 3.1: From SCRM to SC resilience

In the present study, we have considered *six* major categories of risks with explicit focus on electronic manufacturing industry and have identified *fourteen* of the drivers contributing to these risks. The demand variation exaggerates in a supply chain like a *bull whip*, termed as the bullwhip effect. Bullwhips and/or forecast errors causes mismatches in demand and supply resulting in *forecast risks* (Chen, et al., 2013) When there is under or over utilization of existing capacities and/or there is lack of capacity flexibility to deal with fluctuating demands, *capacity risks* arises (Tang & Tomlin, 2008). Suppliers are the vital sources of external risks in supply chains. Prior to take decision on sourcing and procurement, supplier selection should be made properly. Even then, there are risks related to fluctuations in exchange rates while opting for outsourcing. Supply failure and uncertainty about receivables are other potential threats. All of these can be categorized under *procurement risks* (Giunipero & Eltantawy, 2004).

Along with that, there *risks related to inventory*. Inventory value and the associated cost must be justified and the obsolescence cost of products should be considered while taking inventory decisions of various products (Faisal, et al., 2007). Information systems must be safe, secure and robust to avoid *system risks* related to e- commerce, system integration and even loss of information system. Key information should be further secured using information protection systems and information sharing should be done with right partners. Apart from these risks, increased globalization and vertical integration results in critical *risks related to IPR* (Manuj, 2013). Sourcing to different nations with different IPR and too much reliance on offshoring are strategic decisions associated with ample risks. The risks categorized and the drivers contributing to these risks are elaborated as follows:

3.1.1. Forecast risks

Forecast risks occur due to the mismatch between company's forecast and the actual demand (Cavinato, 2004). Firms should consider not only the demand forecasts, but also should take into consideration of the forecast errors in order to moderate the concomitant risks. Companies can reduce the effects of bullwhips to reduce order fluctuations by adjusting pricing and incentives (Chan & Chan, 2010). The ability of the supply chain to have a clear view of demand and supply conditions, inventories across stages and planning schedules is termed as supply chain visibility. Continuous replenishment programme (CRP), collaborative planning, forecasting, and replenishment (CPFR), and other modern supply chain initiatives can reduce bullwhips and in so doing increases the visibility of the supply chain (Liao, et al., 2010).

3.1.2. Capacity risks

Capacity can be used as a buffer for managing supply chain risks. Along with that, it benefits the supply chain in averting and mitigating major disruptive events. Building excess capacities or lower utilization of existing capacities are strategic decisions requiring time and cost, and are associated with ample risk (Chen, et al., 2013). The usual risks related to capacity are the cost of building excess capacity, capacity inflexibilities to meet changes in demand, excess utilization of the source capacities or different combinations of them (Chopra & Sodhi, 2012). Appropriate planning mechanism for capacities in the initial and expansion phase is essential to deal with the vulnerabilities related to capacity decisions.

3.1.3. Procurement risks

As a result of global sourcing, supply chains are becoming more vulnerable to exchange rate fluctuations. Supply failure can even lead to disruption of the entire supply chain. In most times, single sourcing increases the risks related to supply failure. Thus, keeping a flexible supply base can moderate these risks to some extent (Das, 2011). Inflexibility of the supply source can lead to delays and discontented customers. The supply risks associated can be reduced by keeping redundant suppliers and by improving visibility through collaboration. Also, uncertainties related to the supplier yield or quality can cause mismatches in the supply and demand (Giunipero & Eltantawy, 2004). Flexible supply contracts and multiple supplier selection strategies can be adopted to reduce the yield risks (Gosling & Naim, 2010). Procurement risks become severe if there are existing issues related to supply term contracts. By making flexible supply contracts and through initiatives like spot market purchasing, the chances of occurrences of such risks can be restrained. In addition to these, random supply uncertainties can occur due to cost, commitment or continuity in supplier relations.

3.1.4. Inventory risks

Inventory can be used as a buffer mechanism to deal with routine variability. Usually in a manufacturing supply chain, there are *three* types of inventories. Raw material inventories acts as a buffer against delivery delays. Work in process inventories can buffer production rate fluctuations and retail inventories can be used as a buffer against demand variability. But excess inventory in any form hurts financial performances. The extent of risk from inventory depends on (i) value of the product (ii) product obsolescence and (iii) uncertainty in demand or supply (Tse & Tan, 2012). Expertise practices need to be adopted for keeping the exact level of inventory at stages for dealing with the demands of different products. Established firms practice several quantitative and qualitative techniques for optimizing their inventory levels. *Three* staple approaches for reducing inventory risks, as seen in literature are: pooling of inventory, product standardization and adopting postponement strategies (Sodhi & Tang, 2012).

3.1.5. System risks

Information security is one of the critical elements of resilience determining the continuous success of a supply chain. Increasing the level of integration of information technology practices into the core business operations intensifies the security issues in supply chains. Addition of some type of back up information system (information redundancy) and securing the existing information systems can be potential solutions to these kinds of risks (Peck, 2005). Having a well-designed and well-communicated recovery process that duplicates all data and transactions can reduce the impacts of these risks. System risks occur due to loss of information system arising as a result of a major disruption event or due to issues related with integration practices or may be the outcome of an outdated e-commerce application (Tuncel & Alpan, 2010).

3.1.6. IPR risks

Outsourcing and offshoring made it difficult for contemporary supply chains to protect their IPR. Increased dependence on outsourcing causes a loss of control of demand along with an associated risk of losing key information shared among partners (Giunipero & Eltantawy, 2004). Vertical integration can be defined as the degree to which a firm owns its upstream suppliers and its downstream buyers. Vertical integration increases the complexity of supply chains and hence the associated risks. Increased vertical integration and global sourcing are the major contributors of IPR risks. Companies can possibly mitigate intellectual property risk by keeping a part of the production in-house or under the direct control of the company (Lavastre, et al., 2012). Sourcing to nations with similar intellectual property regulations will also help to reduce the vulnerabilities allied to these risks.

3.2. Methodology

Grey theory and its advantageous are discussed in the previous chapter. As said earlier, human judgments create ambiguities and grey theory is an enhanced tool to deal with ambiguities in judgments (Deng, 1982; Deng, 1989). Decision-making trial and evaluation laboratory (DEMATEL) method could effectively be used to structure complicated causal relationships among the variables using matrices and/or graphs (Tseng, 2009). Unlike other multi-attribute decision-making methods such as; Analytical Hierarchical Process (AHP), Analytical Network Process (ANP), TOPSIS etc., where factors are considered independent, DEMATEL method is a structural modeling technique that tries to find out the interdependence amongst the elements of a system through a pronounced causal diagram (Hsu, et al., 2013; Shieh, et al., 2010).

The *step* by *step* procedure for the methodology implementation is elaborated below for a detailed understanding. Firstly, the inputs are collected from analysts in the form of a matrix representing the influence relation of one risk over the other in linguistic scales. These linguistic labels are converted into corresponding grey scales using a predefined conversion table. Then, the average grey relation matrix is constructed using the grey averaging operator and the same is to be converted into a crisp relation matrix using grey whitenization operators. A direct crisp relation matrix is constructed from the same leading to the formulation of a total relation matrix. Each element in the total relation matrix represents a specific influential relation. The sum of particular row elements constitutes the r values and those of the column elements represent the c values. The value $r + c$ for the same row and column number indicate the effects given by the driver and $r - c$ represents the effects received by the driver. Thus, a plot of $r + c$ vs $r - c$ could study the relations binding cause and effects amongst the drivers and the same was conducted here. The procedure for Grey-DEMATEL method is elaborated as follows;

Notations

$\otimes x_{ij}^{k}$	Grey matrices of influence ratings	$\otimes \tilde{x}_{ij}$	Average grey influence ratings
$\otimes \dot{x}_{ij}$	Normalized grey average influence ratings	y_{ij}	Total normalized crisp ratings
z_{ij}	Final crisp ratings	T	Total relation matrix

Step1: Compute the initial relation matrices

Let the number of identified drivers be '*n*' and the respondents chosen to be *L*. Each respondent *k* is given the task of evaluating the direct influence of driver *i* over driver *j* on an integer scale varying from *0, 1, 2, 3, 4, 5,* representing *"no influence", "very* *low influence", "low influence", medium influence", "high influence"* and *"very high influence"* respectively among *n* drivers. Thus *L* initial relation matrices were developed based on the influence ratings,

Step2: Compute the grey relation matrices

The integer scale ratings can be converted into associated grey scales specifying an upper range and a lower range of values. i.e.

$$\otimes x_{ij}^{k} = \left(\underline{\otimes}\, x_{ij}^{k},\ \ \overline{\otimes}\, x_{ij}^{k}\right) \tag{3.1}$$

where $1 \leq k \leq L;\ 1 \leq i \leq n;\ 1 \leq j \leq n$

The initial relation matrices are converted into grey relation matrices based on the obtained grey values, i. e. $[\otimes\, x_{ij}^{1}], [\otimes\, x_{ij}^{2}], [\otimes\, x_{ij}^{3}], \ldots, [\otimes\, x_{ij}^{L}]$

Step3: Compute the average grey relation matrix

The average grey relation matrix $[\otimes\, \tilde{x}_{ij}]$ can be constructed from *L* grey relation matrices, $[\otimes\, x_{ij}^{k}]$; $k = 1 - L$ as,

$$\otimes\, \tilde{x}_{ij} = \left(\frac{\sum_k \underline{\otimes} x_{ij}^{k}}{L}, \frac{\sum_k \overline{\otimes} x_{ij}^{k}}{L}\right) \tag{3.2}$$

Step4: Compute the crisp relation matrix from the average grey relation matrix

The grey values can be converted into crisp values by a *three* step procedure as;

(i) Normalization of the grey value

$$\underline{\otimes}\, \dot{x}_{ij} = \left(\underline{\otimes}\, \tilde{x}_{ij} - {}^{min}_{\ \ j}\underline{\otimes}\, \tilde{x}_{ij}\right)/\Delta_{min}^{max} \tag{3.3}$$

where $\underline{\otimes}\, \dot{x}_{ij}$ represents the normalized lower limit value of the grey number $\otimes\, \tilde{x}_{ij}$

$$\overline{\otimes}\, \dot{x}_{ij} = \left(\overline{\otimes}\, \tilde{x}_{ij} - {}^{min}_{\ \ j}\,\overline{\otimes}\, \tilde{x}_{ij}\right)/\Delta_{min}^{max} \tag{3.4}$$

where $\overline{\otimes}\, \dot{x}_{ij}$ represents the normalized upper limit value of the grey number $\otimes\, \tilde{x}_{ij}$;

$$\Delta_{min}^{max} = {}^{max}_{j}\overline{\otimes}\,\tilde{x}_{ij} - {}^{min}_{j}\underline{\otimes}\,\tilde{x}_{ij} \tag{3.5}$$

(ii) Calculating total normalized crisp value

$$y_{ij} = \left(\frac{\left(\underline{\otimes}\dot{x}_{ij}(1-\underline{\otimes}\dot{x}_{ij})\right)+(\overline{\otimes}\dot{x}_{ij}\times\overline{\otimes}\dot{x}_{ij})}{(1-\underline{\otimes}\dot{x}_{ij}+\overline{\otimes}\dot{x}_{ij})}\right) \tag{3.6}$$

(iii) Computing the final crisp values

$$z_{ij} = \left(min\,\underline{\otimes}\,\tilde{x}_{ij} + \left(y_{ij} \times \Delta_{min}^{max}\right)\right) \tag{3.7}$$

and, $Z = [z_{ij}]$ (3.8)

Step5: Compute the normalized direct crisp relation matrix

The normalized direct crisp relation matrix *R* is obtained by multiplying *Z* with *M* as;

$$M = \frac{1}{\underset{1 \le i \le n}{max} \sum_{j=1}^{n} z_{ij}} \tag{3.9}$$

and, $R = Z \times M$ (3.10)

Each element in matrix *R* falls between *zero* and *one.*

Step6: Compute the total relation matrix

The total relation matrix *T* is obtained as,

$$T = R \times (I - R)^{-1} \tag{3.11}$$

where *I* is the identity matrix.

Step7: Obtain the cause and effect parameters

Let t_{ij} represents the elements in the total relation matrix, *T*. Define *r* and *c* be $n\times 1$ and $1\times n$ vectors representing sum of row elements and sum of column elements for the total relation matrix *T*, respectively. Let r_i represents the sum of i^{th} row elements in matrix T, then r_i summarizes both direct and indirect effects given by driver i towards the other drivers. Let c_j represents the sum of j^{th} column elements in matrix T, then c_j summarizes both direct and indirect effects received by driver j from other drivers, i.e.,

$$r_i = \sum_{j=1}^{n} t_{ij} \; \forall \, i \qquad (3.12)$$

$$c_j = \sum_{i=1}^{n} t_{ij} \; \forall \, j \qquad (3.13)$$

When $j=i$, the sum $(r_i + c_j)$ shows the total effects given and received by driver i; i. e, $(r_i + c_j)$ represents the degree of importance that driver i plays in the entire system. On the other hand $(r_i - c_j)$ outlines the net effect that the driver i contributes to the entire system. If $(r_i - c_j)$ is positive, driver i is the net cause. Driver i is the net effect if $(r_i - c_j)$ comes out to be negative.

Step8: Set up threshold and plot the digraph

As matrix T provides the information on how one driver affects the other, it is necessary for a decision maker to set up a threshold value to filter out comparably negligible effects. By doing so; only the effects greater than the threshold value would appear on digraph. Digraph showing the causal relations can be plotted from the dataset of $(r_i + c_j), (r_i - c_j) \forall \, i = j$.

3.3. A Real Case Application of the Model

The proposed framework in this research was assessed in an electronic manufacturing company '*ABC*' in India. The case electronics manufacturing company is selected as a representative case for studying the practical implications. *ABC* is one among the global leaders in electronic goods manufacturing, particularly in smartphones and tablet segments. Their strategy of hitting the rural markets with efficient and responsive products has got wide acceptance globally. Widely distributed service centers also add to customer delights. Their supply chain network is distributed widely, with markets spread across continents. Having a global manufacturing network increases the risks and hence the vulnerability of the supply chain of *ABC*. *ABC* has set a major manufacturing and assembly plant in India with international offices across Asia, Europe and Latin America. They have captured market attention with improved product specifications by means of innovative gadgets.

ABC has a strong direct supplier base with collaborative relations ensuring enhanced visibilities, which helps them to reduce the inventories and utilize the capacities to the highest extent possible. Even still, *ABC*'s supply chain recently has to face vulnerability issues due to delivery delays from indirect suppliers. *ABC* planned to take some major modifications in their risk management approaches, thereafter. Along with the plans for modifications, they documented the key solution to the problem as, 'the management of various risks become meaningful only if the drivers of the risks are properly identified, addressed and mitigated'. This apprehension expedited them to take proactive steps for reducing the vulnerability of the supply chain as a whole. For facilitating them, we have identified and classified the risks predominant in *ABC* into *six* major groups, as perceived from the insights of a general electronic manufacturing firm that is briefed above and *fourteen* of the major drivers contributing to these risks were also identified. The risks considered, the drivers contributing to these and the relevant literatures are shown in Table 3.1.

Table 3.1: Risk category and risk drivers considered

Sl. No.	Supply Chain Risk Category	Supply Chain Risk Drivers	Ref. Codes	Relevant Literature	Remarks
A.	**Forecast**			(Christopher & Holweg, 2011)	Forecasts may go wrong with assumptions made in static lead times, transit times, transportation and distribution routes.
1.		Forecast errors	**FRER**	(Zhao, et al., 2002)	Bringing qualitative insights can potentially reduce forecast errors and can improve the accuracy and reliability of forecasts.

Sl. No.	Supply Chain Risk Category	Supply Chain Risk Drivers	Ref. Codes	Relevant Literature	Remarks
2.		Bullwhip effects	**BWEF**	(Lee, 2002)	Companies can possibly reduce the impact of bull whips by adjusting pricing and incentives to decrease the variation in orders.
B.	**Capacity**			(Pettit, 2010)	Risks related with capacity arise due to cost of capacity and capacity inflexibility.
1.		Cost of capacity	**CCPY**	(Ambulkar, et al., 2015)	Moving with low capacity utilizations can build redundancy, but the efficiency of the firm reduces considerably due to the increased cost of capacity.
2.		Capacity inflexibility	**CIFY**	(Tang & Tomlin, 2008)	Capacity inflexibility is the condition where facility fails to respond to changes in demand.
C.	**Procurement**			(Büyüközkan & Çifçi, 2011)	The risks related with exchange rate fluctuations and poor supplier strategies can be included under this category.
1.		Supply uncertainty	**SUCY**	(Monroe, et al., 2014)	Supply uncertainty can be in the form of supply cost, supply commitment or supply continuity.
2.		Supply failure	**SFLR**	(Candace, et al., 2011)	Large companies with multiple time zones and regulations have severe supplier risks.
3.		Fluctuating exchange rates	**FEXR**	(Liu & Nagurney, 2011)	Exchange rate risks can be reduced by financial hedges, balancing region wise cost and revenue and by building flexible global capacity.
D.	**Inventory**			(Cheng, et al., 2011)	Keeping sufficient inventories throughout the stages improves redundancy, however too much reduction in inventories has an adverse effect on resilience.
1.		Inventory value and cost	**IVAC**	(Cavusoglu, et al., 2012)	Excess inventory can be expensive for short life cycle products.
2.		Product obsolescence	**PROB**	(Holweg, et al., 2011)	Product obsolescence refers to the period and situation where a piece of technology or product turns not to be useful, productive or compatible.
E.	**System**			(Manuj & Mentzer, 2008)	The breakdown of information infrastructure or ineffective knowledge sharing can result in serious risks system risks.

Sl. No.	Supply Chain Risk Category	Supply Chain Risk Drivers	Ref. Codes	Relevant Literature	Remarks
1.		Issues regarding e-commerce applications	**IREA**	(Tummala & Schoenherr, 2011)	Investment in appropriate technology can reduce the chances of disruptions, but careful and regular updating of technology is needed depending on the operating environment.
2.		Loss of information system	**LOIS**	(Bode, et al., 2011)	Computer based information systems are central to the supply chain and the failure can bring substantial losses.
3.		Issues related to system integration	**IRSI**	(Christopher & Peck, 2004)	Practices of integration of information technology practices into core business operations, increases the risk for disruptions.
F.	**IPR**			(Manuj & Mentzer, 2008)	Outsourcing or off-shoring results in reduced manufacturing costs, making difficult to protect the Intellectual Property (IP).
1.		Global sourcing	**GLSG**	(Chopra & Sodhi, 2012)	Outsourcing to low cost countries lower the cost of goods sold, but making the companies more vulnerable to loss of its IP.
2.		Vertical integrations	**VRIG**	(Barlas & Gunduz, 2011)	The more vertically company is integrated, the more will be the associated IP risk.

The *step by step* procedure to implement the proposed methodology in the case electronic manufacturing company *ABC* for managing their vulnerability issues is as follows; a sample of the calculations has been added in Annexure 2.

Step 1**:** A group of *four* supply chain analysts was formed to rate the influence among *fourteen* of the drivers triggering *six* major supply chain risks for the supply chain of *ABC*. The analysts were experts in the field of supply chains with more than *ten* years of working experience. They rated the influence of one risk driver over the other on a number scale varying from *0* to *5*, depending on the level of influence from *"no influence"* to *"very high influence"*. *Four* initial relation matrices *(14×14)* were developed based on the number scale ratings. A grey scale was united with consistent numbers ranging from *0* to *5*. The grey values are defined in Table 3.2.

Table 3.2: Linguistic assessment and the associated normal and grey values

Linguistic assessment	Normal values	Associated grey values
No influence	0	[0.0, 0.1]
Very low influence	1	[0.1, 0.3]
Low influence	2	[0.2, 0.5]
Medium influence	3	[0.4, 0.7]
High influence	4	[0.6, 0.9]
Very high influence	5	[0.9, 1.0]

Step 2: *Four* grey initial relationship matrices were developed ([$\otimes x_{ij}^{1}$], [$\otimes x_{ij}^{2}$], [$\otimes x_{ij}^{3}$], and [$\otimes x_{ij}^{4}$]) based on the ratings obtained from the *four* analysts using equation (3.1). The first matrices are shown in Table 3.3, 3.4, 3.5 and 3.6.

Table 3.3: Grey relation matrix for supply chain risk drivers given by analyst-1

	FRER	BWEF	CCPY	CIFY	SUCY	SFLR	FEXR	IVAC	PROB	IREA	LOIS	IRSI	GLSG	VRIG
FRER	0	0.6	0.2	0.1	0.2	0	0	0.4	0.4	0.1	0	0	0	0.1
	0.1	0.9	0.5	0.3	0.5	0.1	0.1	0.7	0.7	0.3	0.1	0.1	0.1	0.3
BWEF	0.6	0	0.6	0.4	0.2	0	0	0.6	0.2	0.1	0	0	0	0.1
	0.9	0.1	0.9	0.7	0.5	0.1	0.1	0.9	0.5	0.3	0.1	0.1	0.1	0.3
CCPY	0	0.2	0	0.6	0.1	0	0	0.1	0.2	0	0	0.1	0.4	0.9
	0.1	0.5	0.1	0.9	0.3	0.1	0.1	0.3	0.5	0.1	0.1	0.3	0.7	1
CIFY	0	0.6	0.9	0	0.1	0	0	0.4	0.2	0.2	0	0.1	0.2	0.4
	0.1	0.9	1	0.1	0.3	0.1	0.1	0.7	0.5	0.5	0.1	0.3	0.5	0.7
SUCY	0.2	0.9	0.6	0.6	0	0.6	0	0.4	0.2	0.2	0	0.1	0.9	0.4
	0.5	1	0.9	0.9	0.1	0.9	0.1	0.7	0.5	0.5	0.1	0.3	1	0.7
SFLR	0.9	0.9	0.9	0.9	0.9	0	0	0.6	0.2	0.4	0.2	0.1	0.9	0.2
	1	1	1	1	1	0.1	0.1	0.9	0.5	0.7	0.5	0.3	1	0.5
FEXR	0.6	0.6	0.9	0.9	0.9	0.4	0	0.6	0.2	0.2	0	0.2	0.9	0.4
	0.9	0.9	1	1	1	0.7	0.1	0.9	0.5	0.5	0.1	0.5	1	0.7
IVAC	0.1	0.4	0.2	0.4	0.1	0.1	0	0	0.6	0.1	0	0	0.2	0.4
	0.3	0.7	0.5	0.7	0.3	0.3	0.1	0.1	0.9	0.3	0.1	0.1	0.5	0.7
PROB	0.2	0.1	0.4	0.4	0.2	0.2	0	0.2	0	0.4	0.2	0.2	0.1	0.1
	0.5	0.3	0.7	0.7	0.5	0.5	0.1	0.5	0.1	0.7	0.5	0.5	0.3	0.3
IREA	0.4	0.6	0.6	0.6	0.4	0.2	0	0.6	0.2	0	0.9	0.6	0.1	0.1
	0.7	0.9	0.9	0.9	0.7	0.5	0.1	0.9	0.5	0.1	1	0.9	0.3	0.3
LOIS	0.6	0.9	0.6	0.9	0.9	0.2	0	0.2	0.2	0.6	0	0.6	0.4	0.4
	0.9	1	0.9	1	1	0.5	0.1	0.5	0.5	0.9	0.1	0.9	0.7	0.7
IRSI	0.6	0.6	0.6	0.6	0.9	0.2	0	0.4	0.2	0.6	0.9	0	0.4	0.4
	0.9	0.9	0.9	0.9	1	0.5	0.1	0.7	0.5	0.9	1	0.1	0.7	0.7
GLSG	0.9	0.9	0.6	0.6	0.9	0.2	0.9	0.4	0.2	0.2	0.2	0.2	0	0.4
	1	1	0.9	0.9	1	0.5	1	0.7	0.5	0.5	0.5	0.5	0.1	0.7
VRIG	0.2	0.2	0.4	0.4	0.2	0.1	0.1	0.4	0.6	0.6	0.2	0.9	0.2	0
	0.5	0.5	0.7	0.7	0.5	0.3	0.3	0.7	0.9	0.9	0.5	1	0.5	0.1

* *FRER* indicates the risk driver '*Forecast errors*' as in Table. 3.1. Similarly for all. Level of influence of risk driver *i* over *j* is represented as grey value $\left[\frac{\underline{\otimes}x_{ij}^{1}}{\overline{\otimes}x_{ij}^{1}}\right]$.

Table 3.4: Grey relation matrix for supply chain risk drivers given by analyst-2

	FRER	BWEF	CCPY	CIFY	SUCY	SFLR	FEXR	IVAC	PROB	IREA	LOIS	IRSI	GLSG	VRIG
FRER	0	0.4	0.4	0.2	0.2	0	0	0.4	0.4	0.1	0	0	0	0.1
	0.1	0.7	0.7	0.5	0.5	0.1	0.1	0.7	0.7	0.3	0.1	0.1	0.1	0.3
BWEF	0.6	0	0.6	0.4	0.2	0	0	0.6	0.2	0.2	0	0	0	0.1
	0.9	0.1	0.9	0.7	0.5	0.1	0.1	0.9	0.5	0.5	0.1	0.1	0.1	0.3
CCPY	0	0.2	0	0.6	0.1	0	0	0.1	0.2	0	0	0.1	0.2	0.6
	0.1	0.5	0.1	0.9	0.3	0.1	0.1	0.3	0.5	0.1	0.1	0.3	0.5	0.9
CIFY	0	0.6	0.9	0	0.1	0	0	0.4	0.2	0.2	0	0.1	0.2	0.4
	0.1	0.9	1	0.1	0.3	0.1	0.1	0.7	0.5	0.5	0.1	0.3	0.5	0.7
SUCY	0.2	0.9	0.6	0.6	0	0.9	0	0.4	0.2	0.4	0	0.1	0.6	0.4
	0.5	1	0.9	0.9	0.1	1	0.1	0.7	0.5	0.7	0.1	0.3	0.9	0.7
SFLR	0.9	0.6	0.9	0.6	0.9	0	0	0.6	0.2	0.4	0.2	0.1	0.6	0.4
	1	0.9	1	0.9	1	0.1	0.1	0.9	0.5	0.7	0.5	0.3	0.9	0.7
FEXR	0.6	0.6	0.9	0.9	0.6	0.4	0	0.6	0.2	0.2	0	0.2	0.9	0.4
	0.9	0.9	1	1	0.9	0.7	0.1	0.9	0.5	0.5	0.1	0.5	1	0.7
IVAC	0.1	0.4	0.2	0.4	0.2	0.1	0	0	0.9	0.1	0	0	0.2	0.2
	0.3	0.7	0.5	0.7	0.5	0.3	0.1	0.1	1	0.3	0.1	0.1	0.5	0.5
PROB	0.2	0.1	0.4	0.4	0.2	0.2	0	0.2	0	0.4	0.2	0.2	0.1	0.1
	0.5	0.3	0.7	0.7	0.5	0.5	0.1	0.5	0.1	0.7	0.5	0.5	0.3	0.3
IREA	0.4	0.6	0.6	0.9	0.4	0.2	0	0.6	0.2	0	0.6	0.6	0.1	0.2
	0.7	0.9	0.9	1	0.7	0.5	0.1	0.9	0.5	0.1	0.9	0.9	0.3	0.5
LOIS	0.6	0.9	0.4	0.9	0.9	0.2	0	0.2	0.4	0.6	0	0.6	0.4	0.4
	0.9	1	0.7	1	1	0.5	0.1	0.5	0.7	0.9	0.1	0.9	0.7	0.7
IRSI	0.6	0.6	0.6	0.6	0.9	0.2	0	0.6	0.2	0.6	0.9	0	0.4	0.2
	0.9	0.9	0.9	0.9	1	0.5	0.1	0.9	0.5	0.9	1	0.1	0.7	0.5
GLSG	0.9	0.6	0.6	0.6	0.9	0.2	0.9	0.4	0.2	0.2	0.2	0.2	0	0.4
	1	0.9	0.9	0.9	1	0.5	1	0.7	0.5	0.5	0.5	0.5	0.1	0.7
VRIG	0.2	0.2	0.4	0.6	0.2	0.1	0.2	0.4	0.6	0.6	0.4	0.9	0.2	0
	0.5	0.5	0.7	0.9	0.5	0.3	0.5	0.7	0.9	0.9	0.7	1	0.5	0.1

Table 3.5: Grey relation matrix for supply chain risk drivers given by analyst-3

	FRER	BWEF	CCPY	CIFY	SUCY	SFLR	FEXR	IVAC	PROB	IREA	LOIS	IRSI	GLSG	VRIG
FRER	0	0.6	0.2	0.2	0.2	0	0	0.4	0.2	0.1	0	0	0	0.1
	0.1	0.9	0.5	0.5	0.5	0.1	0.1	0.7	0.5	0.3	0.1	0.1	0.1	0.3
BWEF	0.6	0	0.6	0.4	0.2	0	0	0.6	0.2	0.1	0	0	0	0.1
	0.9	0.1	0.9	0.7	0.5	0.1	0.1	0.9	0.5	0.3	0.1	0.1	0.1	0.3
CCPY	0	0.2	0	0.9	0.1	0	0	0.1	0.4	0	0	0.1	0.4	0.9
	0.1	0.5	0.1	1	0.3	0.1	0.1	0.3	0.7	0.1	0.1	0.3	0.7	1
CIFY	0	0.9	0.9	0	0.2	0	0	0.4	0.4	0.2	0	0.1	0.2	0.4
	0.1	1	1	0.1	0.5	0.1	0.1	0.7	0.7	0.5	0.1	0.3	0.5	0.7
SUCY	0.2	0.9	0.6	0.9	0	0.6	0	0.4	0.2	0.1	0	0.1	0.6	0.4
	0.5	1	0.9	1	0.1	0.9	0.1	0.7	0.5	0.3	0.1	0.3	0.9	0.7
SFLR	0.9	0.9	0.6	0.9	0.9	0	0	0.6	0.4	0.4	0.1	0.1	0.6	0.2
	1	1	0.9	1	1	0.1	0.1	0.9	0.7	0.7	0.3	0.3	0.9	0.5
FEXR	0.6	0.6	0.9	0.9	0.6	0.4	0	0.9	0.2	0.2	0	0.4	0.9	0.4
	0.9	0.9	1	1	0.9	0.7	0.1	1	0.5	0.5	0.1	0.7	1	0.7
IVAC	0.1	0.4	0.2	0.4	0	0.1	0	0	0.6	0.2	0	0	0.2	0.4
	0.3	0.7	0.5	0.7	0.1	0.3	0.1	0.1	0.9	0.5	0.1	0.1	0.5	0.7
PROB	0.2	0.1	0.4	0.6	0.2	0.2	0	0.2	0	0.6	0.2	0.2	0.2	0
	0.5	0.3	0.7	0.9	0.5	0.5	0.1	0.5	0.1	0.9	0.5	0.5	0.5	0.1
IREA	0.4	0.4	0.4	0.6	0.4	0.2	0	0.6	0.2	0	0.9	0.6	0.1	0.1
	0.7	0.7	0.7	0.9	0.7	0.5	0.1	0.9	0.5	0.1	1	0.9	0.3	0.3
LOIS	0.6	0.9	0.6	0.6	0.9	0.4	0	0.2	0.2	0.4	0	0.6	0.6	0.4
	0.9	1	0.9	0.9	1	0.7	0.1	0.5	0.5	0.7	0.1	0.9	0.9	0.7
IRSI	0.6	0.6	0.6	0.4	0.9	0.2	0	0.6	0.4	0.6	0.9	0	0.2	0.4
	0.9	0.9	0.9	0.7	1	0.5	0.1	0.9	0.7	0.9	1	0.1	0.5	0.7
GLSG	0.9	0.9	0.9	0.6	0.9	0.2	0.9	0.4	0.4	0.2	0.2	0.4	0	0.4
	1	1	1	0.9	1	0.5	1	0.7	0.7	0.5	0.5	0.7	0.1	0.7
VRIG	0.2	0.2	0.4	0.4	0.2	0	0	0.4	0.6	0.6	0.2	0.6	0.2	0
	0.5	0.5	0.7	0.7	0.5	0.1	0.1	0.7	0.9	0.9	0.5	0.9	0.5	0.1

Table 3.6: Grey relation matrix for supply chain risk drivers given by analyst-4

	FRER	BWEF	CCPY	CIFY	SUCY	SFLR	FEXR	IVAC	PROB	IREA	LOIS	IRSI	GLSG	VRIG
FRER	0	0.9	0.1	0.1	0.2	0	0	0.6	0.2	0.1	0	0	0	0.1
	0.1	1	0.3	0.3	0.5	0.1	0.1	0.9	0.5	0.3	0.1	0.1	0.1	0.3
BWEF	0.6	0	0.9	0.4	0.2	0	0	0.6	0.2	0.2	0	0	0	0.1
	0.9	0.1	1	0.7	0.5	0.1	0.1	0.9	0.5	0.5	0.1	0.1	0.1	0.3
CCPY	0	0.4	0	0.6	0.1	0	0	0.2	0.2	0	0	0.2	0.4	0.6
	0.1	0.7	0.1	0.9	0.3	0.1	0.1	0.5	0.5	0.1	0.1	0.5	0.7	0.9
CIFY	0	0.6	0.9	0	0.2	0	0	0.4	0.4	0.2	0	0.1	0.4	0.4
	0.1	0.9	1	0.1	0.5	0.1	0.1	0.7	0.7	0.5	0.1	0.3	0.7	0.7
SUCY	0.2	0.9	0.6	0.9	0	0.9	0	0.4	0.2	0.2	0	0.1	0.9	0.4
	0.5	1	0.9	1	0.1	1	0.1	0.7	0.5	0.5	0.1	0.3	1	0.7
SFLR	0.9	0.9	0.9	0.9	0.6	0	0	0.6	0.2	0.2	0.2	0.2	0.9	0.2
	1	1	1	1	0.9	0.1	0.1	0.9	0.5	0.5	0.5	0.5	1	0.5
FEXR	0.6	0.9	0.9	0.9	0.6	0.4	0	0.6	0.2	0.2	0	0.1	0.9	0.4
	0.9	1	1	1	0.9	0.7	0.1	0.9	0.5	0.5	0.1	0.3	1	0.7
IVAC	0.1	0.6	0.2	0.4	0.1	0.2	0	0	0.6	0.2	0	0	0.4	0.4
	0.3	0.9	0.5	0.7	0.3	0.5	0.1	0.1	0.9	0.5	0.1	0.1	0.7	0.7
PROB	0.2	0.1	0.4	0.4	0.2	0.2	0	0.2	0	0.4	0.2	0.2	0.1	0.1
	0.5	0.3	0.7	0.7	0.5	0.5	0.1	0.5	0.1	0.7	0.5	0.5	0.3	0.3
IREA	0.4	0.6	0.9	0.6	0.4	0.4	0	0.6	0.2	0	0.9	0.6	0.2	0.1
	0.7	0.9	1	0.9	0.7	0.7	0.1	0.9	0.5	0.1	1	0.9	0.5	0.3
LOIS	0.6	0.9	0.6	0.9	0.9	0.4	0	0.2	0.2	0.4	0	0.6	0.2	0.4
	0.9	1	0.9	1	1	0.7	0.1	0.5	0.5	0.7	0.1	0.9	0.5	0.7
IRSI	0.6	0.6	0.4	0.6	0.9	0.4	0	0.4	0.2	0.6	0.9	0	0.2	0.4
	0.9	0.9	0.7	0.9	1	0.7	0.1	0.7	0.5	0.9	1	0.1	0.5	0.7
GLSG	0.9	0.9	0.9	0.6	0.9	0.2	0.9	0.4	0.2	0.4	0.2	0.4	0	0.4
	1	1	1	0.9	1	0.5	1	0.7	0.5	0.7	0.5	0.7	0.1	0.7
VRIG	0.2	0.2	0.4	0.6	0.2	0.1	0.2	0.4	0.6	0.9	0.2	0.9	0.2	0
	0.5	0.5	0.7	0.9	0.5	0.3	0.5	0.7	0.9	1	0.5	1	0.5	0.1

Step 3: In order to have uniformity of judgment, we have given equal weightings to all the analysts and the average relation matrix $[\otimes \tilde{x}_{ij}]$ is computed using equation (3.2). This matrix is presented in Table 3.7.

Table 3.7: Average grey relation matrix for supply chain risk drivers

	FRER	BWEF	CCPY	CIFY	SUCY	SFLR	FEXR	IVAC	PROB	IREA	LOIS	IRSI	GLSG	VRIG
FRER	0	0.625	0.225	0.15	0.2	0	0	0.45	0.3	0.1	0	0	0	0.1
	0.1	0.875	0.5	0.4	0.5	0.1	0.1	0.75	0.6	0.3	0.1	0.1	0.1	0.3
BWEF	0.6	0	0.675	0.4	0.2	0	0	0.6	0.2	0.15	0	0	0	0.1
	0.9	0.1	0.925	0.7	0.5	0.1	0.1	0.9	0.5	0.4	0.1	0.1	0.1	0.3
CCPY	0	0.25	0	0.675	0.1	0	0	0.125	0.25	0	0	0.125	0.35	0.75
	0.1	0.55	0.1	0.925	0.3	0.1	0.1	0.35	0.55	0.1	0.1	0.35	0.65	0.95
CIFY	0	0.675	0.9	0	0.15	0	0	0.4	0.3	0.2	0	0.1	0.25	0.4
	0.1	0.925	1	0.1	0.4	0.1	0.1	0.7	0.6	0.5	0.1	0.3	0.55	0.7
SUCY	0.2	0.9	0.6	0.75	0	0.75	0	0.4	0.2	0.225	0	0.1	0.75	0.4
	0.5	1	0.9	0.95	0.1	0.95	0.1	0.7	0.5	0.5	0.1	0.3	0.95	0.7
SFLR	0.9	0.825	0.825	0.825	0.825	0	0	0.6	0.25	0.35	0.175	0.125	0.75	0.25
	1	0.975	0.975	0.975	0.975	0.1	0.1	0.9	0.55	0.65	0.45	0.35	0.95	0.55
FEXR	0.6	0.675	0.9	0.9	0.675	0.4	0	0.675	0.2	0.2	0	0.225	0.9	0.4
	0.9	0.925	1	1	0.925	0.7	0.1	0.925	0.5	0.5	0.1	0.5	1	0.7
IVAC	0.1	0.45	0.2	0.4	0.1	0.125	0	0	0.675	0.15	0	0	0.25	0.35
	0.3	0.75	0.5	0.7	0.3	0.35	0.1	0.1	0.925	0.4	0.1	0.1	0.55	0.65
PROB	0.2	0.1	0.4	0.45	0.2	0.2	0	0.2	0	0.45	0.2	0.2	0.125	0.075
	0.5	0.3	0.7	0.75	0.5	0.5	0.1	0.5	0.1	0.75	0.5	0.5	0.35	0.25
IREA	0.4	0.55	0.625	0.675	0.4	0.25	0	0.6	0.2	0	0.825	0.6	0.125	0.125
	0.7	0.85	0.875	0.925	0.7	0.55	0.1	0.9	0.5	0.1	0.975	0.9	0.35	0.35
LOIS	0.6	0.9	0.55	0.825	0.9	0.3	0	0.2	0.25	0.5	0	0.6	0.4	0.4
	0.9	1	0.85	0.975	1	0.6	0.1	0.5	0.55	0.8	0.1	0.9	0.7	0.7
IRSI	0.6	0.6	0.55	0.55	0.9	0.25	0	0.5	0.25	0.6	0.9	0	0.3	0.35
	0.9	0.9	0.85	0.85	1	0.55	0.1	0.8	0.55	0.9	1	0.1	0.6	0.65
GLSG	0.9	0.825	0.75	0.6	0.9	0.2	0.9	0.4	0.25	0.25	0.2	0.3	0	0.4
	1	0.975	0.95	0.9	1	0.5	1	0.7	0.55	0.55	0.5	0.6	0.1	0.7
VRIG	0.2	0.2	0.4	0.5	0.2	0.075	0.125	0.4	0.6	0.675	0.25	0.825	0.2	0
	0.5	0.5	0.7	0.8	0.5	0.25	0.35	0.7	0.9	0.925	0.55	0.975	0.5	0.1

Step 4: The crisp relation matrix *Z* was developed from the average grey relation matrix by a *three* step procedure using modified- CFCS method. The crisp relation matrix obtained using equations (3.3), (3.4), (3.5), (3.6), (3.7) and (3.8) is given in Table 3.8.

Table 3.8: Crisp relation matrix for supply chain risk drivers

	FRER	BWEF	CCPY	CIFY	SUCY	SFLR	FEXR	IVAC	PROB	IREA	LOIS	IRSI	GLSG	VRIG
FRER	0	0.726	0.285	0.189	0.267	0	0	0.558	0.383	0.118	0	0	0	0.118
BWEF	0.733	0	0.783	0.5	0.267	0	0	0.733	0.267	0.189	0	0	0	0.118
CCPY	0	0.325	0	0.783	0.118	0	0	0.153	0.325	0	0	0.153	0.442	0.827
CIFY	0	0.783	0.9	0	0.189	0	0	0.5	0.383	0.267	0	0.118	0.325	0.5
SUCY	0.267	0.9	0.733	0.827	0	0.827	0	0.5	0.267	0.285	0	0.118	0.827	0.5
SFLR	0.9	0.868	0.868	0.868	0.868	0	0	0.739	0.329	0.446	0.229	0.154	0.831	0.329
FEXR	0.733	0.783	0.9	0.9	0.783	0.5	0	0.783	0.267	0.267	0	0.285	0.9	0.5
IVAC	0.119	0.565	0.271	0.507	0.119	0.154	0	0	0.79	0.191	0	0	0.329	0.448
PROB	0.271	0.119	0.507	0.565	0.271	0.271	0	0.271	0	0.565	0.271	0.271	0.154	0.086
IREA	0.507	0.684	0.734	0.79	0.507	0.329	0	0.743	0.271	0	0.87	0.743	0.154	0.154
LOIS	0.733	0.9	0.675	0.867	0.9	0.383	0	0.267	0.325	0.617	0	0.733	0.5	0.5
IRSI	0.736	0.736	0.678	0.678	0.9	0.327	0	0.619	0.327	0.736	0.9	0	0.385	0.444
GLSG	0.9	0.867	0.827	0.733	0.9	0.267	0.9	0.5	0.325	0.325	0.267	0.383	0	0.5
VRIG	0.27	0.27	0.504	0.621	0.27	0.086	0.154	0.504	0.739	0.788	0.329	0.868	0.27	0

* *FRER* indicates the risk driver '*Forecast errors*' as in Table. 3.1. Similarly for all. Crisp rating on influence of risk driver *i* over risk driver *j* is represented as $[z_{ij}]$.

Step 5: The crisp relation matrix obtained was normalized using equations (3.9) and (3.10) to obtain the normalized direct crisp relation matrix *R*, shown in Table 3.9.

Table 3.9: Normalized direct crisp relation matrix for supply chain risk drivers

	FRER	BWEF	CCPY	CIFY	SUCY	SFLR	FEXR	IVAC	PROB	IREA	LOIS	IRSI	GLSG	VRIG
FRER	0	0.094	0.037	0.025	0.035	0	0	0.073	0.05	0.015	0	0	0	0.015
BWEF	0.095	0	0.102	0.065	0.035	0	0	0.095	0.035	0.025	0	0	0	0.015
CCPY	0	0.042	0	0.102	0.015	0	0	0.02	0.042	0	0	0.02	0.057	0.107
CIFY	0	0.102	0.117	0	0.025	0	0	0.065	0.05	0.035	0	0.015	0.042	0.065
SUCY	0.035	0.117	0.095	0.107	0	0.107	0	0.065	0.035	0.037	0	0.015	0.107	0.065
SFLR	0.117	0.113	0.113	0.113	0.113	0	0	0.096	0.043	0.058	0.03	0.02	0.108	0.043
FEXR	0.095	0.102	0.117	0.117	0.102	0.065	0	0.102	0.035	0.035	0	0.037	0.117	0.065
IVAC	0.015	0.073	0.035	0.066	0.015	0.02	0	0	0.103	0.025	0	0	0.043	0.058
PROB	0.035	0.015	0.066	0.073	0.035	0.035	0	0.035	0	0.073	0.035	0.035	0.02	0.011
IREA	0.066	0.089	0.095	0.103	0.066	0.043	0	0.097	0.035	0	0.113	0.097	0.02	0.02
LOIS	0.095	0.117	0.088	0.113	0.117	0.05	0	0.035	0.042	0.08	0	0.095	0.065	0.065
IRSI	0.096	0.096	0.088	0.088	0.117	0.043	0	0.08	0.043	0.096	0.117	0	0.05	0.058
GLSG	0.117	0.113	0.107	0.095	0.117	0.035	0.117	0.065	0.042	0.042	0.035	0.05	0	0.065
VRIG	0.035	0.035	0.066	0.081	0.035	0.011	0.02	0.066	0.096	0.102	0.043	0.113	0.035	0

Step 6: The total relation matrix *T* created by equation (3.11) is shown in Table 3.10.

Table 3.10: Total relation matrix for supply chain risk drivers

	FRER	BWEF	CCPY	CIFY	SUCY	SFLR	FEXR	IVAC	PROB	IREA	LOIS	IRSI	GLSG	VRIG
FRER	0.0348	0.1426	0.0952	0.0836	0.0644	0.0178	0.0045	0.1177	0.0895	0.0447	0.0144	0.0208	0.0298	0.0513
BWEF	0.1286	0.0743	0.1703	0.1379	0.073	0.0212	0.0061	0.1502	0.0895	0.0608	0.0182	0.0277	0.0407	0.0676
CCPY	0.0514	0.119	0.089	0.1804	0.0665	0.0246	0.0146	0.0877	0.0991	0.0519	0.0272	0.0601	0.0981	0.156
CIFY	0.06	0.184	0.2087	0.1018	0.0808	0.0285	0.0132	0.1392	0.1149	0.0857	0.0299	0.057	0.0907	0.1271
SUCY	0.1388	0.2655	0.2565	0.2629	0.1018	0.1475	0.0254	0.1934	0.1391	0.119	0.0456	0.0783	0.1886	0.1651
SFLR	0.2272	0.2926	0.2979	0.2947	0.2213	0.0594	0.027	0.2428	0.1648	0.1501	0.0794	0.0923	0.2028	0.1631
FEXR	0.2147	0.2917	0.3129	0.3096	0.2197	0.1245	0.0297	0.2577	0.1646	0.135	0.0538	0.1115	0.2211	0.1916
IVAC	0.0695	0.149	0.1254	0.1512	0.0676	0.0453	0.0121	0.071	0.156	0.0744	0.0274	0.039	0.0852	0.1086
PROB	0.0954	0.115	0.1649	0.1713	0.098	0.0661	0.0103	0.1136	0.0635	0.1224	0.0679	0.077	0.075	0.0763
IREA	0.1731	0.2566	0.2651	0.2723	0.1751	0.097	0.0162	0.2285	0.1464	0.0944	0.1604	0.1619	0.1155	0.1332
LOIS	0.2176	0.3065	0.2877	0.3062	0.2373	0.1131	0.0236	0.1972	0.1669	0.1827	0.0639	0.1713	0.1694	0.1874
IRSI	0.219	0.2907	0.2871	0.2875	0.2387	0.1091	0.0221	0.2368	0.1709	0.1983	0.1722	0.0868	0.1578	0.1828
GLSG	0.2392	0.3065	0.3089	0.2957	0.238	0.1021	0.1346	0.2297	0.1712	0.1451	0.0877	0.1273	0.1173	0.1929
VRIG	0.1345	0.1875	0.2234	0.2377	0.1384	0.0646	0.0358	0.1892	0.1919	0.1862	0.1019	0.1774	0.1184	0.0997

Step 7: *Let r* and *c* be *14×1* and *1×14* vectors representing sum of row elements and sum of column elements for the total relation matrix *T*, respectively. Using equations (3.12) and (3.13), r_i and c_j are calculated. The cause and effect parameters $(r_i + c_j)$ and $(r_i - c_j)$ were calculated for values *i=j,* which is displayed in Table 3.11.

Table 3.11: Cause/ Effect parameters for supply chain risk drivers

Risk Drivers	r_i	c_j	r_i+c_j	r_i-c_j
FRER	0.811	2.004	2.815	-1.193
BWEF	1.066	2.982	4.048	-1.916
CCPY	1.126	3.093	4.219	-1.967
CIFY	1.322	3.093	4.415	-1.771
SUCY	2.128	2.021	4.149	0.107
SFLR	2.515	1.021	3.536	1.494
FEXR	2.638	0.375	3.013	2.263
IVAC	1.182	2.455	3.637	-1.273
PROB	1.317	1.928	3.245	-0.611
IREA	2.296	1.651	3.947	0.645
LOIS	2.631	0.95	3.581	1.681
IRSI	2.66	1.288	3.948	1.372
GLSG	2.696	1.71	4.406	0.986
VRIG	2.087	1.903	3.99	0.184

Step 8: As the number of relations to be plotted is very high, we have fixed a threshold value *(θ)* by adding *1.5* times the standard deviation *(σ)* to the mean *(μ)* of the elements in the total relation matrix *T*, to filter out comparably negligible effects. Figure 3.2 illustrates the obtained digraph representing the causal relationships among risk drivers, plotted from the dataset of $\left((r_i + c_j), (r_i - c_j)\right) \forall\, i = j$.

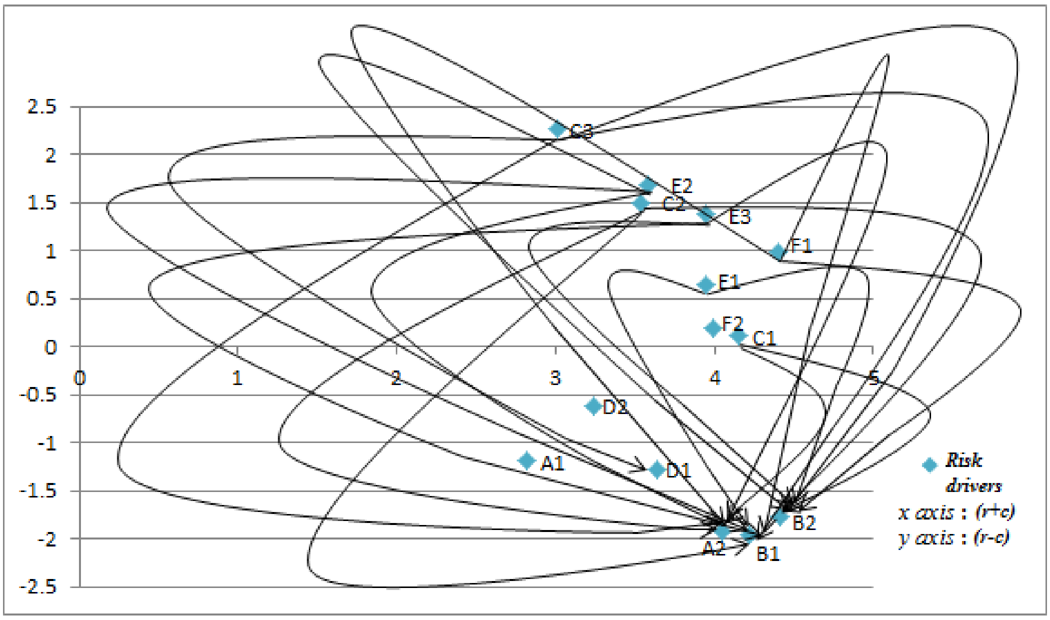


Figure 3.2: Digraph showing causal relations among supply chain risk drivers

3.4. Analysis of Findings

In this research we have used Grey- DEMATEL methodology to find out causal relations among supply chain risk drivers typically seen in an electronic supply chain. For the effective implementation of SCRM practices, it is essential to identify the influential relations among attributes and practices. Drivers of supply chain risk as well the enablers of risk mitigation are having critical interrelationships among themselves. These are complementary problems of interest in building supply chain resilience and were found missing in literature. This research was conducted to address this gap and the resulting digraphs were plotted.

Digraph representing the cause-effect relation is as shown in Figure 3.2 in which the arrow represents the direction from causal risk driver to effect risk driver. Setting a threshold value *(θ)* of 0.2576, *two* way relations were not seen in present study. Based on digraph, risk drivers can be prioritized on importance according to the $(r_i + c_j)\ \forall\ i = j$ values. i.e. *CIFY (B2)> GLSG (F1)> CCPY (B1)> SUCY (C1)> BWEF (A2)> VRIG (F2)> IRSI (E3)> IREA (E1)> IVAC (D1)> LOIS (E2)> SFLR (C2)> PROB (D2)> FEXR (C3)> FRER (A1).* The causal drivers can be sorted on size according to the $(r_i - c_j)\ \forall\ i = j$ values as, *FEXR (C3)> LOIS (E2)> SFLR (C2)> IRSI (E3)> GLSG (F1)> IREA (E1)> VRIG (F2)> SUCY (C1).*

Thus, *fluctuating exchange rates (C3)* is found to be the prime causal driver initiating the effects of other supply chain risk drivers too, followed by *loss of information system (E2)* and *supply failure (C2)*. The risk drivers *C2* and *E2* can be categorized as disruption events, where the probability of occurrence is low, but their impacts are rather high. It is obvious from the nature of disruption events that it can initiate the effects of many supply chain risk drivers. An important managerial implication of this research is that steps taken for minimizing causal risk drivers can in turn lead to decreased effect risk drivers, thus leading to better management of supply chain vulnerability issues. The meticulous analyses of the primary causal drivers were explicated as follows:

Fluctuating exchange rates (C3) are usually less predictable type of risk driver, but the preparedness to avoid disruption can be done using enhanced visibilities and collaborative partner relationships. Along with that, sudden demand perturbations occurring as a result of fluctuating exchange rates can be managed over and done with postponement decisions applied to the maximum extent possible. Sourcing to the nations with same currency circulations can help to reduce the impacts of driver *C3*.

Loss of information system (E2) can be either a disruption event tampering the entire supply network or may be occurring with a partner or sub-contractor resulting in partial loss of the information to be processed. Supply chain visibility gets seriously affected due to the impact of this risk driver and hence it is essential to make sure that the information systems are always protected and performing on the track. Securing the information systems with backups and parallel networks can mitigate the effects of *E2*.

Supply failure (C2) occurs when *one* or more of the existing suppliers are unable to provide their deliverables on time due to certain staid reasons. Supply failure is a disruptive event in which the supply lags behind demand expectations resulting in extended lead times, unfulfilled orders and unsatisfied customers. Adopting flexible supply strategies or flexible supply contracts can reduce the chances of occurrence of *C2*.

The effect drivers can be sorted on size as, *PROB (D2)> FRER (A1)> IVAC (D1)> CIFY (B2)> BWEF (A2)> CCPY (B1).* Thus, risk arising from the *cost of capacity (B1)* is the effect driver for most of the drivers, followed by *bull whip effects (A2)* and *capacity inflexibility (B2).* On a closer analysis of the results we can see that the *fluctuating exchange rates (C3)* is a major cause for the initialization of effect risk drivers related to *cost of capacity (B1), bull whip effects (A2), capacity inflexibility (B2)* and *inventory value and cost (D1).* Disruption events such as, *loss of information system (E2)* and *supply failure (C2)* can also be the cause of initializing major effect drivers such as, *cost of capacity (B1), bull whip effects (A2)* and *capacity inflexibility (B2).*

How far the cause- effect relations vary if the weightings given for analysts vary? Is there any personnel bias in the influence rating given by analysts? In order to answer these questions, sensitivity analysis was conducted by giving highest weighting for analysts 1, 2, 3 and 4 separately, keeping equal weightings for others. *Four* total relationship matrices were developed based on sensitivity analysis. Results of sensitivity analysis show that the primary cause and effect drivers obtained in all scenarios remain the same, which strongly confirm the unbiasness of the solution. Also, the order of prioritization for the cause and effect drivers of supply chain risks remain virtually same in all cases with negligible order discrepancies, which substantiates no serious bias in the influence rating given by supply chain analysts. This is also evident from the minor changes perceived in cause-effect relations on plotted digraphs. The digraphs plotted and the causal relations obtained are displayed in Figures 3.3, 3.4, 3.5 and 3.6.

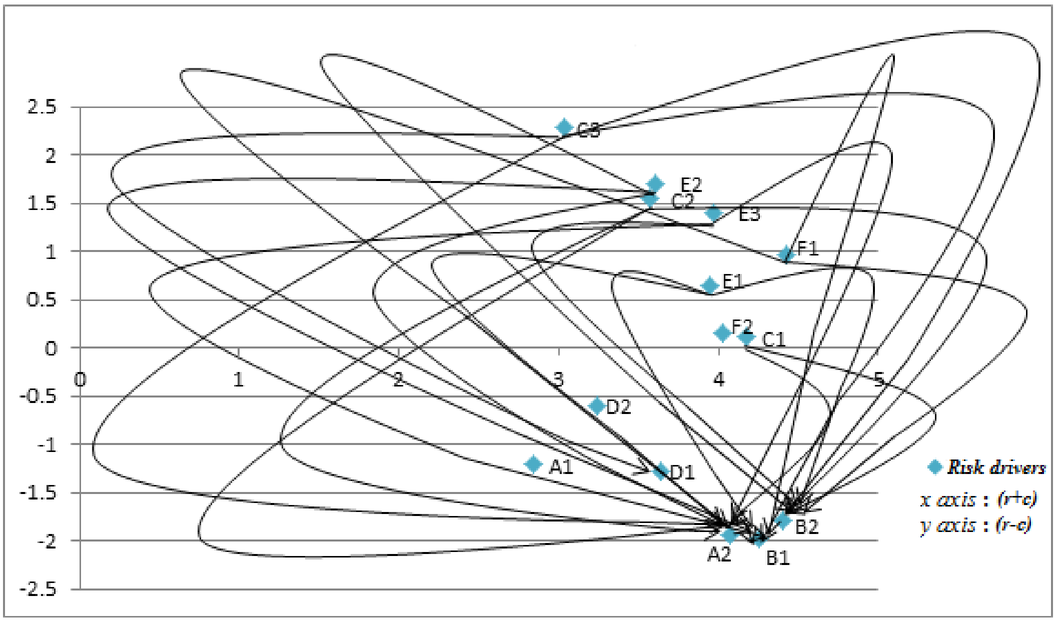


Figure 3.3: Digraph obtained by sensitivity analysis showing causal relations among supply chain risk drivers by giving highest weighting for analyst 1

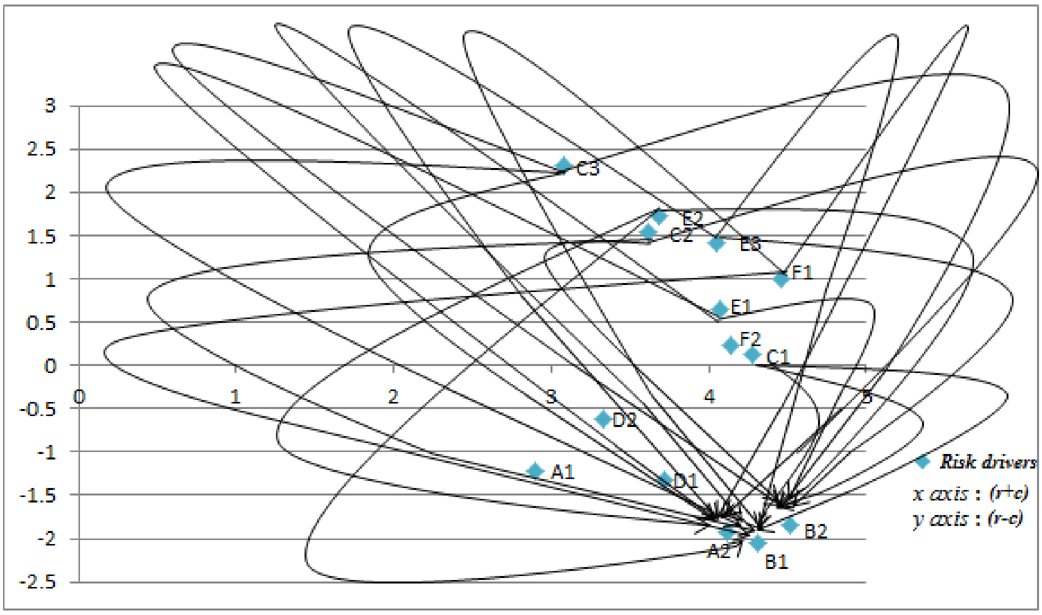


Figure 3.4: Digraph obtained by sensitivity analysis showing causal relations among supply chain risk drivers by giving highest weighting for analyst 2

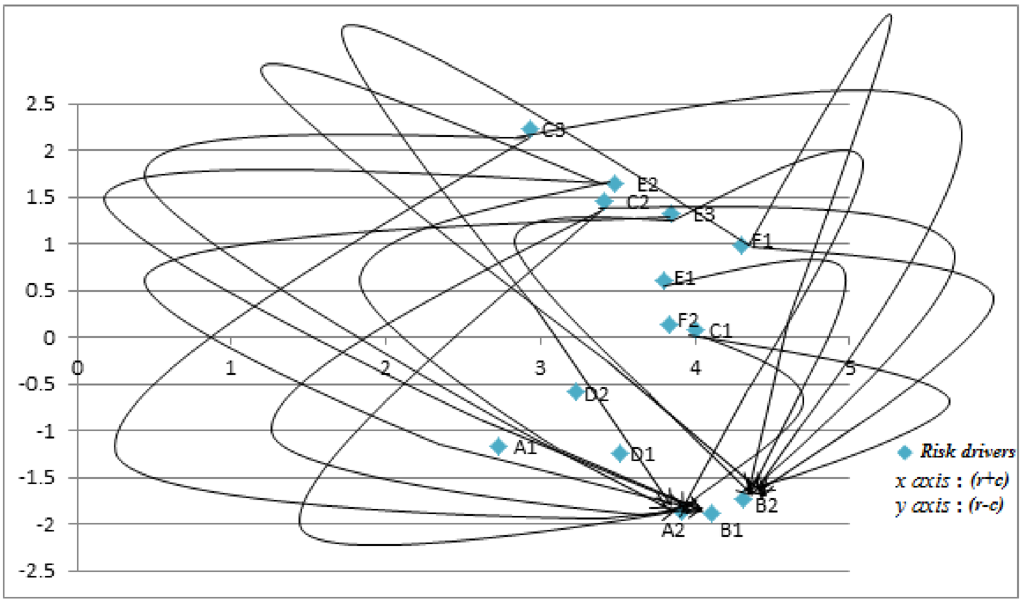


Figure 3.5: Digraph obtained by sensitivity analysis showing causal relations among supply chain risk drivers by giving highest weighting for analyst 3

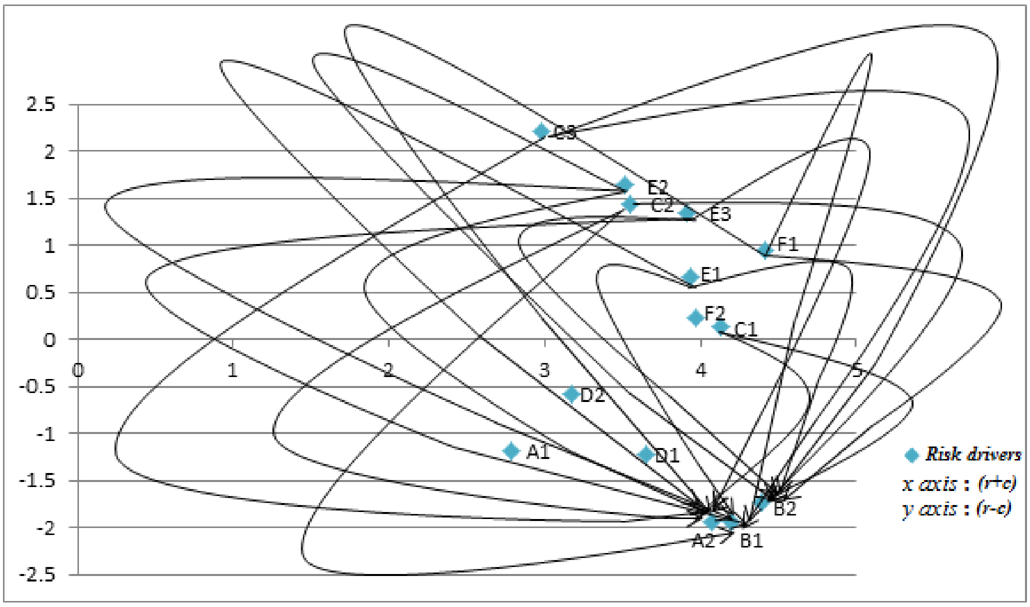


Figure 3.6: Digraph obtained by sensitivity analysis showing causal relations among supply chain risk drivers by giving highest weighting for analyst 4

On a profound investigation of the digraphs obtained on sensitivity analysis, it is substantially professed that there exist no *two* way relations among predominant risk drivers considering an acceptable threshold of *1.5* times the standard deviation added to the mean value of the elements in the total relation matrix. This exemplifies the fact as evidenced from the digraph plots that; there exist no set of drivers which can be the mutual cause and effect in view of the acceptable threshold taken in the model. Reducing the threshold intensifies the chances of occurrences of *two* way cause- effect relations among some of these risk drivers, which would be least probably the primary causal drivers. Threshold value can be suitably fixed according to the needs of the user and the cause- effect relations among drivers can be further studied to find those drivers that are mutual cause and effect.

For validating the results of grey DEMATEL, a comparison of the same has been done with Interpretive Structural Modeling (ISM) methodology. The average relation matrix as obtained from the analysts is taken into consideration for comparison. As the rating of importance were given in a scale of 5, only those prominent relations (in this case > *2*) were assigned to be predominantly existing and the other relations were assumed to be non- influential as such influences does not exist or might be feeble in consideration. Thus a binary relational matrix consisting of *0* and *1* was constructed that forms the direct reachability matrix. After consideration of all transitive relations, the final reachability matrix is constructed as shown in Table 3.12. The final reachability matrix is level partitioned to arrange the drivers in level wise based on influential relations.

The reachability and antecedent matrices were constructed successively and the elements in the top of the level wise matrix will not reach any elements above them. Hence, the reachability of the top level represents the elements itself. Antecedent set consists of elements that help in achieving it. If the intersection of reachability and antecedent sets represents the reachability set itself, then those elements are said to be in the top level. The top level elements are removed and the process is continued again. On completion of the iterative procedure, the digraphs are plotted as shown in Figure 3.7. The results agree with the results of grey – DEMATEL as the principal causal and effect drivers do not change in the plotted digraphs and hence the results are validated. From the ISM model, *fluctuating exchange rates (C3)* emerges as the principal causal driver and risks arising from *cost of capacity (B1)* and *bull whip effects (A2)* emerge as the principal effect drivers, supporting the results of the grey- DEMATEL model.

As discussed earlier, the complementary research problem of identifying and analyzing the causal relations amongst the enablers of risk mitigation also needs to be researched. This helps in reducing the gap from the effective implementation of risk management practices towards achieving supply chain resilience. The problem is discussed in chapter 4.

Table 3.12: Final reachability matrix for supply chain risk drivers

	A1	A2	B1	B2	C1	C2	C3	D1	D2	E1	E2	E3	F1	F2
A1	0	1	0	0	0	0	0	1	0	0	0	0	0	0
A2	1	0	1	1	0	0	0	1	0	0	0	0	0	0
B1	0	1	0	1	0	0	0	0	0	0	0	0	0	1
B2	0	1	1	1	0	0	0	1	1	0	0	0	0	1
C1	1	1	1	1	1	1	0	1	1	1	0	0	1	1
C2	1	1	1	1	1	0	0	1	1	1	0	0	1	1
C3	1	1	1	1	1	1	0	1	1	1	0	1	1	1
D1	0	1	1	1	0	0	0	0	1	0	0	0	0	1
D2	0	1	1	1	0	0	0	1	0	1	0	0	0	0
E1	1	1	1	1	1	0	0	1	1	0	1	1	1	1
E2	1	1	1	1	1	1	0	1	1	1	0	1	1	1
E3	1	1	1	1	1	1	0	1	1	1	1	0	1	1
F1	1	1	1	1	1	1	1	1	1	1	0	1	1	1
F2	1	1	1	1	1	0	0	1	1	1	1	1	1	0

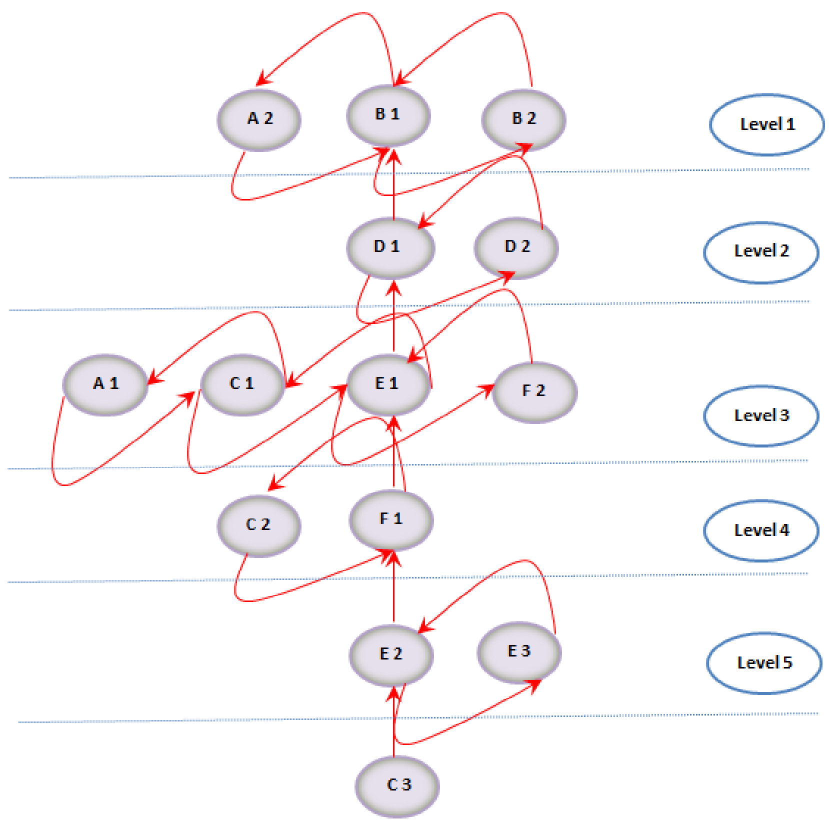


Figure 3.7: Level wise representation of risk drivers as in ISM

CHAPTER 4

CAUSE- EFFECT RELATIONS AMONG ENABLERS OF RISK MITIGATION USING GREY THEORY AND DEMATEL APPROACHES

4.1. Framework of Enablers of SC Risk Mitigation

Supply chain risk mitigation is effective only when the practices of risk mitigation are implemented suitably. But the practices of risk management should be adopted on basis of their net effects, as discussed in chapter 2. Even still, there exists a big gap from the effective implementation of supply chain risk management practices towards the achieving supply chain resilience. This occurs due to the pronounced interrelationships among supply chain risks and also among various enablers of risk mitigation. These interrelationships should be properly identified to reduce the gap from the implementation of supply chain risk mitigation practices towards achieving resilient supply chains. The cause- effect relations were identified among the drivers of supply chain risks in chapter 3 and the complementary research problem of identifying the cause- effect relations among enablers of risk mitigation is addressed in this chapter. A combination of grey theory and DEMATEL methodologies were used to address the present problem.

Considering literature, Zsidisin & Smith (2005) commented that organizations with well-defined policies of supply chain risk management (SCRM) perform better than those have no such policies. Supply chain risk management need to be strategically designed and diligently maintained to avoid internal and external losses for a company. Zsidisin & Ritchie (2008), Zsidisin & Wagner (2010) have emphasized the importance of investing more in resources for management of supply chain risks. Poirier & Quinn (2003) conducted a survey over a wide domain of companies and found that lack of proper contingency plans were one of the primary causes of supply chain disruptions. Asbjørnslett (2009) pointed the relationship between efficiency and vulnerability that, 'the more efficient the supply chain is, the more it is vulnerable towards risks'.

Risk management system is defined as an action plan that specifies the risk needs to be addressed and on how to address them. Blackhurst et al. (2005) identified *eighteen* enabler strategies for risk management that companies can adopt and implement on a cost-benefit basis. Hopp et al. (2012) mentions *four* strategies to manage supply chain disruptions as, *do nothing, redundancy, contingency planning and crisis management*. Tang & Tomlin (2008) vividly points the role of flexibility in managing various kinds of supply chain risks, by mentioning the types of flexibilities needed and the mitigating strategies to be adopted for each type of risk. Soni et al. (2014) proposed a resilient index for measuring supply chain resilience considering the major enablers using deterministic modeling, employing graph theory and matrix approaches.

An analysis of literature reveals that most of the works in supply chain risk management and risk mitigation strategies are rather qualitative in nature. Quantifying the enablers for supply chain risk mitigation to find the causal relationships among them is not seen in literature on supply chain management. Top management would be interested in those enablers which can be the causal driver for many of the other enablers of supply chain risk mitigation. Enablers of supply chain risk mitigation are rather interconnected. In this research, we have identified *fifteen* enablers of supply chain risk mitigation with specific focus on electronic manufacturing industries. Grey-DEMATEL methodology has been used to find the causal relationships among the enablers of supply chain risk mitigation.

Increasing the level of collaboration with suppliers and having more redundant suppliers help to reduce many of supply related ambiguities. Implementing flexible supply strategies through multiple suppliers helps in shifting order quantities across suppliers, apparently reducing supply risks (Tang & Tomlin, 2008). Introduction of flexible supply contracts help to take advantages of long term and short term contracts thereby reducing supply risks through shifting order quantities across time (Gligor, et al., 2015). Collaborative partner relations give more visibility of inventories and capacities available for better management of issues related with supply chain risk management.

Agility can be enhanced through better visibility and velocity in supply chains. Firms must have a proper awareness of what is happening in their supply chain. This includes activities related with internal operations, customers, suppliers and location of inventory, capacity and critical assets (Hendricks & Singhal, 2005). Velocity of the supply chain represents its responsiveness. Suitable strategies can be adopted to keep efficiencies related to velocity trade-offs. Firms should have synchronized planning and its execution. Strategic risk planning needs to be implemented and reflected in each of the supply chain operations (Christopher & Peck, 2004). Dynamic assortment planning increases control of product demand and improves the capability to manage demand. During a disruption event, it helps a firm to influence the demand of different products quickly (Tang, 2006).

Inaccurate forecasts are one of the primary reasons for supply- demand mismatches. Quantitative forecasting considering the variance should be included in planning. Short term and aggregate forecasts are more reliable. The mean and variance of lead time should be purposefully reduced to improve forecast accuracy (Blackhurst, et al., 2005). Success is critically dependent on a supply chain's capability to collect and disseminate information among its partners, with the ultimate objective of replacing inventory by information. Information breakdowns can result in severe system risks. Information should be safe, secure and needs to be delivered on time. Investment in appropriate technologies can reduce potential chances of supply chain disruptions. Most of web based technologies available links supply chain partners for ensuring visibility of information (Faisal, et al., 2007).

Postponement or delayed differentiation is a strategy which delays product differentiation closer to the time when demand information of the product is available (Tang & Tomlin, 2008). Flexible processes adopted through flexible manufacturing systems enable supply chains to shift production quantities across internal resources. Interchangeable manufacturing and the use of standardized parts increases manufacturing flexibilities (Tang, 2006). Strategic stocking increases product availability, improves capability to manage supply and respond better with market fluctuations (Waters, 2011).

Responsive pricing can improve pricing flexibilities. Flexibility is imparted by delaying the time at which prices are set. This actually helps in shifting the demand across different products. Integrated supply chains are those in which the practices of supply chain risk management are incorporated with planning and execution in such a way that each operation reflects the risk mitigation practices. Integrated supply chains are less prone to disruptions (Dekker, et al., 2013).

4.2. Methodology

The methodology is described in detail in Chapter 4 and the explanation of the steps is as elaborated in the second paragraph of the methodology section. ***Step1*** to ***Step6*** is similar as described in Chapter 3. And the cause- effect parameters are obtained as follows;

Step7: Obtain the cause and effect parameters

Assume t_{ij} represents the elements in the total relation matrix, *T*. Let *r* and *c* be defined as $n\times 1$ and $1\times n$ vectors representing sum of row elements and sum of column elements for the total relation matrix *T*, respectively. If r_i represents the sum of i^{th} row elements in matrix *T*, then r_i summarizes both direct and indirect effects given by enabler *i* towards the other enablers. If c_j represents the sum of j^{th} column elements in matrix *T,* then c_j summarizes both direct and indirect effects received by enabler *j* from other enablers, i.e.,

$$r_i = \sum_{j=1}^{n} t_{ij} \; \forall \; i \tag{4.1}$$

$$c_j = \sum_{i=1}^{n} t_{ij} \; \forall \; j \tag{4.2}$$

When *j=i*, the sum $\left(r_i + c_j\right)$ shows the total effects given and received by enabler *i*; i. e, $\left(r_i + c_j\right)$ represents the degree of importance that the enabler *i* plays in the entire system. On the other hand $\left(r_i - c_j\right)$ outlines the net effect that the enabler *i* contributes to the entire system. If $\left(r_i - c_j\right)$ is positive, enabler *i* is the net cause. Enabler *i* is the net effect if $\left(r_i - c_j\right)$ comes out to be negative.

Step8: Set up threshold and plot the digraph

As matrix *T* provides information on how one enabler affects another, a threshold value needs to be set to avoid comparably negligible effects. Setting up a threshold value typifies the appearance of effects greater than threshold value on digraph. Threshold value is usually set by computing the mean value of elements in the total relation matrix *T*. Digraph displaying causal relations is plotted from the dataset of $\left(\left(r_i + c_j\right), \left(r_i - c_j\right)\right) \forall \; i = j$.

4.3. A Real Case Application of the Proposed Model

A case study of an electronic manufacturing company as discussed in Chapter 4 was taken for identifying the cause- effect relations among the enablers of risk mitigation practices. This ensures the efficacy of such practices and the managers can really concentrate on chief causal enablers of risk mitigation. As discussed in the previous chapter, *XYZ*'s supply chain recently faced some issues related with supply chain risk management due to problems with indirect suppliers. *XYZ* planned to take some major modifications in their risk mitigation strategies, thereafter. Thus, risk mitigation strategies and the enablers play a vital role for the case company managers to take proactive initiatives. The enablers for risk mitigation of *XYZ* were identified and classified into *fifteen* categories. The enablers of risk mitigation considered in the study, and their relevant literatures are shown in Table 4.1. A summary of codes used for the enablers of risk mitigation is shown in Table 4.2.

Table 4.1: Enablers of supply chain risk mitigation

Sl No.	Enablers of SC risk mitigation	Relevant Literature	What this enabler does?	How the enabler enhances resilience?
E1.	**Flexible supply base**	(Tang & Tomlin, 2008)	Have redundant suppliers	Shift order quantities across suppliers
E2.	**Flexible supply contracts**	(Cheng, et al., 2011)	Introducing binding contracts with obligations	Shift order quantities across time
E3.	**Collaborative partner relations**	(Chen, et al., 2013)	Increase trust among partners	Risk hedging opportunities
E4.	**Supply chain visibility**	(Caridi, et al., 2010)	Proper awareness of events	Information sharing
E5.	**Supply chain velocity**	(Gligor, et al., 2013)	Efficiency, responsiveness tradeoffs	Favor responsiveness over cost for shorter lifecycle products
E6.	**Strategic risk planning**	(Tang & Musa, 2011)	Synchronized planning and execution	Planning for each and every operations
E7.	**Dynamic assortment planning**	(Sauré & Zeevi, 2013)	Increases control of product demand	Better capability to manage demand
E8.	**Accurate demand forecasting**	(Lee, 2004)	Avoid supply-demand mismatches	Short term, aggregate forecasts preferred
E9.	**Information security**	(Banerjee, 2015)	Replace inventory by information	Safe, secure and delivered on time
E10.	**Technology adaptation**	(Manuj & Mentzer, 2008)	Adaptation from obsolete technologies	Investment in appropriate technologies
E11.	**Postponement strategies**	(Choi, et al., 2012)	Increases product flexibility	Increases capability to manage supply

Sl No.	Enablers of SC risk mitigation	Relevant Literature	What this enabler does?	How the enabler enhances resilience?
E12.	**Flexible processes**	(Baud-Lavigne, et al., 2012)	Flexible manufacturing systems	Standardized parts to reduce inventory
E13.	**Strategic Stocking**	(Barlas & Gunduz, 2011)	Not-to-stock decisions for high risk products	Better supply management capabilities
E14.	**Responsive pricing strategies**	(Billington, et al., 2012)	Swing production quantities across different products	Swing demand across different products
E15.	**Integrated supply chains**	(Jayaram, et al., 2011)	Incorporated SCRM practices	Less prone to disruptions

Table 4.2: Summary table for enablers of supply chain risk mitigation

Enabler	Reference code
E1	FSB
E2	FSC
E3	CPR
E4	SVI
E5	SVE
E6	SRP
E7	DAP
E8	ADF
E9	ISE
E10	TAD
E11	PST
E12	FPR
E13	SST
E14	RPS
E15	ISC

The application of proposed model to the case electronics manufacturing company *XYZ* is elaborated as follows;

***Step1*:** A group comprising of *four* supply chain analysts was formed to evaluate the direct influence among *fifteen* enablers of risk mitigation for the case company *XYZ.*

They evaluated the direct influence of one enabler over other on scales varying from *"no influence"* to *"very high influence"*. *Four* initial relation matrices *(15×15)* were developed based on those ratings.

Step2: *Four* initial grey relationship matrices were developed ($[\otimes y_{ij}^{1}]$, $[\otimes y_{ij}^{2}]$, $[\otimes y_{ij}^{3}]$, and $[\otimes y_{ij}^{4}]$) based on the influence ratings obtained from the *four* analysts using equation (3.1) and are shown in Tables 4.3, 4.4, 4.5 and 4.6.

Table 4.3: Grey relation matrix for enablers of risk mitigation by SC analyst-1

	FSB	FSC	CPR	SVI	SVE	SRP	DAP	ADF	ISE	TAD	PST	FPR	SST	RPS	ISC
FSB	0	0.1	0.4	0.2	0.6	0.1	0.1	0	0	0.1	0.4	0.2	0.1	0.2	0.4
	0.1	0.3	0.7	0.5	0.9	0.3	0.3	0.1	0.1	0.3	0.7	0.5	0.3	0.5	0.7
FSC	0.4	0	0.6	0.4	0.2	0.6	0.1	0.1	0	0.1	0.4	0.2	0.1	0.4	0.2
	0.7	0.1	0.9	0.7	0.5	0.9	0.3	0.3	0.1	0.3	0.7	0.5	0.3	0.7	0.5
CPR	0.2	0.6	0	0.9	0.6	0.4	0.2	0.2	0.1	0.2	0.6	0.4	0.2	0.6	0.4
	0.5	0.9	0.1	1	0.9	0.7	0.5	0.5	0.3	0.5	0.9	0.7	0.5	0.9	0.7
SVI	0.1	0.2	0.9	0	0.6	0.6	0.4	0.9	0.2	0.1	0.2	0.2	0.4	0.4	0.6
	0.3	0.5	1	0.1	0.9	0.9	0.7	1	0.5	0.3	0.5	0.5	0.7	0.7	0.9
SVE	0.1	0.2	0.2	0.2	0	0.1	0.1	0.2	0.1	0.2	0.4	0.2	0.1	0.6	0.4
	0.3	0.5	0.5	0.5	0.1	0.3	0.3	0.5	0.3	0.5	0.7	0.5	0.3	0.9	0.7
SRP	0.2	0.2	0.4	0.4	0.4	0	0.6	0.4	0.4	0.2	0.2	0.2	0.4	0.4	0.4
	0.5	0.5	0.7	0.7	0.7	0.1	0.9	0.7	0.7	0.5	0.5	0.5	0.7	0.7	0.7
DAP	0.2	0.2	0.4	0.6	0.6	0.4	0	0.6	0.4	0.4	0.4	0.4	0.4	0.6	0.6
	0.5	0.5	0.7	0.9	0.9	0.7	0.1	0.9	0.7	0.7	0.7	0.7	0.7	0.9	0.9
ADF	0.2	0.2	0.2	0.6	0.6	0.2	0.2	0	0.2	0.4	0.6	0.6	0.6	0.6	0.6
	0.5	0.5	0.5	0.9	0.9	0.5	0.5	0.1	0.5	0.7	0.9	0.9	0.9	0.9	0.9
ISE	0.1	0.1	0.2	0.2	0.2	0.1	0.1	0.2	0	0.2	0.2	0.2	0.1	0.2	0.6
	0.3	0.3	0.5	0.5	0.5	0.3	0.3	0.5	0.1	0.5	0.5	0.5	0.3	0.5	0.9
TAD	0.1	0.1	0.1	0.2	0.4	0.2	0.1	0.2	0.1	0	0.2	0.2	0.4	0.4	0.4
	0.3	0.3	0.3	0.5	0.7	0.5	0.3	0.5	0.3	0.1	0.5	0.5	0.7	0.7	0.7
PST	0.1	0.1	0.2	0.2	0.4	0.2	0.2	0.2	0.2	0.2	0	0.4	0.9	0.6	0.4
	0.3	0.3	0.5	0.5	0.7	0.5	0.5	0.5	0.5	0.5	0.1	0.7	1	0.9	0.7
FPR	0.1	0.1	0.2	0.2	0.4	0.4	0.4	0.2	0.2	0.6	0.4	0	0.6	0.6	0.4
	0.3	0.3	0.5	0.5	0.7	0.7	0.7	0.5	0.5	0.9	0.7	0.1	0.9	0.9	0.7
SST	0.1	0.1	0.4	0.2	0.2	0.2	0.2	0.4	0.2	0.2	0.6	0.2	0	0.6	0.4
	0.3	0.3	0.7	0.5	0.5	0.5	0.5	0.7	0.5	0.5	0.9	0.5	0.1	0.9	0.7
RPS	0.1	0.1	0.4	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.4	0.4	0.6	0	0.4
	0.3	0.3	0.7	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.7	0.7	0.9	0.1	0.7
ISC	0.4	0.4	0.4	0.6	0.6	0.4	0.4	0.6	0.6	0.6	0.4	0.4	0.6	0.6	0
	0.7	0.7	0.7	0.9	0.9	0.7	0.7	0.9	0.9	0.9	0.7	0.7	0.9	0.9	0.1

*' *FSB*' indicates the enabler of supply chain risk mitigation, '*Flexible supply base*' as in Tables 4.1 and 4.2. Similarly other elements of table can be read. The level of influence of risk driver *i* over the risk driver *j* is represented as grey value $\left[\frac{\underline{\otimes} y_{ij}}{\overline{\otimes} y_{ij}}\right]$.

Table 4.4: Grey relation matrix for enablers of risk mitigation by SC analyst-2

	FSB	FSC	CPR	SVI	SVE	SRP	DAP	ADF	ISE	TAD	PST	FPR	SST	RPS	ISC
FSB	0	0.1	0.4	0.2	0.6	0.1	0.1	0	0	0.1	0.4	0.1	0.1	0.2	0.4
	0.1	0.3	0.7	0.5	0.9	0.3	0.3	0.1	0.1	0.3	0.7	0.3	0.3	0.5	0.7
FSC	0.4	0.1	0.6	0.4	0.2	0.6	0.1	0.1	0	0.1	0.4	0.4	0.1	0.4	0.2
	0.7	0.3	0.9	0.7	0.5	0.9	0.3	0.3	0.1	0.3	0.7	0.7	0.3	0.7	0.5
CPR	0.2	0.6	0	0.9	0.6	0.4	0.2	0.1	0.1	0.2	0.6	0.4	0.2	0.6	0.4
	0.5	0.9	0.1	1	0.9	0.7	0.5	0.3	0.3	0.5	0.9	0.7	0.5	0.9	0.7
SVI	0.1	0.2	0.9	0	0.6	0.6	0.4	0.9	0.2	0.1	0.2	0.2	0.4	0.4	0.6
	0.3	0.5	1	0.1	0.9	0.9	0.7	1	0.5	0.3	0.5	0.5	0.7	0.7	0.9
SVE	0.1	0.2	0.2	0.2	0	0.1	0.1	0.2	0.1	0.2	0.4	0.1	0.1	0.6	0.4
	0.3	0.5	0.5	0.5	0.1	0.3	0.3	0.5	0.3	0.5	0.7	0.3	0.3	0.9	0.7
SRP	0.2	0.2	0.4	0.4	0.4	0	0.6	0.4	0.4	0.2	0.2	0.2	0.4	0.4	0.4
	0.5	0.5	0.7	0.7	0.7	0.1	0.9	0.7	0.7	0.5	0.5	0.5	0.7	0.7	0.7
DAP	0.2	0.2	0.4	0.6	0.6	0.4	0.1	0.6	0.4	0.4	0.4	0.4	0.4	0.6	0.6
	0.5	0.5	0.7	0.9	0.9	0.7	0.3	0.9	0.7	0.7	0.7	0.7	0.7	0.9	0.9
ADF	0.2	0.2	0.2	0.6	0.6	0.2	0.2	0	0.2	0.4	0.6	0.6	0.6	0.6	0.6
	0.5	0.5	0.5	0.9	0.9	0.5	0.5	0.1	0.5	0.7	0.9	0.9	0.9	0.9	0.9
ISE	0.1	0.1	0.2	0.2	0.2	0.1	0.1	0.2	0	0.2	0.2	0.2	0.1	0.2	0.6
	0.3	0.3	0.5	0.5	0.5	0.3	0.3	0.5	0.1	0.5	0.5	0.5	0.3	0.5	0.9
TAD	0.1	0.1	0.1	0.2	0.4	0.2	0.1	0.2	0.1	0	0.2	0.2	0.4	0.4	0.6
	0.3	0.3	0.3	0.5	0.7	0.5	0.3	0.5	0.3	0.1	0.5	0.5	0.7	0.7	0.9
PST	0.1	0.1	0.2	0.2	0.4	0.1	0.2	0.2	0.2	0.2	0	0.4	0.9	0.6	0.4
	0.3	0.3	0.5	0.5	0.7	0.3	0.5	0.5	0.5	0.5	0.1	0.7	1	0.9	0.7
FPR	0.1	0.1	0.2	0.2	0.4	0.4	0.4	0.2	0.2	0.6	0.4	0	0.6	0.4	0.4
	0.3	0.3	0.5	0.5	0.7	0.7	0.7	0.5	0.5	0.9	0.7	0.1	0.9	0.7	0.7
SST	0.1	0.1	0.6	0.4	0.2	0.2	0.2	0.4	0.2	0.2	0.6	0.2	0	0.6	0.4
	0.3	0.3	0.9	0.7	0.5	0.5	0.5	0.7	0.5	0.5	0.9	0.5	0.1	0.9	0.7
RPS	0.1	0.1	0.4	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.4	0.4	0.6	0	0.4
	0.3	0.3	0.7	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.7	0.7	0.9	0.1	0.7
ISC	0.6	0.6	0.4	0.6	0.6	0.4	0.4	0.4	0.6	0.6	0.4	0.4	0.6	0.6	0
	0.9	0.9	0.7	0.9	0.9	0.7	0.7	0.7	0.9	0.9	0.7	0.7	0.9	0.9	0.1

Table 4.5: Grey relation matrix for enablers of risk mitigation by SC analyst-3

	FSB	FSC	CPR	SVI	SVE	SRP	DAP	ADF	ISE	TAD	PST	FPR	SST	RPS	ISC
FSB	0	0.1	0.4	0.2	0.6	0.1	0.1	0	0	0.1	0.4	0.2	0.1	0.2	0.4
	0.1	0.3	0.7	0.5	0.9	0.3	0.3	0.1	0.1	0.3	0.7	0.5	0.3	0.5	0.7
FSC	0.4	0	0.6	0.4	0.2	0.6	0.1	0.1	0	0.1	0.4	0.2	0.1	0.4	0.2
	0.7	0.1	0.9	0.7	0.5	0.9	0.3	0.3	0.1	0.3	0.7	0.5	0.3	0.7	0.5
CPR	0.2	0.6	0	0.9	0.6	0.4	0.2	0.2	0.2	0.2	0.6	0.2	0.2	0.6	0.4
	0.5	0.9	0.1	1	0.9	0.7	0.5	0.5	0.5	0.5	0.9	0.5	0.5	0.9	0.7
SVI	0.1	0.2	0.9	0	0.6	0.6	0.4	0.9	0.2	0	0.2	0.2	0.4	0.4	0.6
	0.3	0.5	1	0.1	0.9	0.9	0.7	1	0.5	0.1	0.5	0.5	0.7	0.7	0.9
SVE	0.1	0.2	0.2	0.2	0	0.1	0.1	0.2	0.1	0.2	0.2	0.2	0.1	0.6	0.4
	0.3	0.5	0.5	0.5	0.1	0.3	0.3	0.5	0.3	0.5	0.5	0.5	0.3	0.9	0.7
SRP	0.2	0.2	0.4	0.4	0.4	0	0.6	0.4	0.4	0.2	0.2	0.2	0.4	0.4	0.4
	0.5	0.5	0.7	0.7	0.7	0.1	0.9	0.7	0.7	0.5	0.5	0.5	0.7	0.7	0.7
DAP	0.2	0.2	0.4	0.6	0.6	0.4	0	0.6	0.4	0.4	0.4	0.4	0.4	0.6	0.6
	0.5	0.5	0.7	0.9	0.9	0.7	0.1	0.9	0.7	0.7	0.7	0.7	0.7	0.9	0.9
ADF	0.2	0.2	0.2	0.6	0.6	0.2	0.2	0	0.2	0.4	0.6	0.6	0.6	0.6	0.6
	0.5	0.5	0.5	0.9	0.9	0.5	0.5	0.1	0.5	0.7	0.9	0.9	0.9	0.9	0.9
ISE	0.1	0.1	0.2	0.2	0.2	0	0.1	0.2	0	0.2	0.2	0.2	0.1	0.2	0.6
	0.3	0.3	0.5	0.5	0.5	0.1	0.3	0.5	0.1	0.5	0.5	0.5	0.3	0.5	0.9
TAD	0.1	0	0.2	0.2	0.4	0.2	0.1	0.2	0.2	0	0.2	0.2	0.4	0.4	0.6
	0.3	0.1	0.5	0.5	0.7	0.5	0.3	0.5	0.5	0.1	0.5	0.5	0.7	0.7	0.9
PST	0.1	0.1	0.2	0.2	0.4	0.2	0.2	0.2	0.2	0.2	0	0.4	0.9	0.6	0.4
	0.3	0.3	0.5	0.5	0.7	0.5	0.5	0.5	0.5	0.5	0.1	0.7	1	0.9	0.7
FPR	0	0.1	0.2	0.2	0.4	0.4	0.4	0.2	0.2	0.6	0.4	0	0.6	0.6	0.6
	0.1	0.3	0.5	0.5	0.7	0.7	0.7	0.5	0.5	0.9	0.7	0.1	0.9	0.9	0.9
SST	0.1	0.1	0.4	0.2	0.2	0.2	0.2	0.4	0.2	0.2	0.6	0.2	0	0.6	0.4
	0.3	0.3	0.7	0.5	0.5	0.5	0.5	0.7	0.5	0.5	0.9	0.5	0.1	0.9	0.7
RPS	0	0.2	0.4	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.4	0.4	0.6	0	0.4
	0.1	0.5	0.7	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.7	0.7	0.9	0.1	0.7
ISC	0.4	0.6	0.4	0.6	0.6	0.4	0.6	0.6	0.6	0.6	0.4	0.4	0.6	0.6	0
	0.7	0.9	0.7	0.9	0.9	0.7	0.9	0.9	0.9	0.9	0.7	0.7	0.9	0.9	0.1

Table 4.6: Grey relation matrix for enablers of risk mitigation by SC analyst-4

	FSB	FSC	CPR	SVI	SVE	SRP	DAP	ADF	ISE	TAD	PST	FPR	SST	RPS	ISC
FSB	0	0.1	0.4	0.2	0.6	0.1	0.1	0	0.1	0.1	0.4	0.4	0.1	0.2	0.6
	0.1	0.3	0.7	0.5	0.9	0.3	0.3	0.1	0.3	0.3	0.7	0.7	0.3	0.5	0.9
FSC	0.4	0	0.6	0.4	0.2	0.6	0.1	0.1	0	0.1	0.4	0.2	0.1	0.4	0.2
	0.7	0.1	0.9	0.7	0.5	0.9	0.3	0.3	0.1	0.3	0.7	0.5	0.3	0.7	0.5
CPR	0.2	0.6	0	0.9	0.6	0.4	0.4	0.2	0.1	0.2	0.6	0.4	0.4	0.6	0.4
	0.5	0.9	0.1	1	0.9	0.7	0.7	0.5	0.3	0.5	0.9	0.7	0.7	0.9	0.7
SVI	0.6	0.2	0.9	0	0.6	0.6	0.4	0.9	0.2	0.1	0.2	0.2	0.4	0.4	0.6
	0.9	0.5	1	0.1	0.9	0.9	0.7	1	0.5	0.3	0.5	0.5	0.7	0.7	0.9
SVE	0.1	0.2	0.2	0.2	0	0.1	0.1	0.2	0.1	0.2	0.4	0.2	0.1	0.6	0.4
	0.3	0.5	0.5	0.5	0.1	0.3	0.3	0.5	0.3	0.5	0.7	0.5	0.3	0.9	0.7
SRP	0.2	0.4	0.4	0.6	0.4	0	0.6	0.4	0.4	0.2	0.2	0.2	0.4	0.4	0.4
	0.5	0.7	0.7	0.9	0.7	0.1	0.9	0.7	0.7	0.5	0.5	0.5	0.7	0.7	0.7
DAP	0.2	0.1	0.4	0.6	0.6	0.4	0.1	0.6	0.4	0.4	0.4	0.4	0.4	0.6	0.6
	0.5	0.3	0.7	0.9	0.9	0.7	0.3	0.9	0.7	0.7	0.7	0.7	0.7	0.9	0.9
ADF	0.2	0.2	0.2	0.6	0.6	0.2	0.2	0	0.2	0.4	0.6	0.6	0.6	0.6	0.6
	0.5	0.5	0.5	0.9	0.9	0.5	0.5	0.1	0.5	0.7	0.9	0.9	0.9	0.9	0.9
ISE	0.1	0.1	0.2	0.2	0.2	0.1	0.4	0.2	0.1	0.2	0.2	0.2	0.1	0.2	0.6
	0.3	0.3	0.5	0.5	0.5	0.3	0.7	0.5	0.3	0.5	0.5	0.5	0.3	0.5	0.9
TAD	0.1	0.1	0.1	0.2	0.4	0.2	0.1	0.2	0.1	0	0.2	0.2	0.4	0.4	0.4
	0.3	0.3	0.3	0.5	0.7	0.5	0.3	0.5	0.3	0.1	0.5	0.5	0.7	0.7	0.7
PST	0.1	0.1	0.2	0.2	0.4	0.1	0.2	0.2	0.2	0.4	0	0.4	0.9	0.6	0.4
	0.3	0.3	0.5	0.5	0.7	0.3	0.5	0.5	0.5	0.7	0.1	0.7	1	0.9	0.7
FPR	0.1	0.1	0.2	0.2	0.4	0.4	0.4	0.2	0.2	0.6	0.4	0	0.6	0.6	0.4
	0.3	0.3	0.5	0.5	0.7	0.7	0.7	0.5	0.5	0.9	0.7	0.1	0.9	0.9	0.7
SST	0.1	0.1	0.4	0.2	0.2	0.2	0.2	0.6	0.2	0.2	0.6	0.2	0.1	0.6	0.4
	0.3	0.3	0.7	0.5	0.5	0.5	0.5	0.9	0.5	0.5	0.9	0.5	0.3	0.9	0.7
RPS	0.1	0.1	0.4	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.4	0.4	0.6	0	0.4
	0.3	0.3	0.7	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.7	0.7	0.9	0.1	0.7
ISC	0.4	0.4	0.6	0.6	0.6	0.4	0.4	0.6	0.6	0.6	0.4	0.4	0.4	0.6	0
	0.7	0.7	0.9	0.9	0.9	0.7	0.7	0.9	0.9	0.9	0.7	0.7	0.7	0.9	0.1

Step3: In order to have homogeneity of judgment, equal weightings were given to all supply chain analysts and average grey relation matrix $[\otimes\, \tilde{y}_{ij}]$ is computed using equation (3.2) and is shown in Table 4.7.

Table 4.7: Average grey relation matrix for enablers of SC risk mitigation

	FSB	FSC	CPR	SVI	SVE	SRP	DAP	ADF	ISE	TAD	PST	FPR	SST	RPS	ISC
FSB	0	0.1	0.4	0.2	0.6	0.1	0.1	0	0.025	0.1	0.4	0.225	0.1	0.2	0.45
	0.1	0.3	0.7	0.5	0.9	0.3	0.3	0.1	0.15	0.3	0.7	0.5	0.3	0.5	0.75
FSC	0.4	0.025	0.6	0.4	0.2	0.6	0.1	0.1	0	0.1	0.4	0.25	0.1	0.4	0.2
	0.7	0.15	0.9	0.7	0.5	0.9	0.3	0.3	0.1	0.3	0.7	0.55	0.3	0.7	0.5
CPR	0.2	0.6	0	0.9	0.6	0.4	0.25	0.175	0.125	0.2	0.6	0.35	0.25	0.6	0.4
	0.5	0.9	0.1	1	0.9	0.7	0.55	0.45	0.35	0.5	0.9	0.65	0.55	0.9	0.7
SVI	0.225	0.2	0.9	0	0.6	0.6	0.4	0.9	0.2	0.075	0.2	0.2	0.4	0.4	0.6
	0.45	0.5	1	0.1	0.9	0.9	0.7	1	0.5	0.25	0.5	0.5	0.7	0.7	0.9
SVE	0.1	0.2	0.2	0.2	0	0.1	0.1	0.2	0.1	0.2	0.35	0.175	0.1	0.6	0.4
	0.3	0.5	0.5	0.5	0.1	0.3	0.3	0.5	0.3	0.5	0.65	0.45	0.3	0.9	0.7
SRP	0.2	0.25	0.4	0.45	0.4	0	0.6	0.4	0.4	0.2	0.2	0.2	0.4	0.4	0.4
	0.5	0.55	0.7	0.75	0.7	0.1	0.9	0.7	0.7	0.5	0.5	0.5	0.7	0.7	0.7
DAP	0.2	0.175	0.4	0.6	0.6	0.4	0.05	0.6	0.4	0.4	0.4	0.4	0.4	0.6	0.6
	0.5	0.45	0.7	0.9	0.9	0.7	0.2	0.9	0.7	0.7	0.7	0.7	0.7	0.9	0.9
ADF	0.2	0.2	0.2	0.6	0.6	0.2	0.2	0	0.2	0.4	0.6	0.6	0.6	0.6	0.6
	0.5	0.5	0.5	0.9	0.9	0.5	0.5	0.1	0.5	0.7	0.9	0.9	0.9	0.9	0.9
ISE	0.1	0.1	0.2	0.2	0.2	0.075	0.175	0.2	0.025	0.2	0.2	0.2	0.1	0.2	0.6
	0.3	0.3	0.5	0.5	0.5	0.25	0.4	0.5	0.15	0.5	0.5	0.5	0.3	0.5	0.9
TAD	0.1	0.075	0.125	0.2	0.4	0.2	0.1	0.2	0.125	0	0.2	0.2	0.4	0.4	0.5
	0.3	0.25	0.35	0.5	0.7	0.5	0.3	0.5	0.35	0.1	0.5	0.5	0.7	0.7	0.8
PST	0.1	0.1	0.2	0.2	0.4	0.15	0.2	0.2	0.2	0.25	0	0.4	0.9	0.6	0.4
	0.3	0.3	0.5	0.5	0.7	0.4	0.5	0.5	0.5	0.55	0.1	0.7	1	0.9	0.7
FPR	0.075	0.1	0.2	0.2	0.4	0.4	0.4	0.2	0.2	0.6	0.4	0	0.6	0.55	0.45
	0.25	0.3	0.5	0.5	0.7	0.7	0.7	0.5	0.5	0.9	0.7	0.1	0.9	0.85	0.75
SST	0.1	0.1	0.45	0.25	0.2	0.2	0.2	0.45	0.2	0.2	0.6	0.2	0.025	0.6	0.4
	0.3	0.3	0.75	0.55	0.5	0.5	0.5	0.75	0.5	0.5	0.9	0.5	0.15	0.9	0.7
RPS	0.075	0.125	0.4	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.4	0.4	0.6	0	0.4
	0.25	0.35	0.7	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.7	0.7	0.9	0.1	0.7
ISC	0.45	0.5	0.45	0.6	0.6	0.4	0.45	0.55	0.6	0.6	0.4	0.4	0.55	0.6	0
	0.75	0.8	0.75	0.9	0.9	0.7	0.75	0.85	0.9	0.9	0.7	0.7	0.85	0.9	0.1

Step4: The crisp relation matrix *Z* was constructed from average grey relation matrix by a *three* step procedure involving modified- CFCS method is as indicated in Table 4.8.

Table 4.8: Crisp relation matrix for enablers of supply chain risk mitigation

	FSB	FSC	CPR	SVI	SVE	SRP	DAP	ADF	ISE	TAD	PST	FPR	SST	RPS	ISC
FSB	0	0.112	0.5	0.267	0.746	0.12	0.106	0	0.027	0.12	0.509	0.29	0.111	0.273	0.568
FSC	0.527	0.025	0.733	0.5	0.273	0.746	0.106	0.118	0	0.12	0.509	0.332	0.111	0.509	0.273
CPR	0.284	0.725	0	0.9	0.746	0.509	0.302	0.227	0.156	0.273	0.746	0.45	0.311	0.746	0.509
SVI	0.275	0.259	0.9	0	0.746	0.746	0.475	0.9	0.273	0.086	0.273	0.273	0.484	0.509	0.746
SVE	0.124	0.259	0.267	0.267	0	0.12	0.106	0.267	0.12	0.273	0.45	0.231	0.111	0.746	0.509
SRP	0.284	0.316	0.5	0.558	0.509	0	0.705	0.5	0.509	0.273	0.273	0.273	0.484	0.509	0.509
DAP	0.284	0.218	0.5	0.733	0.746	0.509	0.05	0.733	0.509	0.509	0.509	0.509	0.484	0.746	0.746
ADF	0.284	0.259	0.267	0.733	0.746	0.273	0.245	0	0.273	0.509	0.746	0.746	0.714	0.746	0.746
ISE	0.124	0.112	0.267	0.267	0.273	0.086	0.191	0.267	0.027	0.273	0.273	0.273	0.111	0.273	0.746
TAD	0.124	0.08	0.153	0.267	0.509	0.273	0.106	0.267	0.156	0	0.273	0.273	0.484	0.509	0.627
PST	0.124	0.112	0.267	0.267	0.509	0.193	0.245	0.267	0.273	0.332	0	0.509	0.878	0.746	0.509
FPR	0.089	0.112	0.267	0.267	0.509	0.509	0.475	0.267	0.273	0.746	0.509	0	0.714	0.686	0.568
SST	0.124	0.112	0.558	0.325	0.273	0.273	0.245	0.558	0.273	0.273	0.746	0.273	0.025	0.746	0.509
RPS	0.089	0.146	0.5	0.267	0.273	0.273	0.245	0.267	0.273	0.273	0.509	0.509	0.714	0	0.509
ISC	0.587	0.609	0.558	0.733	0.746	0.509	0.533	0.675	0.746	0.746	0.509	0.509	0.657	0.746	0

***Step5**:* Normalization was done for the crisp relation matrix using equations to obtain normalized direct crisp relation matrix *P*.

***Step6**:* Total relation matrix *T* built using equation (3.11) is shown in Table 4.9.

Table 4.9: Total relation matrix

	FSB	FSC	CPR	SVI	SVE	SRP	DAP	ADF	ISE	TAD	PST	FPR	SST	RPS	ISC
FSB	0.0319	0.0507	0.1118	0.0891	0.1513	0.0627	0.0532	0.0529	0.043	0.0622	0.1197	0.0843	0.0775	0.1137	0.1337
FSC	0.0982	0.0509	0.1572	0.1327	0.1238	0.1446	0.0681	0.0801	0.051	0.0729	0.1383	0.1035	0.0967	0.1588	0.1252
CPR	0.0884	0.1407	0.1095	0.2018	0.2049	0.145	0.1075	0.1209	0.0875	0.1126	0.1941	0.1424	0.1498	0.2247	0.1862
SVI	0.0917	0.0992	0.2071	0.1199	0.2156	0.1718	0.1315	0.1968	0.1066	0.1016	0.1565	0.1322	0.1738	0.2107	0.2199
SVE	0.0467	0.0647	0.0901	0.0906	0.0724	0.0648	0.0545	0.0828	0.0553	0.0798	0.116	0.0814	0.0831	0.1634	0.1303
SRP	0.0839	0.0935	0.152	0.1614	0.1724	0.0816	0.1442	0.1431	0.1208	0.1087	0.1385	0.1181	0.1576	0.1891	0.1792
DAP	0.0952	0.0964	0.1732	0.2012	0.2244	0.1535	0.0908	0.1881	0.1365	0.1525	0.187	0.163	0.1858	0.2458	0.2328
ADF	0.0891	0.0927	0.1408	0.1882	0.2116	0.1223	0.1057	0.1014	0.1055	0.1457	0.202	0.1787	0.2019	0.2345	0.2199
ISE	0.0468	0.0496	0.0873	0.0901	0.1019	0.0594	0.0633	0.0828	0.0444	0.08	0.0946	0.0835	0.0788	0.1118	0.1535
TAD	0.0485	0.048	0.0817	0.0943	0.1311	0.0826	0.0582	0.0885	0.0631	0.0538	0.1022	0.0882	0.1251	0.1449	0.1486
PST	0.0551	0.0595	0.1091	0.109	0.1479	0.0869	0.0834	0.1022	0.085	0.1023	0.0909	0.1263	0.1834	0.1918	0.1558
FPR	0.058	0.0664	0.1196	0.1218	0.1629	0.1287	0.1163	0.1136	0.094	0.1551	0.1555	0.0824	0.1801	0.2011	0.1775
SST	0.0584	0.0639	0.1427	0.1225	0.1316	0.0989	0.0865	0.1352	0.0877	0.0991	0.1736	0.1083	0.0999	0.197	0.1611
RPS	0.0506	0.062	0.1293	0.1078	0.1217	0.0937	0.082	0.0991	0.0828	0.0939	0.1407	0.1233	0.1628	0.1085	0.1511
ISC	0.1323	0.1419	0.1913	0.2107	0.236	0.1625	0.1471	0.1881	0.1651	0.1829	0.1991	0.1713	0.211	0.2588	0.1683

***Step7:** Let r* and *c* defined to be *15×1* and *1×15* vectors representing sum of row elements and sum of column elements for the total relation matrix *T*, respectively.

Using equations (4.1) and (4.2), r_i and c_j values are computed. The cause and effect parameters $(r_i + c_j)$ and $(r_i - c_j)$ were computed from the total relation matrix for values i=j, which is presented in Table 4.10.

Table 4.10: Cause/ effect parameters for enablers of supply chain risk mitigation

Enablers	r_i	c_j	r_i+c_j	r_i-c_j
FSB	1.238	1.075	2.313	0.163
FSC	1.602	1.18	2.782	0.422
CPR	2.216	2.003	4.219	0.213
SVI	2.335	2.041	4.376	0.294
SVE	1.276	2.41	3.686	-1.134
SRP	2.044	1.659	3.703	0.385
DAP	2.526	1.392	3.918	1.134
ADF	2.34	1.776	4.116	0.564
ISE	1.228	1.328	2.556	-0.1
TAD	1.359	1.603	2.962	-0.244
PST	1.689	2.209	3.898	-0.52
FPR	1.933	1.787	3.72	0.146
SST	1.766	2.167	3.933	-0.401
RPS	1.609	2.755	4.364	-1.146
ISC	2.766	2.543	5.309	0.223

Step8: The number of relations to be plotted is a large measure; a threshold value *(θ)* was set by adding *1.5* times the standard deviation *(σ)* to the mean *(μ)* of the elements in the total relation matrix *T*, to filter out comparably negligible cause/effects among enablers. Figure 4.1 enunciates the digraph displaying causal relationship among the enablers of risk mitigation, plotted from the dataset of $\left((r_i + c_j), (r_i - c_j)\right) \forall\, i = j$. The arrow represents the direction from cause enabler to effect enabler of supply chain risk mitigation. *Two* way relationships between enablers are represented in dotted lines in the figure.

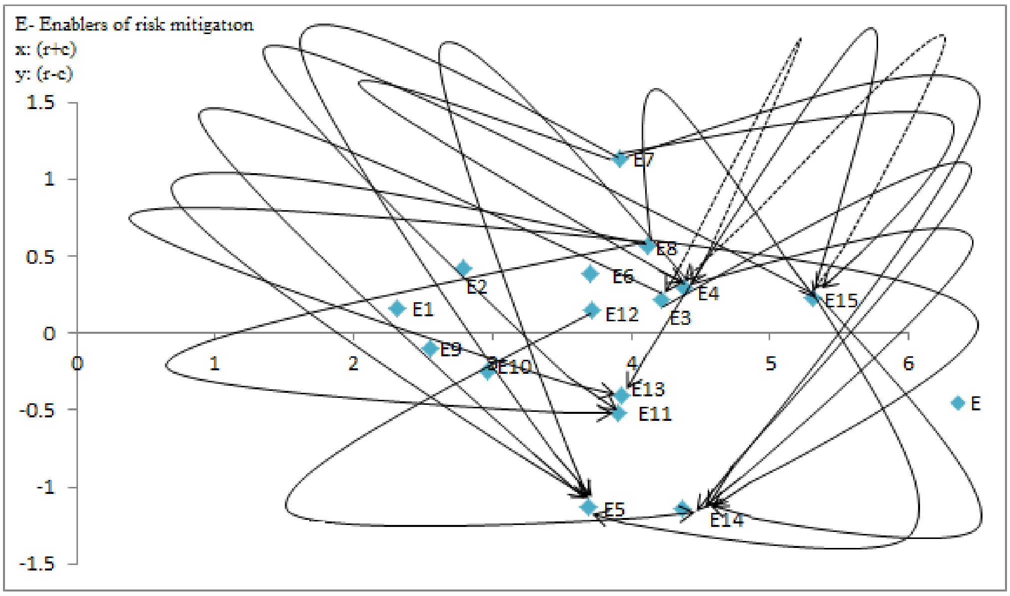


Figure 4.1: Digraph showing causal relations of enablers of SC risk mitigation

4.4. Analysis of Findings

As discussed above, a combination of Grey theory and DEMATEL methodologies were employed in this research to find out the cause- effect relation among enablers of supply chain risk mitigation typically seen in case of an electronic supply chain. A threshold value *(θ)* of 0.1986 is set in this study to reduce the effects which are comparably insignificant. The enablers are prioritized on its importance based on $(r_i + c_j)\ \forall\ i = j$ values as follows, *FSB> ISE> FSC> TAD> SVE> SRP> FPR> PST> DAP> SST> ADF> CPR> RPS> SVI> ISC.*

The causal (driver) enablers were ranked based upon its $(r_i - c_j)\ \forall\ i = j$ values as, *DAP> ADF> FSC> SRP> SVI> ISC> CPR> FSB> FPR*. Thus, *dynamic assortment planning (DAP)* is found to be the crucial driving enabler, as it initiates the effects of many other enablers of supply chain risk mitigation, followed by *accurate demand forecasting (ADF)* and *flexible supply contracts (FSC).* From Figure 5.1, it is depicted that *dynamic assortment planning (DAP)* initiates the effects of *supply chain visibility (SVI), supply chain velocity (SVE), responsive pricing* *strategies (RPS)* and *integrated supply chains (ISC)*. The results clearly exemplify the need of assortment planning and accurate forecasting methods in supply chain risk mitigation.

The effect (driven) enablers whose effects are initiated by other enablers can be sorted on size as, *ISE> TAD> SST> PST> SVE> RPS.* Thus, *responsive pricing strategies (RPS)* are the effect enabler for many causal enablers, followed by *supply chain velocity (SVE)* and *postponement strategies (PST).* By assortment planning, it is possible to entice customers for the purchase of widely available products during times when some of the products are facing supply disruptions. Incorporating qualitative and quantitative innards in forecasting can upshot accurate forecasting, that can reduce many of the supply- demand mismatches. An important managerial implication of this research is that any attempts made for implementation of driving causal enablers can in turn lead to initiate driven effect enablers of risk mitigation, thus leading to improved risk mitigation capabilities of supply chains.

How far the cause- effect relations vary, if different weights were assigned for supply chain analysts? Do there exist any personnel bias in the influence rating given by analysts? In an attempt to answer these questions, sensitivity analysis was conducted of the results by giving principal weighting for analysts 1, 2, 3 and 4 separately, keeping equal weightings for the others. This sensitivity analysis could allow us to determine whether the probable biases of a particular manager may have influenced the results obtained in our case study. This will enable to see how a sensitivity analysis might be completed in this methodology from a methodological generalizability aspect. Sensitivity analysis can be conducted in a variety of ways, such as changing the level of weightings given to various enablers or by changing the level of weighting given to a particular manager. We have made focus on this archetypal sensitivity analysis in the latter approach of adjusting the weights of managers, separately (giving highest weighting for each) and provide some insights into the results and are shown in Figures 4.2, 4.3, 4.4 and 4.5.

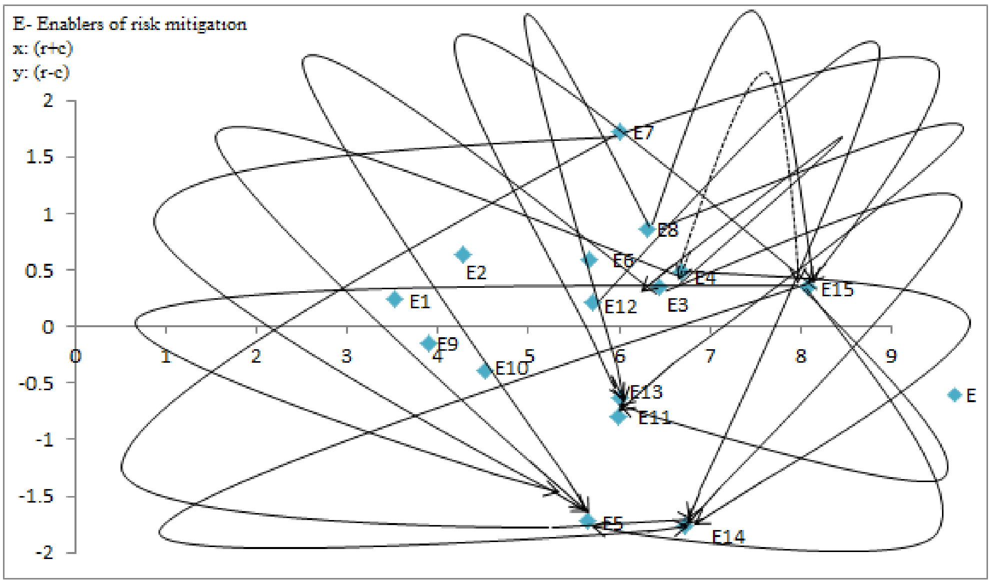


Figure 4.2: Digraph obtained on sensitivity analysis showing causal relations among enablers of risk mitigation by giving highest weighting for supply chain analyst 1

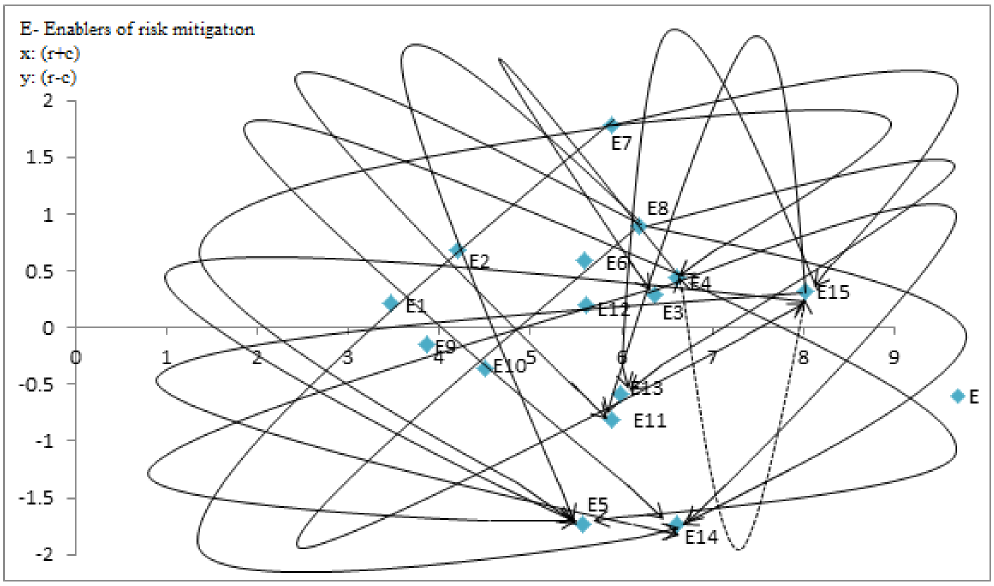


Figure 4.3: Digraph obtained on sensitivity analysis showing causal relations among enablers of risk mitigation by giving highest weighting for supply chain analyst 2

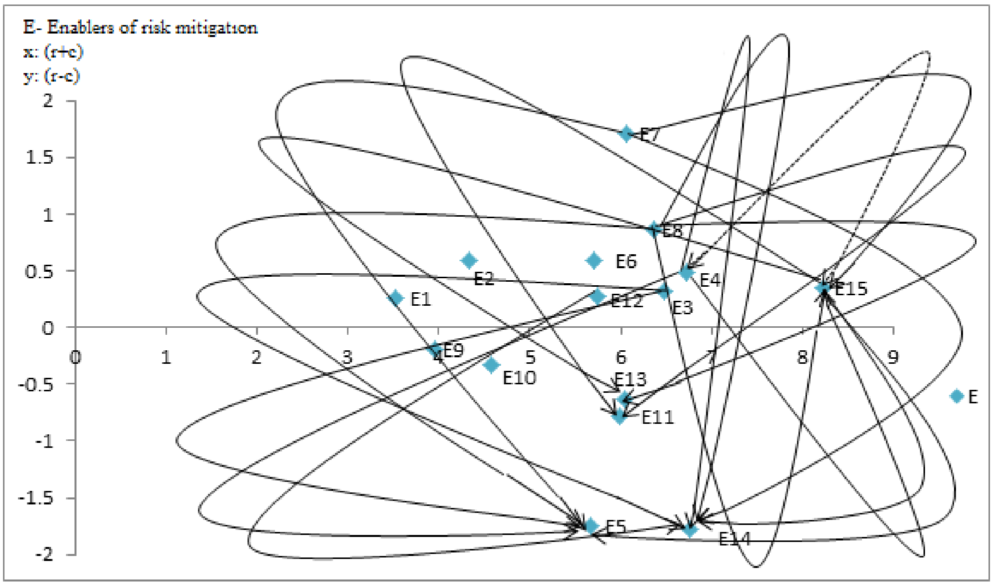


Figure 4.4: Digraph obtained on sensitivity analysis showing causal relations among enablers of risk mitigation by giving highest weighting for supply chain analyst 3

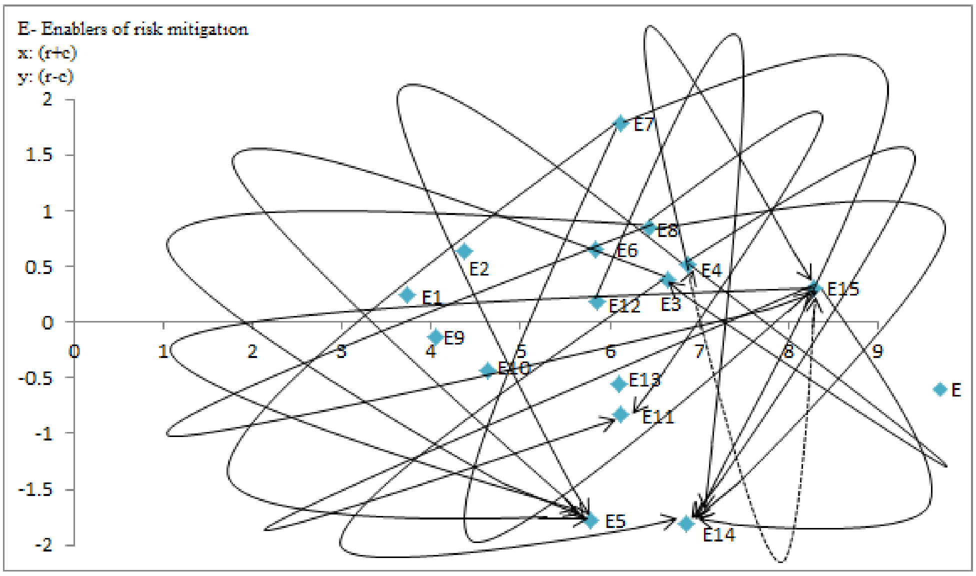


Figure 4.5: Digraph obtained on sensitivity analysis showing causal relations among enablers of risk mitigation by giving highest weighting for supply chain analyst 4

Four separate total relationship matrices were tabulated on the basis of sensitivity analysis. Results of sensitivity analysis show same ranking order for cause/effect enablers in each case, accepting negligible order discrepancies. Hence, there is no serious bias on the influence of ratings given by supply chain analysts. These inferences were perceived from the negligible changes seen in cause-effect relations on digraphs. On a deeper analysis of the results, we could perceive that in general any pair of enablers is mutually influenced by each other. The enablers located above the x axis have the most influence on the network and are located in influential or causal group and the enablers which are under this line are positioned in dysfunctional or influenced groups.

Decreasing the threshold value for consideration enhance the appearance of more causal relations in the digraph. We have observed the causal relations by decreasing the threshold as $\mu + \sigma$ (0.2604). Since it is practically difficult to plot all digraphs, the results in detail are discussed as follows; the remarkable observation on lowering the threshold values is the appearance of some mutual cause and effect relations. On lowering the threshold, it is seen that *collaborative partner relations (E3)* has a mutual cause- effect relation to *integrated supply chains (E15)* and *supply chain visibility (E4)* has a mutual cause- effect relation existing with *accurate demand forecasting (E8)*. Also, there is an appearance of mutual cause- effect relations among *flexible processes (E12)* with *integrated supply chains (E15)*.

The network of enablers can be divided to *four* zones for accurate analysis of their influences as seen in Figure 4.6; where *first zone (Z1)*, represents the enablers with the least relations or in other words, they are independent and their significance is low. *ISE (Information security), TAD (Technology adaptation)* and *SVE (Supply chain velocity)* come under this zone. Second z*one (Z2)* is a gauge of true causal relations and their influence on enabler's network is trivial. *FSB (Flexible supply base), FSC (Flexible supply contracts), SRP (Strategic risk planning)* and *FPR (Flexible processes)* comes under this zone.

Third zone (Z3) represents the enablers with the highest significance; located in causal group and are essentially considered, being the most important factors. The enablers that are most protuberant, furthest to the right on the graph, are most strongly connected, as evidenced by the most significant digraph relationships. *DAP (Dynamic assortment planning), ADF (Accurate demand forecasting), SVI (Supply chain visibility), CPR (Collaborative partner relations)* and *ISC (Integrated supply chains)* are counted in this zone. *Fourth zone (Z4)* indicates enablers with high significance but is located in the dysfunctional group. These enablers are in fact the major snags in the network and the organization must immediately address them. *PST (Postponement strategies), SST (Strategic Stocking)* and *RPS (Responsive pricing strategies)* are in this zone.

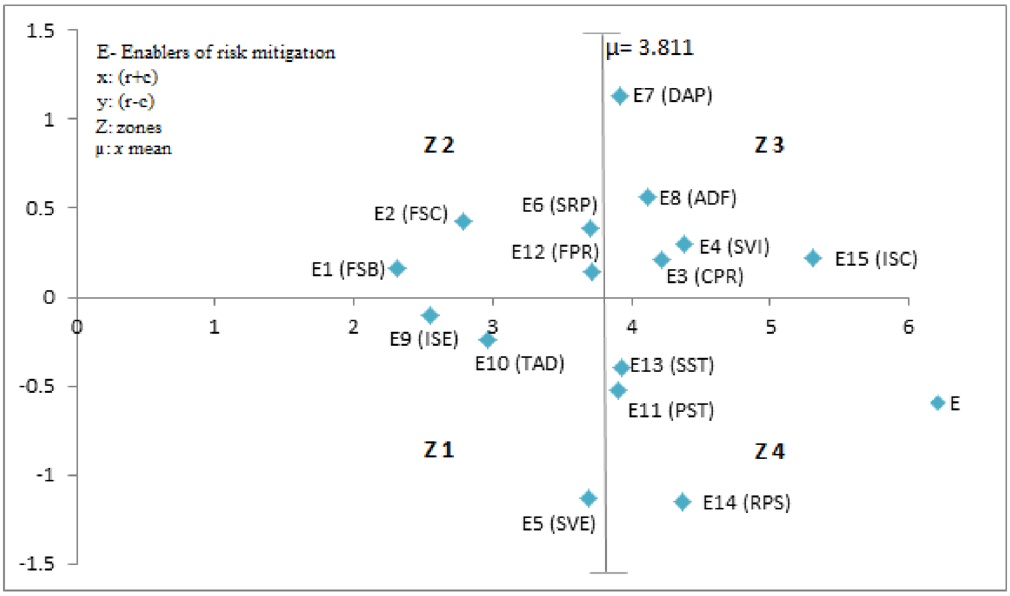


Figure 4.6: Enablers of supply chain risk mitigation represented in zones

The gaps towards achieving supply chain resilience through effective risk management in supply chains have been discussed in chapters 3 and 4. From the literature on supply chain disruptions, it is regarded that most of the supply chain disasters are rather supply related. It is essentially important to manage the upstream supply chain for achieving supply chain resilience. This process should start right from the selection of suppliers. For addressing this gap, a supplier selection problem for achieving resilience is proposed and discussed in the next chapter.

CHAPTER 5

SUPPLIER SELECTION FOR RESILIENCE USING GREY RELATIONAL ANALYSIS

5.1. Framework of suppliers in a resilient supply chain

Supply chain disruptions and the preparedness to avoid or to mitigate the effects of disruptions need substantial attention to build supply chain resilience. From the analysis of literature on supply chain risk management and resilience, it is seen that the major disruptive events are occurring in the upstream of the supply chain. So, utmost care is needed to deal with supplier relationship management and the related areas. This should start right from the selection of suppliers. Suppliers should meet the requirements of resilience for the firm and a research in this direction was not addressed till date. Hence, the traits of suppliers for building resilience were identified and a problem of selection of suppliers for resilience has been addressed in this chapter. The results were obtained using grey relational analysis.

Considering the present problem, a supplier to be selected in the context of a resilient supply chain is termed as a *'Resilient supplier'*. We define a resilient supplier as, "*suppliers who are able to provide good quality products at economy rates and flexible enough to accommodate demand fluctuations with shorter lead times over a lower ambience of risk without compromising on safety and environment practices"*. Literature review reveals that attributes of quality, cost and flexibility are given primary importance in supplier selection problems (Choi & Hartley, 1996; Verma & Pullman, 1998; Ghodsypour & O'Brien, 1998; Lee, et al., 2009). Apart from this, a supplier needs to be responsive enough to adapt with fluctuations in demand (Christopher & Peck, 2004; Ndubisi, et al., 2005). In quest of supply chain resilience, supplier should be least vulnerable to disruptions with better awareness of possible risk events and having well established practices of supply chain continuity management (Shen, et al., 2013). Also, it is preferable for suppliers to have research and development (R&D) division to ensure technical support and having practices of safety and environment (Mahapatra, et al., 2010; Seuring, 2010). The framework for selection of suppliers in a resilient supply chain is shown in Figure 5.1.

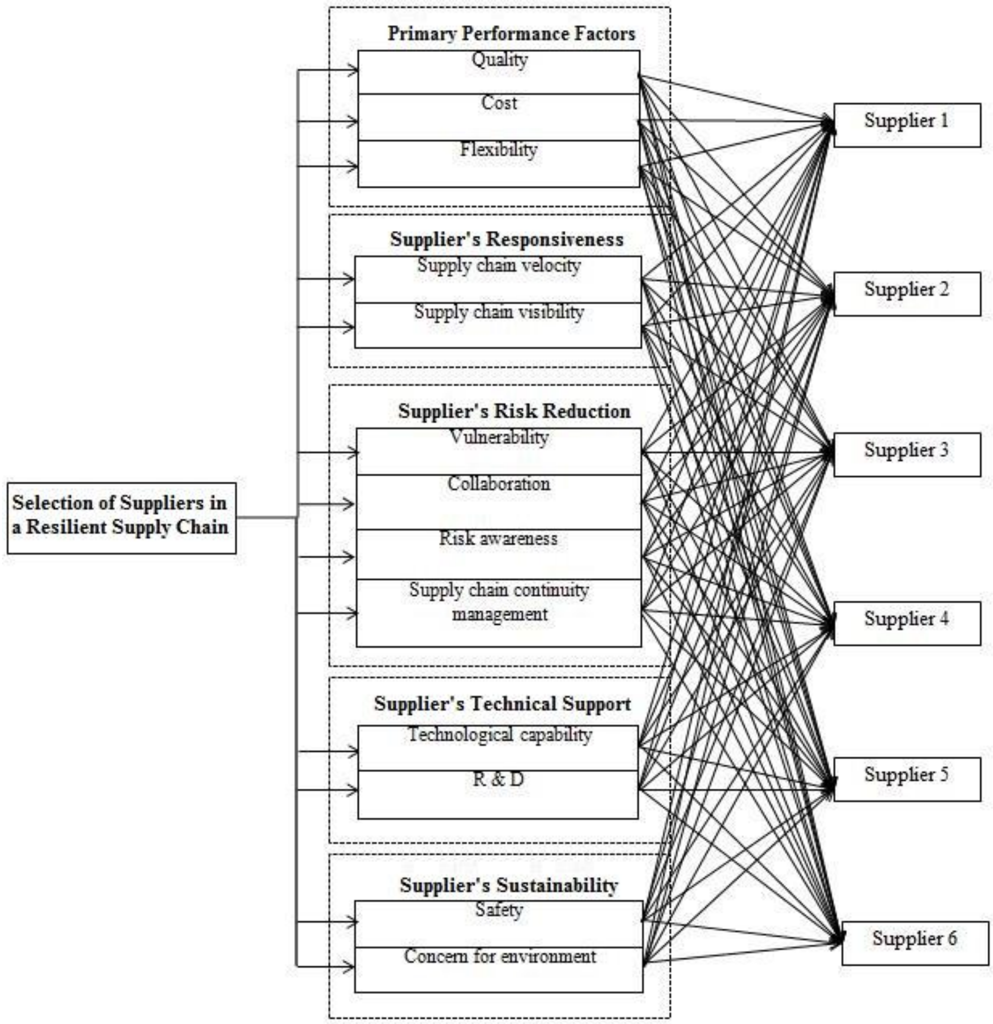


Figure 5.1: Attributes for the selection of suppliers in a resilient supply chain

The parameters considered for selection of suppliers in a resilient supply chain are:

(i) Primary performance factors

(ii) Supplier's responsiveness

(iii) Supplier's risk reduction

(iv) Supplier's technical support, and

(v) Supplier's sustainability

5.1.1. Primary performance factors

In this research, quality, cost and flexibility are taken as primary performance factors for selection of suppliers in a resilient supply chain. There is a preferable choice of suppliers providing good quality materials at reasonable rates and flexible enough to adjust with demands. Flexibility is the ability of the supplier to manage disruptions and respond better with fluctuating demands that can be improved by high redundancy, improved adaptability and standardization of processes (Ponomarov & Holcomb, 2009).

5.1.2. Supplier's responsiveness

Supplier is said to be responsive, if he has a good visibility and better supply chain velocities. A supplier needs to have a high supply chain velocity, *i. e.* responsive enough to reduce the elapsed time from the placement of order to the point of delivery. Christopher & Holweg (2011) opines that a supplier must have sufficient acceleration to comply with the fluctuations in demand. Visibility is the ability of the supplier to have a vivid view of upstream and downstream inventories, demand and supply conditions and production and purchasing schedules. Resilience is enhanced with better visibility of suppliers. Information sharing increases the visibility of the supplier's supply chain in both upstream and downstream levels.

5.1.3. Supplier's risk reduction

Suppliers should be least vulnerable to disruptions. They must work in collaboration with the firm. Also, suppliers should have better awareness of possible risks and well established practices of supply chain continuity management for reducing the potential risks. Factors like swift technological changes, changing customer preferences, information exploration and increasing competition increases relevance of symbiotic marketing. Collaborative working with suppliers reduces risks related to forecasting and inventory management. Most of the disruptions from the supply side can be mitigated by increasing the level of collaboration among the partners.

Tools such as supply chain planning, supply chain (operations) management, supply chain change management etc., must be effectively implemented among the suppliers to reduce potential vulnerabilities (Christopher & Lee, 2004). Understanding of various risks related with assets, process, organizations and environment makes the supplier aware of risks and thus helps in mitigating them. Supply chain continuity management is another parameter that needs to be taken for selection of suppliers. Developing a risk management culture is essential for improving the resilience of supplier. Risk assessments should form a formal part of the decision making process at all levels of the organization to become the process of supply chain continuity management.

5.1.4. Supplier's technical support

Supplier must be strong in technical capabilities. It is preferable that they have a robust research and development (R&D) division to ensure a good level of technical support. Technological capability of the supplier needs to be high enough to adapt with recent innovations in technology. New technologies should be incorporated to keep the quality standards and for reducing the risks (Mahapatra, et al., 2010). R&D activities enable suppliers to adapt with present market turbulences for producing better quality products.

5.1.5. Supplier's Sustainability

Suppliers should give priority to greener practices throughout, considering safety and environment to maintain sustainable competitiveness. Environmental concerns essentially includes environment protection system certification (e.g., ISO 14001 certification) and safety practices principally involves the use of PPE'S (Personal Protective Equipment) and maintaining incident/accident records, hazard and assessment records. In recent years, organizations are proactively choosing greener suppliers to curb the environmental impacts and to reduce carbon foot prints of products (Seuring & Müller, 2008; Seuring, 2010). Proactive methods should be implemented by suppliers to follow greener strategies. The attributes considered for the selection of suppliers in a resilient supply chain and the recent literature dealt with them are shown in Table 5.1.

Table 5.1: Attributes for resilient supplier selection in resilient supply chains

SRA_j^*	Attribute	Relevant Literature	Remarks
SRA_1	**Quality**	(Mahapatra, et al., 2010)	A supplier should keep quality standards of the company, thereby improving organizational performance.
SRA_2	**Cost**	(Li, et al., 2007)	Effective cost management of purchases among suppliers is an inevitable factor in achieving corporate success..
SRA_3	**Flexibility**	(Jayaram, et al., 2011)	Flexibility is the ability of the supplier to manage disruptions and respond to fluctuating demands.
SRA_4	**Supply Chain Velocity**	(Bode, et al., 2011)	Elapsed time from the placement of order to the point of delivery of product should be reduced.
SRA_5	**Supply Chain Visibility**	(Tse & Tan, 2012)	Visibility is the ability of the supplier to have a vivid view of upstream and downstream inventories, demand and supply conditions.
SRA_6	**Vulnerability**	(Hsu, et al., 2013)	There should be robust sales and operations planning process for suppliers to identify and react to sources of vulnerabilities.

SRA_j^*	Attribute	Relevant Literature	Remarks
SRA_7	**Level of Collaboration**	(Zsidisin & Smith, 2005)	Supplier collaboration reduces forecasting and inventory management risks, thereby enhancing resilience of supply chains.
SRA_8	**Risk Awareness**	(Lavastre, et al., 2012)	Supplier should be aware of various levels of risks, such as risks related with assets, process, organizations and environment.
SRA_9	**Supply Chain Continuity Management**	(Golicic & Smith, 2013)	The supplier's risk management culture for resilience should have the considerations of supply chain continuity management.
SRA_{10}	**Technological Capability**	(Bai & Sarkis, 2010)	Suppliers must be technologically capable to adapt themselves towards innovations.
SRA_{11}	**Research and Development**	(Chiang, et al., 2012)	Suppliers should have a strong R&D wing to incorporate innovations in technology and to adapt with the present market turbulences.
SRA_{12}	**Safety**	(Bai & Sarkis, 2010)	Suppliers must provide their employees with a safe and healthy working environment in order to prevent accidents.
SRA_{13}	**Concern for Environment**	(Hsu, et al., 2013)	Proactive methods should be implemented by suppliers for protection environment as a whole.

* SRA_j indicates the Supplier Resilient Attribute, $j = \{1, 2, 3, \ldots, 13\}$

Attributes considered in this context for the selection of a resilient supplier, other than cost and supply chain velocity are qualitative in nature and can be described subjectively in terms of linguistic labels. Grey relational analysis could judiciously be used for supplier selection in these situations.

5.2. Grey Relational Analysis

Grey theory as proposed (Deng, 1982) has several advantages to deal with uncertainty of the situations as discussed in the earlier chapters. It is flexible to deal with grey numbers and related methodologies to obtain interpretable results. On comparing with fuzzy set theory, grey theory is more flexible to deal with situational uncertainty. Fuzzy set theory is employed when there are clear intensions and unclear extensions where grey theory is commonly adopted for situations with clear extensions and unclear intensions. Grey relational analysis investigates uncertain relationships between one main factor and all the other factors in a system (Kuo, et al., 2008). Also, grey relational analysis is found to be suitably implemented in supplier selection problems (Golmohammadi & Mellat-Parast, 2012).

Li et al. (2007) developed a grey-based decision-making approach to classical supplier selection problem. They considered the primary attributes for supplier selection and calculated grey possibility values for selection of suppliers. Kuo et al. (2008) elaborates the application of grey relational analysis in MADM problems in comparison with DEA. Baskaran et al. (2012) evaluated sustainability of the suppliers in a textile manufacturing firm using grey relational analysis. Golmohammadi & Mellat-Parast (2012) integrated fuzzy pairwise comparison with grey relational analysis for supplier selection problem. Tseng & Chiu (2013) used grey relational analysis and fuzzy set theory for selection of green supplier alternative.

For detailed understanding of the methodology and its implementation, the procedure is briefly elaborated as follows; initially, a group of supply chain analysts is to be identified for the case company for evaluation. These supply chain analysts are given the task of rating the supplier performances on various resilience attributes by considering alternative choices of suppliers. Also, the weightings for different attributes of resilience are determined by them. The average of the ratings of analysts is calculated using the grey averaging operators. The obtained decision matrix is to be normalized for both cost and benefit attributes and then multiplied with the corresponding weightings to obtain the weighted normalized grey decision matrix.

Then, an ideal choice of supplier is framed by taking the best performances of alternatives across the criteria. Every supplier is to be compared with this ideal referential supplier. The closeness of the alternative supplier towards this ideal referential supplier gives the increasing preference for selection of them. For this, we are calculating the grey possibility values. A grey possibility value represents the possibility that the considered supplier is away from the ideal supplier. Decreasing order of these possibility values gives an increasing preference of selection of the supplier. The detailed ten steps for grey relational analysis are as follows;

Notations

S_i	Supplier alternatives	$\otimes W_j{}^k$	Grey number of attribute weightings
$\otimes G_{ij}{}^k$	Grey number of attribute ratings	S^{max}	Ideal referential supplier
$\otimes G_{ij}{}^*$	Normalized grey number of attribute ratings	D	Grey decision matrix
$\otimes V_{ij}$	Weighted normalized grey number of attribute ratings	D^*	Normalized grey decision matrix
P	Possibility values	D^{**}	Weighted normalized grey decision matrix

Step1: Formation of group of analysts to identify the potential alternate suppliers

A committee consisting of supply chain analysts examines the suppliers fitting with operational capabilities of the company and the current market requirements. Let $S_i = \{S_1, S_2, S_3, \ldots, S_m\}$ be the m set of supplier alternatives, where $i = (1, 2, 3, \ldots, m)$.

Step2: Surveying on attributes imparting resilience

Identify the factors of resilient supplier selection. Let there be n additively independent resilient attributes, as Supplier Resilient Attribute (SRA) taken for comparison. *i.e.,* $SRA_j = \{SRA_1, SRA_2, SRA_3, \ldots, SRA_n\}$, where $j = (1, 2, 3, \ldots, n)$.

Step3: Linguistic to grey scale of assessment of weights for attributes

Let $\otimes W_j = \{\otimes W_1, \otimes W_2, \otimes W_3, \ldots, \otimes W_n\}$ be the grey vector of attribute weights. The linguistic assessments of ratings can be converted into associated grey values, having a lower bound $(\underline{G})$ and an upper bound $(\overline{G})$.

Suppose there are t supply chain analysts in the committee, represented by A_k, $k = (1, 2, 3, ..., t)$. The weights in linguistic scales assigned for attribute j by the k^{th} supply chain analyst is represented as, $\{W_j^1, W_j^2, W_j^3, ..., W_j^t\}$. Let $\{\otimes W_j^1, \otimes W_j^2, \otimes W_j^3, ..., \otimes W_j^t\}$ be the set of grey number associated with the corresponding weights. The average attribute weight for each attribute j is calculated as,

$$\otimes W_j = \frac{1}{t}[\otimes {W_j}^1 + \otimes {W_j}^2 + \otimes {W_j}^3 + \cdots + \otimes {W_j}^t] \tag{5.1}$$

$$i.\ e., \otimes W_j = \frac{1}{t}\sum_{k=1}^{t}\left(\otimes {W_j}^k\right) \tag{5.2}$$

where $\otimes {W_j}^k$ be the grey number of weight of attribute j assigned by analyst k; i. e.,

$$\otimes {W_j}^k = \left[\underline{W}_j{}^k, \overline{W}_j{}^k\right] \tag{5.3}$$

Thus equation (5.2) can be modified as,

$$\otimes W_j = \left[\left(\frac{1}{t}\sum_{k=1}^{t}\left(\underline{W}_j{}^k\right)\right), \left(\frac{1}{t}\sum_{k=1}^{t}\left(\overline{W}_j{}^k\right)\right)\right] \tag{5.4}$$

Step4: Linguistic to grey scale of assessment of attributes

The attribute j of resilience are rated by analyst k for the supplier i as G_{ij}^k, $i = (1, 2, 3, ..., m); j = (1, 2, 3, ..., n); k = (1, 2, 3, ..., t)$ can be represented by the grey number,

$$\otimes {G_{ij}}^k = \left[\underline{G}_{ij}{}^k, \overline{G}_{ij}{}^k\right] \tag{5.5}$$

The average rating can be calculated as,

$$\otimes G_{ij} = \frac{1}{t}\left[\otimes {G_{ij}}^1 + \otimes {G_{ij}}^2 + \otimes {G_{ij}}^3 + \cdots + \otimes {G_{ij}}^t\right] \tag{5.6}$$

$$i.\ e., \otimes G_{ij} = \frac{1}{t}\sum_{k=1}^{t}\left(\otimes {G_{ij}}^k\right) \tag{5.7}$$

Equation (5.7) can be modified as,

$$\otimes G_{ij} = \left[\left(\frac{1}{t}\sum_{k=1}^{t}\left(\underline{G}_{ij}{}^k\right)\right), \left(\frac{1}{t}\sum_{k=1}^{t}\left(\overline{G}_{ij}{}^k\right)\right)\right] \tag{5.8}$$

Step5: Establish the grey decision matrix

Grey decision matrix *D* is obtained from the obtained from average grey ratings, $\otimes G_{ij}$. Here each grey number represents an upper bound and a lower bound.

$$D = \begin{bmatrix} \otimes G_{11} & \otimes G_{12} & \cdots & \otimes G_{1n} \\ \otimes G_{21} & \otimes G_{22} & \cdots & \otimes G_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ \otimes G_{m1} & \otimes G_{m2} & \cdots & \otimes G_{mn} \end{bmatrix} \quad (5.9)$$

Step6: Normalize the grey decision matrix

Normalization is to limit values in [0, 1]. It can be either minimization (cost attribute) or maximization (benefit attribute). The minimization attribute is normalized as,

$$\otimes G_{ij}^{*} = \left[\frac{G_j^{min}}{\overline{G}_{ij}}, \frac{G_j^{min}}{\underline{G}_{ij}}\right] \quad (5.10)$$

where, $G_j^{min} = \min_{1 \le i \le m} \{\underline{G}_{ij}\}$ (5.11)

The maximization attribute is normalized as,

$$\otimes G_{ij}^{*} = \left[\frac{\underline{G}_{ij}}{G_j^{max}}, \frac{\overline{G}_{ij}}{G_j^{max}}\right] \quad (5.12)$$

where, $G_j^{max} = \max_{1 \le i \le m} \{\overline{G}_{ij}\}$ (5.13)

The normalized grey decision matrix, D^* is represented as,

$$D^* = \begin{bmatrix} \otimes G_{11}^{*} & \otimes G_{12}^{*} & \cdots & \otimes G_{1n}^{*} \\ \otimes G_{21}^{*} & \otimes G_{22}^{*} & \cdots & \otimes G_{2n}^{*} \\ \vdots & \vdots & \ddots & \vdots \\ \otimes G_{m1}^{*} & \otimes G_{m2}^{*} & \cdots & \otimes G_{mn}^{*} \end{bmatrix} \quad (5.14)$$

Step7: Establish the weighted normalized grey decision matrix

The weighted normalized grey decision matrix ($\otimes V_{ij}$) is the product of normalized grey decision matrix ($\otimes G_{ij}^{*}$) and criteria weights ($\otimes W_j$)

i. e., $\otimes V_{ij} = \left[\left(\otimes G_{ij}{}^{*} \right) * \left(\otimes W_j \right) \right]$ (5.15)

The grey number multiplication can be done in the following way as,

$$\otimes V_{ij} = \left[\left[min \left(\underline{G}_{ij} * \underline{W}_j, \underline{G}_{ij} * \overline{W}_j, \overline{G}_{ij} * \underline{W}_j, \overline{G}_{ij} * \overline{W}_j \right) \right], \left[max \left(\underline{G}_{ij} * \underline{W}_j, \underline{G}_{ij} * \overline{W}_j, \overline{G}_{ij} * \underline{W}_j, \overline{G}_{ij} * \overline{W}_j \right) \right] \right] \quad (5.16)$$

where, $\otimes V_{ij} = \left[\underline{V}_{ij}, \overline{V}_{ij} \right]$ (5.17)

The weighted normalized grey decision matrix, D^{**} is represented as,

$$D^{**} = \begin{bmatrix} \otimes V_{11} & \otimes V_{12} & \cdots & \otimes V_{1n} \\ \otimes V_{21} & \otimes V_{22} & \cdots & \otimes V_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ \otimes V_{m1} & \otimes V_{m2} & \cdots & \otimes V_{mn} \end{bmatrix} \quad (5.18)$$

Step8: Establish the ideal referential set of supplier alternatives

From the possible set of supplier alternatives, $S_i = \{S_1, S_2, S_3, \ldots, S_m\}$, $i = (1, 2, 3, \ldots, m)$, the ideal referential set of alternatives represented by $S^{max} = \{G_1^{max}, G_2^{max}, G_3^{max}, \ldots, G_n^{max}\}$ is obtained as,

$$S^{max} = \begin{bmatrix} \left[\max_{1 \le i \le m} \underline{V}_{i1}, \max_{1 \le i \le m} \overline{V}_{i1} \right], \left[\max_{1 \le i \le m} \underline{V}_{i2}, \max_{1 \le i \le m} \overline{V}_{i2} \right], \\ \left[\max_{1 \le i \le m} \underline{V}_{i3}, \max_{1 \le i \le m} \overline{V}_{i3} \right], \ldots, \left[\max_{1 \le i \le m} \underline{V}_{in}, \max_{1 \le i \le m} \overline{V}_{in} \right] \end{bmatrix} \quad (5.19)$$

Step9: Calculate the grey possibility by comparison

Calculate the grey possibility by comparing the supplier set, $S_i = \{S_1, S_2, S_3, \ldots, S_m\}$, $i = (1, 2, 3, \ldots, m)$, with ideal referential supplier S^{max}; given as,

$$P(S_i \le S^{max}) = \frac{1}{n} \sum_{j=1}^{n} \left[P(\otimes V_{ij} \le \otimes G_j{}^{max} \right] \quad (5.20)$$

The possibility, a grey number is less than or equal to another is estimated as follows,

$$P(S_i \le S^{max}) = \frac{1}{n} \sum_{j=1}^{n} \left[\frac{\max(0, L_j{}^{*} - \max(0, \overline{V}_{ij} - \underline{G}_j{}^{max})}{L_j{}^{*}} \right] \quad (5.21)$$

Equation (5.21) can be elaborated as,

$$P(S_i \le S^{max}) = \frac{1}{n}\left[\left[\frac{max(0, L_1{}^{*} - max(0, \overline{V}_{i1} - \underline{G_1}^{max})}{L_1{}^{*}}\right] + \left[\frac{max(0, L_2{}^{*} - max(0, \overline{V}_{i2} - \underline{G_2}^{max})}{L_2{}^{*}}\right] + \left[\frac{max(0, L_3{}^{*} - max(0, \overline{V}_{i3} - \underline{G_3}^{max})}{L_3{}^{*}}\right] +, \ldots, + \left[\frac{max(0, L_n{}^{*} - max(0, \overline{V}_{in} - \underline{G_n}^{max})}{L_n{}^{*}}\right]\right] \quad (5.22)$$

where L_j^{*}, $j = \{1, 2, 3, \ldots, n\}$ represents the sum of the length of grey numbers, $\otimes V_{ij}$ *and* $\otimes G_j^{max}$, which can be shown as,

$$L_j{}^{*} = L(\otimes V_{ij}) + L(\otimes G_j{}^{max}) \quad (5.23)$$

The length of a grey number $L(\otimes V_{ij})$ is calculated as,

$$L(\otimes V_{ij}) = \overline{V}_{ij} - \underline{V}_{ij} \quad (5.24)$$

Thus, equation (5.24) can be written as,

$$L_j{}^{*} = \left[(\overline{V}_{ij} - \underline{V}_{ij}) + \left(\overline{G}_j{}^{max} - \underline{G}_j{}^{max}\right)\right] \quad (5.25)$$

Step10: Prioritize the suppliers

After obtaining $(P\ (S_i \le S^{max}))$, prioritization is done for suppliers. If the possibility value is less, the supplier is better and close to the ideal supplier and vice versa.

5.3. A Real Case Company Example

The model developed in this research was tested in an electronic manufacturing company '*ABC*' in India. The company is a major manufacturer of electronic gadgets mainly, laptops and mobiles in India. *ABC* prefers to have reliable products on comparatively low cost ranges with adequate responsiveness. *ABC*'s global supply chain has extraction of raw materials and processing, on its one end and batch production of components followed by final product assembly at the other. The supply chain network of *ABC* is spread over the world with markets in Asia, Europe and Latin America; hence a choice of global supplier would be preferable. In-house manufacturing is preferred by *ABC*, following strict social and environmental standards.

Regular market surveys and customer surveys keeps their products updated all time. Global manufacturing network heightens their risk profile. Thus suppliers resilient enough to respond to varying demands assume great significance. All suppliers must comply with the standards of *ABC*. The company always tries to incorporate latest of features available in markets for increased customer delights. Widely distributed service centres ensure that customers get the required level of service. The company has shortlisted about six suppliers for supply of a typical component used in their mobiles based on their past supplier data. The case study was conducted to select the best of supplier choice available. Grey relational analysis suits best as any new supplier could easily be incorporated into decision making process if any situation of that arises.

In this research, the weights and ratings of supplier attributes for alternative suppliers available are described by linguistic variables expressed in grey numbers. Also, the grey possibility is calculated for determining the ranking of all suppliers in a resilience supply chain context. The case study enables us to evaluate the suppliers in a practical setting. A sample of the calculations has been added in Annexure 3. This *step* by *step* procedure is presented as follows:

Step1: A committee consisting of *five* supply chain analysts was given the task of identifying the potential alternative suppliers under consideration. These supply chain analysts were experts in this field having an experience of over 10 years working in supply chains. In this case, there were *six* alternative suppliers available.

Step2: The *thirteen* attributes listed in the Table 5.1 were taken into consideration for the selection of suppliers. The supplier resilient attributes (SRA_j), $j = \{1, 2, 3, \ldots, 13\}$ taken in order are, *Quality, Cost, Flexibility, Supply chain velocity, Supply chain visibility, Vulnerability, Level of collaboration, Risk awareness, Supply chain* *continuity management, Technological capability, R&D, Safety and Concern for environment.*

Step3: The committee rated the importance of attributes for imparting resilience as weightings, in linguistic scales varying from *Very Low* to *Very High* viz, *Very Low [VL], Low [L], Fairly Low [FL], Medium [M], Fairly High [FH], High [H] and Very High [VH]*. The committee also rated the performance of the suppliers on corresponding attributes in linguistic scales varying from *Very Poor* to *Very Good* viz, *Very Poor [VP], Poor [P], Medium Poor [MP], Fair [F], Medium Good [MG], Good [G] and Very Good [VG]*. The sets of grey numbers associated with the ratings were decided. This is shown in Table 5.2.

Table 5.2: Linguistic assessment and the associated grey values

Rating of attributes	
Linguistic assessment	**Associated grey values**
Very Poor (VP)	[0, 1]
Poor (P)	[1, 3]
Medium Poor (MP)	[3, 4]
Fair (F)	[4, 5]
Medium Good (MG)	[5, 6]
Good (G)	[6, 9]
Very Good (VG)	[9, 10]

Weights of attributes	
Linguistic assessment	**Associated grey values**
Very Low (VL)	[0.0, 0.1]
Low (L)	[0.1, 0.3]
Medium Low (ML)	[0.3, 0.4]
Medium (M)	[0.4, 0.5]
Medium High (MH)	[0.5, 0.6]
High (H)	[0.6, 0.9]
Very High (VH)	[0.9, 1.0]

Step4: The linguistic evaluations of the weights of the attributes, given by analysts were converted into grey numbers. Average of the grey weights given to attributes is calculated using equations (5.1), (5.2), (5.3) & (5.4) and is shown in Table 5.3. For

clarity, the average grey weight of attribute SRA_1 is obtained as, $\otimes W_1 = [0.84, 0.98]$. Using Table 5.2, the linguistic ratings by analysts were converted into corresponding grey values. Average of the grey ratings of supplier's performances on attributes is calculated using equations (5.5), (5.6), (5.7) & (5.8) and is shown in Table 5.4.

Table 5.3: Average grey weights of attributes obtained from analysts

Attributes (SRA_j)	Performance Rating (W_j^k)					Average Grey Weights ($\otimes W_j$)
	W_j^1	W_j^2	W_j^3	W_j^4	W_j^5	
SRA_1*	VH	VH	VH	H	VH	(0.84, 0.98)
SRA_2	VH	H	VH	H	VH	(0.78, 0.96)
SRA_3	VH	VH	H	H	H	(0.72, 0.94)
SRA_4	VH	VH	VH	H	H	(0.78, 0.96)
SRA_5	H	MH	MH	H	MH	(0.54, 0.72)
SRA_6	MH	H	MH	H	H	(0.56, 0.78)
SRA_7	MH	MH	H	MH	MH	(0.52, 0.66)
SRA_8	MH	M	MH	M	M	(0.44, 0.54)
SRA_9	H	MH	H	H	MH	(0.56, 0.78)
SRA_{10}	M	ML	M	ML	ML	(0.34, 0.44)
SRA_{11}	MH	H	MH	MH	MH	(0.52, 0.66)
SRA_{12}	ML	M	ML	ML	M	(0.34, 0.44)
SRA_{13}	M	M	ML	ML	M	(0.36, 0.46)

* SRA_1 indicates the attribute *Quality* in Table. 5.1. Similarly other elements of table can be read.

Table 5.4: Average grey rating of suppliers on attributes, obtained from analysts

Attributes (SRA_j)	Suppliers (S_i)	Performance Rating (G_{ij}^k)					Average Grey Performance Rating ($\otimes G_{ij}$)
		G_{ij}^1	G_{ij}^2	G_{ij}^3	G_{ij}^4	G_{ij}^5	
SRA_1*	S_1	VG	VG	G	VG	G	(7.8, 9.6)
	S_2	G	VG	G	G	G	(6.6, 9.2)
	S_3	G	G	MG	G	G	(5.8, 8.4)
	S_4	G	G	MG	MG	MG	(5.4, 7.2)
	S_5	MG	MG	MG	F	MG	(4.8, 5.8)
	S_6	G	VG	VG	G	VG	(7.8, 9.6)
SRA_2	S_1	MG	MG	G	F	G	(5.2, 7.0)
	S_2	G	MG	G	G	MG	(5.6, 7.8)
	S_3	F	MG	MP	F	F	(4.0, 5.0)
	S_4	VG	G	VG	G	G	(7.2, 9.4)
	S_5	F	F	MG	MG	F	(4.4, 5.4)
	S_6	MP	F	F	MP	MP	(3.4, 4.4)

Attributes (SRA_j)	Suppliers (S_i)	Performance Rating (G_{ij}^k)					Average Grey Performance Rating ($\otimes G_{ij}$)
		G_{ij}^1	G_{ij}^2	G_{ij}^3	G_{ij}^4	G_{ij}^5	
SRA_3	S_1	VG	VG	G	G	G	(7.2, 9.4)
	S_2	G	MG	F	MG	MG	(5.0, 6.4)
	S_3	MG	G	MG	G	G	(5.6, 7.8)
	S_4	F	F	MG	MG	F	(4.4, 5.4)
	S_5	MG	G	MG	G	G	(5.6, 7.8)
	S_6	F	F	MG	F	F	(4.2, 5.2)
SRA_4	S_1	F	MP	MG	MG	MP	(4.0, 5.0)
	S_2	G	MG	MG	G	G	(5.6, 7.8)
	S_3	F	MG	MP	F	F	(4.0, 5.0)
	S_4	VG	G	MG	G	G	(6.4, 8.6)
	S_5	F	MP	P	P	MP	(2.4, 3.8)
	S_6	MP	P	MP	F	P	(2.4, 3.8)
SRA_5	S_1	VG	VG	G	VG	G	(7.8, 9.6)
	S_2	G	MG	F	G	MG	(5.2, 7.0)
	S_3	MG	G	MG	G	G	(5.6, 7.8)
	S_4	F	F	MG	F	F	(4.2, 5.2)
	S_5	MG	G	MG	G	G	(5.6, 7.8)
	S_6	F	F	MG	MG	F	(4.4, 5.4)
SRA_6	S_1	P	MP	F	MP	F	(3.0, 4.2)
	S_2	G	MG	MG	G	G	(5.6, 7.8)
	S_3	F	MG	F	MG	F	(4.4, 5.4)
	S_4	MP	P	MP	P	P	(1.8, 3.4)
	S_5	F	MG	MP	F	F	(4.0, 5.0)
	S_6	F	F	MP	MP	P	(3.0, 4.2)
SRA_7	S_1	G	VG	G	G	G	(6.6, 9.2)
	S_2	G	MG	F	MG	MG	(5.0, 6.4)
	S_3	MG	G	MG	G	G	(5.6, 7.8)
	S_4	VG	G	MG	G	VG	(7.0, 8.8)
	S_5	MG	G	MG	MG	G	(5.4, 7.2)
	S_6	VG	VG	G	VG	VG	(8.4, 9.8)
SRA_8	S_1	P	MP	F	MP	F	(3.0, 4.2)
	S_2	G	MG	MG	MG	G	(5.4, 7.2)
	S_3	F	MG	MP	P	F	(3.4, 4.6)
	S_4	F	MP	MP	P	P	(2.4, 3.8)
	S_5	F	MG	P	F	F	(3.6, 4.8)
	S_6	VG	G	VG	G	G	(7.2, 9.4)
SRA_9	S_1	P	MP	P	F	MP	(2.4, 3.8)
	S_2	G	MG	F	MG	MG	(4.8, 5.8)
	S_3	MP	P	MP	F	F	(3.0, 4.2)

Attributes (SRA_j)	Suppliers (S_i)	Performance Rating (G_{ij}^k) G_{ij}^1	G_{ij}^2	G_{ij}^3	G_{ij}^4	G_{ij}^5	Average Grey Performance Rating ($\otimes G_{ij}$)
	S_4	F	G	MG	G	G	(5.4, 7.6)
	S_5	VG	G	MG	G	VG	(7.0, 8.8)
	S_6	F	F	MG	F	F	(4.2, 5.2)
SRA_{10}	S_1	VG	G	G	MG	MG	(6.2, 8.0)
	S_2	G	MG	MG	G	G	(5.6, 7.8)
	S_3	F	MG	MP	MP	F	(3.8, 4.8)
	S_4	VG	G	VG	G	VG	(7.8, 9.6)
	S_5	F	MG	G	VG	VG	(6.6, 8.0)
	S_6	VG	G	MG	G	VG	(7.0, 8.8)
SRA_{11}	S_1	P	MP	P	P	P	(1.4, 3.2)
	S_2	G	MG	F	MG	MG	(5.0, 6.4)
	S_3	VG	VG	VG	G	VG	(8.4, 9.8)
	S_4	G	G	MG	VG	G	(6.4, 8.6)
	S_5	G	G	MG	G	G	(5.8, 8.4)
	S_6	G	VG	MG	VG	G	(7.0, 8.8)
SRA_{12}	S_1	P	MP	MP	P	MP	(2.2, 3.6)
	S_2	G	MG	MG	G	G	(5.6, 7.8)
	S_3	F	MG	F	MG	F	(4.4, 5.4)
	S_4	VG	G	VG	VG	G	(7.8, 9.6)
	S_5	F	MP	P	MP	F	(3.0, 4.2)
	S_6	G	G	F	F	MG	(5.0, 6.8)
SRA_{13}	S_1	MG	MG	G	G	F	(5.2, 7.0)
	S_2	F	MG	MG	G	F	(4.8, 6.2)
	S_3	MG	MG	F	MG	G	(5.0, 6.4)
	S_4	MG	G	MG	MG	G	(5.4, 7.2)
	S_5	F	MG	MG	MG	F	(4.6, 5.6)
	S_6	G	G	MG	F	MG	(5.2, 7.0)

* SRA_1 indicates the attribute *Quality* and S_1 indicates *Supplier 1*, linguistic performance rating of supplier 1 on the corresponding attribute in Table. 5.1 are shown. Similarly other elements of table can be read.

Step5: Establish the grey decision matrix *D*, $\otimes G_{ij}$, $i = (1, 2, 3, \ldots, 6); j = (1, 2, 3, \ldots, 13)$ from the grey ratings using equation (5.9). Calculated average ratings of the grey decision matrix are:

$$D = \begin{bmatrix} \frac{7.8}{9.6} & \frac{5.2}{7.0} & \frac{7.2}{9.4} & \frac{4.0}{5.0} & \frac{7.8}{9.6} & \frac{3.0}{4.2} & \frac{6.6}{9.2} & \frac{3.0}{4.2} & \frac{2.4}{3.8} & \frac{6.2}{8.0} & \frac{1.4}{3.2} & \frac{2.2}{3.6} & \frac{5.2}{7.0} \\ \frac{6.6}{9.2} & \frac{5.6}{7.8} & \frac{5.0}{6.4} & \frac{5.6}{7.8} & \frac{5.2}{7.0} & \frac{5.6}{7.8} & \frac{5.0}{6.4} & \frac{5.4}{7.2} & \frac{4.8}{5.8} & \frac{5.6}{7.8} & \frac{5.0}{6.4} & \frac{5.6}{7.8} & \frac{4.8}{6.2} \\ \frac{5.8}{8.4} & \frac{4.0}{5.0} & \frac{5.6}{7.8} & \frac{4.0}{5.0} & \frac{5.6}{7.8} & \frac{4.4}{5.4} & \frac{5.6}{7.8} & \frac{3.4}{4.6} & \frac{3.0}{4.2} & \frac{3.8}{4.8} & \frac{8.4}{9.8} & \frac{4.4}{5.4} & \frac{5.0}{6.4} \\ \frac{5.4}{7.2} & \frac{7.2}{9.4} & \frac{4.4}{5.4} & \frac{6.4}{8.6} & \frac{4.2}{5.2} & \frac{1.8}{3.4} & \frac{7.0}{8.8} & \frac{2.4}{3.8} & \frac{5.4}{7.6} & \frac{7.8}{9.6} & \frac{6.4}{8.6} & \frac{7.8}{9.6} & \frac{5.4}{7.2} \\ \frac{4.8}{5.8} & \frac{4.4}{5.4} & \frac{5.6}{7.8} & \frac{2.4}{3.8} & \frac{5.6}{7.8} & \frac{4.0}{5.0} & \frac{5.4}{7.2} & \frac{3.6}{4.8} & \frac{7.0}{8.8} & \frac{6.6}{8.0} & \frac{5.8}{8.4} & \frac{3.0}{4.2} & \frac{4.6}{5.6} \\ \frac{7.8}{9.6} & \frac{3.4}{4.4} & \frac{4.2}{5.2} & \frac{2.4}{3.8} & \frac{4.4}{5.4} & \frac{3.0}{4.2} & \frac{8.4}{9.8} & \frac{7.2}{9.4} & \frac{4.2}{5.2} & \frac{7.0}{8.8} & \frac{7.0}{8.8} & \frac{5.0}{6.8} & \frac{5.2}{7.0} \end{bmatrix} \quad (5.26)$$

where $\otimes G_{ij} = [\underline{G}_{ij},\ \overline{G}_{ij}]$ is represented as $\otimes G_{ij} = \frac{\underline{G}_{ij}}{\overline{G}_{ij}}$

Step6: Normalize the grey decision matrix to make the grey number value lying between [0, 1]. The normalized grey decision matrix D^*, $\otimes G_{ij}^*$, $i = (1, 2, 3, ..., 6); j = (1, 2, 3, ..., 13)$ is obtained according to equations (5.10), (5.11), (5.12), (5.13) & (5.14) as:

$$D^* = \begin{bmatrix} \frac{0.813}{1.000} & \frac{0.486}{0.654} & \frac{0.766}{1.000} & \frac{0.465}{0.581} & \frac{0.813}{1.000} & \frac{0.385}{0.538} & \frac{0.673}{0.939} & \frac{0.571}{0.800} & \frac{0.273}{0.432} & \frac{0.646}{0.833} & \frac{0.143}{0.327} & \frac{0.229}{0.375} & \frac{0.722}{0.972} \\ \frac{0.688}{0.958} & \frac{0.436}{0.607} & \frac{0.532}{0.681} & \frac{0.651}{0.907} & \frac{0.542}{0.729} & \frac{0.718}{1.000} & \frac{0.510}{0.653} & \frac{0.333}{0.444} & \frac{0.540}{0.653} & \frac{0.583}{0.813} & \frac{0.510}{0.653} & \frac{0.583}{0.813} & \frac{0.667}{0.861} \\ \frac{0.604}{0.875} & \frac{0.680}{0.850} & \frac{0.596}{0.830} & \frac{0.465}{0.581} & \frac{0.583}{0.813} & \frac{0.564}{0.692} & \frac{0.571}{0.796} & \frac{0.522}{0.706} & \frac{0.341}{0.477} & \frac{0.396}{0.500} & \frac{0.857}{1.000} & \frac{0.458}{0.563} & \frac{0.694}{0.889} \\ \frac{0.563}{0.750} & \frac{0.362}{0.472} & \frac{0.468}{0.574} & \frac{0.744}{1.000} & \frac{0.438}{0.542} & \frac{0.231}{0.436} & \frac{0.714}{0.896} & \frac{0.632}{1.000} & \frac{0.614}{0.864} & \frac{0.813}{1.000} & \frac{0.653}{0.878} & \frac{0.813}{1.000} & \frac{0.750}{1.000} \\ \frac{0.500}{0.604} & \frac{0.630}{0.773} & \frac{0.596}{0.830} & \frac{0.279}{0.442} & \frac{0.583}{0.813} & \frac{0.513}{0.641} & \frac{0.551}{0.735} & \frac{0.500}{0.667} & \frac{0.795}{1.000} & \frac{0.688}{0.833} & \frac{0.592}{0.857} & \frac{0.313}{0.438} & \frac{0.639}{0.778} \\ \frac{0.813}{1.000} & \frac{0.773}{1.000} & \frac{0.447}{0.553} & \frac{0.279}{0.442} & \frac{0.458}{0.563} & \frac{0.385}{0.538} & \frac{0.857}{1.000} & \frac{0.255}{0.333} & \frac{0.477}{0.591} & \frac{0.729}{0.917} & \frac{0.714}{0.898} & \frac{0.521}{0.708} & \frac{0.722}{0.972} \end{bmatrix} (5.27)$$

where $\otimes G_{ij}^* = \left[\underline{G}_{ij}^*,\ \overline{G}_{ij}^*\right]$ is represented as $\otimes G_{ij}^* = \frac{\underline{G}_{ij}^*}{\overline{G}_{ij}^*}$

Step7: Establish the weighted normalized grey decision matrix D^{**}, $\otimes V_{ij}$, $i = (1, 2, 3, ..., 6); j = (1, 2, 3, ..., 13)$, by grey multiplication of weights assigned to attributes with the corresponding values of normalized grey decision matrix using equations (5.15), (5.16), (5.17) & (5.18). Calculated values of the weighted normalized grey decision matrix are shown as;

$D^{**} =$

$$\begin{bmatrix} \frac{0.683}{0.980} & \frac{0.379}{0.628} & \frac{0.552}{0.940} & \frac{0.363}{0.558} & \frac{0.439}{0.720} & \frac{0.216}{0.420} & \frac{0.350}{0.620} & \frac{0.251}{0.432} & \frac{0.153}{0.337} & \frac{0.220}{0.367} & \frac{0.074}{0.216} & \frac{0.078}{0.165} & \frac{0.260}{0.447} \\ \frac{0.578}{0.939} & \frac{0.340}{0.583} & \frac{0.383}{0.640} & \frac{0.508}{0.871} & \frac{0.293}{0.525} & \frac{0.402}{0.780} & \frac{0.265}{0.431} & \frac{0.147}{0.240} & \frac{0.302}{0.509} & \frac{0.198}{0.358} & \frac{0.265}{0.431} & \frac{0.198}{0.358} & \frac{0.240}{0.396} \\ \frac{0.507}{0.858} & \frac{0.530}{0.816} & \frac{0.429}{0.780} & \frac{0.363}{0.558} & \frac{0.315}{0.585} & \frac{0.316}{0.540} & \frac{0.297}{0.525} & \frac{0.230}{0.381} & \frac{0.191}{0.372} & \frac{0.135}{0.220} & \frac{0.446}{0.660} & \frac{0.156}{0.248} & \frac{0.250}{0.409} \\ \frac{0.473}{0.735} & \frac{0.282}{0.453} & \frac{0.337}{0.540} & \frac{0.580}{0.960} & \frac{0.237}{0.390} & \frac{0.129}{0.340} & \frac{0.371}{0.593} & \frac{0.278}{0.540} & \frac{0.344}{0.674} & \frac{0.276}{0.440} & \frac{0.340}{0.579} & \frac{0.276}{0.440} & \frac{0.270}{0.460} \\ \frac{0.420}{0.592} & \frac{0.491}{0.742} & \frac{0.429}{0.780} & \frac{0.218}{0.424} & \frac{0.315}{0.585} & \frac{0.287}{0.500} & \frac{0.287}{0.485} & \frac{0.220}{0.360} & \frac{0.445}{0.780} & \frac{0.234}{0.367} & \frac{0.308}{0.566} & \frac{0.106}{0.193} & \frac{0.230}{0.358} \\ \frac{0.683}{0.980} & \frac{0.603}{0.960} & \frac{0.322}{0.520} & \frac{0.218}{0.424} & \frac{0.247}{0.405} & \frac{0.216}{0.420} & \frac{0.446}{0.660} & \frac{0.112}{0.180} & \frac{0.267}{0.461} & \frac{0.248}{0.403} & \frac{0.371}{0.593} & \frac{0.177}{0.312} & \frac{0.260}{0.447} \end{bmatrix} \quad (5.28)$$

where $\otimes V_{ij} = [\underline{V}_{ij}, \overline{V}_{ij}]$ is represented as $\otimes V_{ij} = \frac{\underline{V}_{ij}}{\overline{V}_{ij}}$

Step8: Using equation (5.19), the ideal referential set of supplier alternatives is constructed. The calculated set of S^{max} is shown as;

$$S^{max} = \left\{ \begin{matrix} (0.683, 0.980), (0.603, 0.960), (0.552, 0.940), (0.580, 0.960), (0.439, 0.720), (0.402, 0.780), \\ (0.446, 0.660), (0.278, 0.540), (0.445, 0.780), (0.276, 0.440), \\ (0.446, 0.660), (0.276, 0.440), (0.270, 0.460) \end{matrix} \right\}$$

Step9: Grey possibility values obtained using equations (5.20), (5.21), (5.22), (5.23), (5.24) & (5.25) are;

$P(S_1 < S^{max}) = 0.7660$, $P(S_2 < S^{max}) = 0.8021$, $P(S_3 < S^{max}) = 0.7900$, $P(S_4 < S^{max}) = 0.7255$, $P(S_5 < S^{max}) = 0.7997$ *and* $P(S_6 < S^{max}) = 0.7780$.

Step10: Prioritize the suppliers based upon their increasing value of probabilities. Least possibility value shows the supplier is more close to ideal referential supplier. The selection of suppliers according to their level of resilience capabilities in this case is found as follows; $S_4 > S_1 > S_6 > S_3 > S_5 > S_2$. Fourth supplier (S_4) in this case, is the best supplier and second supplier (S_2) comes out to the least preferred choice in terms of their resilient capabilities.

5.4. Analysis of Findings

Supplier selection is a MCDM problem that needs consideration of both qualitative and quantitative attributes. Suppliers should be able to provide an efficient and effective response to possible disruptions. In this research using grey relational analysis we have calculated the exact closeness of each supplier with the ideal referential supplier. Also, critical attributes contributing towards resilience of suppliers have been determined.

This research has some important managerial implications. Top management can ascertain the level in which each of their alternative suppliers stand at any point of time based upon the grey possibility values. For example, supplier, S_4 can be considered to be a good supplier considering the level of resilience. At the other extreme, suppliers, S_2, S_3, *and* S_5 could be avoided on account of their less resilient capabilities. Suppliers, S_1, S_6 could be chosen if on any account the supplier S_4 is not able to supply goods at any point of time.

How does the proposed method perform in comparison with classical supplier selection methods? In order to address the same, a comparison has been made with the most accepted methods in supplier selection viz, AHP and ANP. For AHP, paired comparisons were made on basis of their relative importance of main attributes as well as sub attributes considered for supplier selection over a ratio scale varying from *9* to *1/9* (Saaty, 1988; Saaty, 2001) and the weightings were obtained by calculating the normalized principal Eigen vector.

As suppliers were rated for their performances of attributes on grey scales, a conversion using modified- CFCS (Converting Fuzzy values into Crisp Scores) method was done. The method involves a three step procedure to convert a grey number (average performance rating of i^{th} supplier over j^{th} attribute), $\otimes G_{ij}$ ($\overline{\otimes} G_{ij}$, $\underline{\otimes} G_{ij}$) into crisp score which is elaborated as,

(i) Normalization of the grey value

$$\underline{\otimes} \dot{G}_{ij} = \left(\underline{\otimes} G_{ij} - {}^{min}_{j} \underline{\otimes} G_{ij}\right) / \Delta^{max}_{min} \qquad (5.29)$$

where $\underline{\otimes}\dot{G}_{ij}$ represents the normalized lower limit value of the grey number $\otimes G_{ij}$

$$\overline{\otimes}\dot{G}_{ij} = \left(\overline{\otimes} G_{ij} - \min_j \overline{\otimes} G_{ij}\right)/\Delta_{min}^{max} \tag{5.30}$$

where $\overline{\otimes}\dot{G}_{ij}$ represents the normalized upper limit value of the grey number $\otimes G_{ij}$, and

$$\Delta_{min}^{max} = \max_j \overline{\otimes} G_{ij} - \min_j \underline{\otimes} G_{ij} \tag{5.31}$$

(ii) Computing total normalized crisp value

$$z_{ij} = \left(\frac{\left(\underline{\otimes}\dot{G}_{ij}\left(1-\underline{\otimes}\dot{G}_{ij}\right)\right)+\left(\overline{\otimes}\dot{G}_{ij}\times\overline{\otimes}\dot{G}_{ij}\right)}{\left(1-\underline{\otimes}\dot{G}_{ij}+\overline{\otimes}\dot{G}_{ij}\right)} \right) \tag{5.32}$$

(iii) Calculating the final crisp values

$$z_{ij}^{*} = \left(min\, \underline{\otimes}\, G_{ij} + \left(z_{ij} \times \Delta_{min}^{max}\right)\right) \tag{5.33}$$

and, $Z = \left[z_{ij}^{*}\right]$ (5.34)

The *Z* matrix is obtained by modified CFCS method and has been multiplied by corresponding weightings and was added up for respective suppliers (benefit attributes were given positive values and cost attributes were given negative values), which is then normalized to obtain the Selection Index (SI) for the suppliers in AHP. In ANP, criteria, sub-criteria and alternatives considered for supplier selection are treated equally as nodes in a network. Nodes are grouped in clusters, so that cluster priorities can be introduced. A matrix is constructed by representing all nodes of the network named unweighted super matrix, which is then normalized to weighted super matrix of the network model (Ravi, et al., 2005). The network model for supplier selection in resilient supply chain was constructed using the software '*Super Decisions (Version 2.2.6)*', as shown in Figures 5.2 and 5.3. The weightings were obtained by pairwise comparisons same as in AHP and the performance of alternatives on supplier resilient attributes (*SRA*) were rated from *Z* matrix. The model is synthesized by calculating limit matrix, by taking the weighted super matrix to the power of $k+1$, where k is an arbitrary number to obtain Selection Index (SI) in ANP.

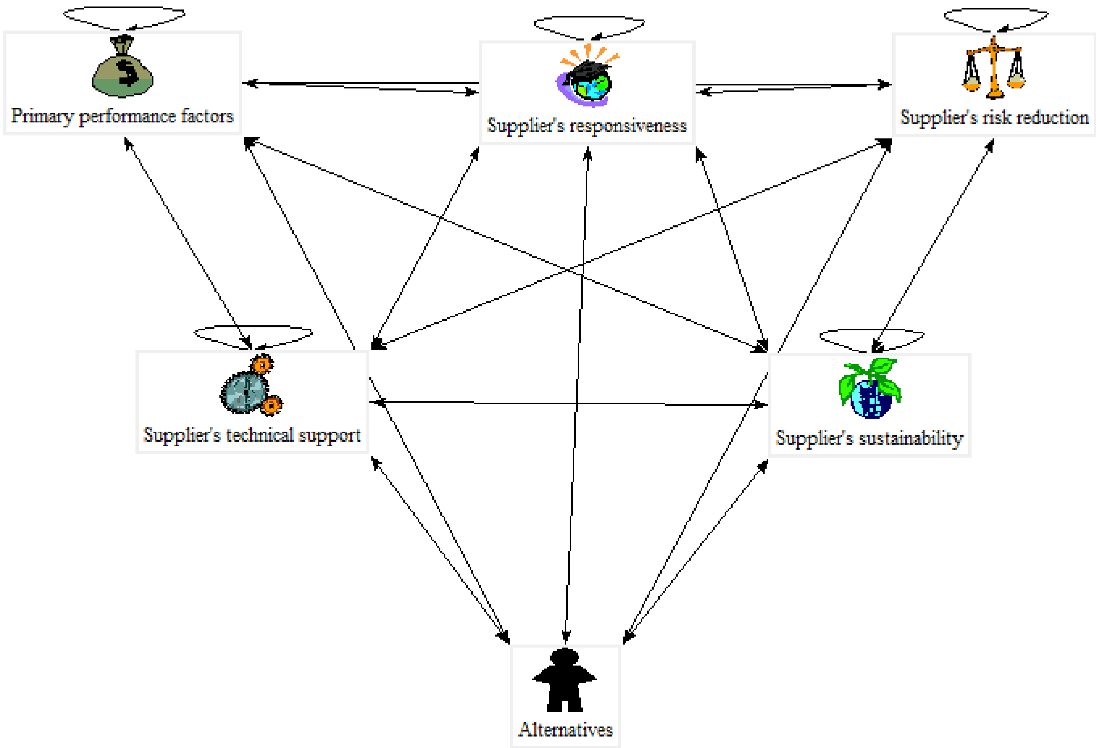


Figure 5.2: Network model showing cluster relations and loops constructed in *Super Decisions (Version 2.2.6)*

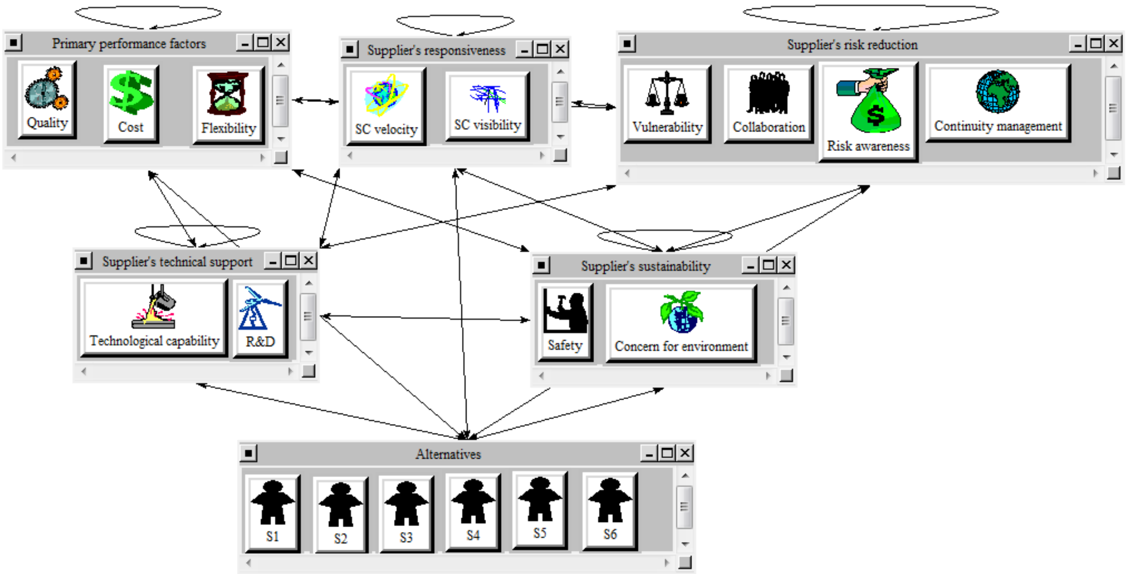


Figure 5.3: Network model constructed in *Super Decisions (Version 2.2.6)*

For uniformity of comparison, the grey possibility values obtained from grey relational analysis were converted into Selection Index (SI) by the transformation; $SI = (1 - P(S_i < S^{max}))$ and by normalizing the values. By doing so, increasing values of SI makes an increase in preference of supplier alternative. Supplier selection priorities on basis of SI scores obtained from GRA, AHP and ANP is shown in Table 5.5.

Table 5.5: Comparison of selection priorities for suppliers from different methods

Ranking order	Proposed GRA method		AHP method		ANP method	
	Suppliers	*Selection Index*	*Suppliers*	*Selection Index*	*Suppliers*	*Selection Index*
1	**S4**	0.205	**S6**	0.189	**S3**	0.199
2	**S1**	0.175	**S1**	0.186	**S1**	0.187
3	**S6**	0.166	**S4**	0.161	**S4**	0.180
4	**S3**	0.157	**S2**	0.160	**S2**	0.159
5	**S5**	0.149	**S3**	0.157	**S6**	0.148
6	**S2**	0.148	**S5**	0.146	**S5**	0.127

Based on the SI scores, the suppliers according to their relative preference of selection by AHP was prioritized as, $S_6 > S_1 > S_4 > S_2 > S_3 > S_5$ and by ANP as, $S_3 > S_1 > S_4 > S_2 > S_6 > S_5$. But, ranking as per grey relational analysis was $S_4 > S_1 > S_6 >$

$S_3>S_5>S_2$. Primary choice of supplier is changed to S_6 instead of S_4, in AHP and S_3 instead of S_4, in ANP; in comparison with grey relational analysis. However, second choice for supplier selection remains unchanged (S_1) in all cases. On a closer examination of results as viewed from ratings; we can see that *supplier 6* performs fairly well at *primary performance attributes*, but more *vulnerable*, having low *visibility* and poor *continuity management* practices implemented. *Supplier 3* also, performs moderately spotless at all attributes, but having poor *continuity management* practices implemented with the lowest *technological capability* available.

Alternatively, *supplier 4* performs reasonably well at all attributes with exceptional *vulnerability* reduction capabilities, excellent *technological capabilities* and having well implemented *safety and environment practices*. *Supplier 4* suits more with the definition of resilient supplier than *supplier 6* or *supplier 3*. Thus, we can say resilient supplier selection through grey relational analysis outperform AHP and ANP.

How do we prioritize supplier selection if a particular supplier attribute is given highest priority for selection by keeping the same old weightings for other attributes? To address this question, sensitivity analysis was performed. The results of sensitivity analysis show that, by changing the weightings of resilient attributes to their maximum values separately, *Supplier 4* has highest probability of selection (least grey possibility value) in all cases followed by *Supplier 1*. The selection order for the other suppliers varies with variations in weightings assigned to attributes. It is observed that *Supplier 3* excels in *safety* compared with their performances in the other attributes. *Supplier 2* and *Supplier 5* perform comparatively poor for almost all attributes. The results of sensitivity analysis and the selection priorities of suppliers are shown in Table 5.6 and Figure 5.4.

Table 5.6: Sensitivity analysis for prioritization of supplier selection

Attributes (SRA_j)	Grey Possibility Values ($P(S_i \leq S^{max})$)						Prioritization of Suppliers
	$P^*(S_1 \leq S^{max})$	$P^*(S_2 \leq S^{max})$	$P^*(S_3 \leq S^{max})$	$P^*(S_4 \leq S^{max})$	$P^*(S_5 \leq S^{max})$	$P^*(S_6 \leq S^{max})$	
SRA_1^*	0.7660	0.8033	0.7924	0.7300	0.7997	0.7780	$S_4>S_1>S_6>S_3>S_5>S_2$
SRA_2	0.7692	0.8021	0.7936	0.7255	0.8057	0.7780	$S_4>S_1>S_6>S_3>S_2>S_5$
SRA_3	0.7660	0.8125	0.7958	0.7255	0.8055	0.7780	$S_4>S_1>S_6>S_3>S_5>S_2$
SRA_4	0.7660	0.8042	0.7900	0.7255	0.7997	0.7780	$S_4>S_1>S_6>S_3>S_5>S_2$
SRA_5	0.7660	0.8149	0.7991	0.7255	0.8089	0.7780	$S_4>S_1>S_6>S_3>S_5>S_2$
SRA_6	0.7684	0.8021	0.8010	0.7255	0.8125	0.7804	$S_4>S_1>S_6>S_3>S_2>S_5$
SRA_7	0.7707	0.8021	0.7999	0.7313	0.8070	0.7780	$S_4>S_1>S_6>S_3>S_2>S_5$
SRA_8	0.7680	0.8021	0.7933	0.7255	0.8038	0.7780	$S_4>S_1>S_6>S_3>S_2>S_5$
SRA_9	0.7660	0.8111	0.7900	0.7329	0.7997	0.7803	$S_4>S_1>S_6>S_3>S_5>S_2$
SRA_{10}	0.7736	0.8103	0.7900	0.7255	0.8072	0.7817	$S_4>S_1>S_6>S_3>S_5>S_2$
SRA_{11}	0.7660	0.8021	0.7900	0.7322	0.8073	0.7837	$S_4>S_1>S_6>S_3>S_2>S_5$
SRA_{12}	0.7660	0.8103	0.7900	0.7255	0.7997	0.7872	$S_4>S_1>S_3>S_6>S_5>S_2$
SRA_{13}	0.7669	0.8057	0.7927	0.7255	0.8060	0.7788	$S_4>S_1>S_6>S_3>S_2>S_5$

* SRA_1 indicates the attribute *Quality* and the corresponding $P^*(S_1 \leq S^{max})$ indicates the improved grey possibility value by assigning maximum weight to SRA_1. Similarly other elements of table can be read.

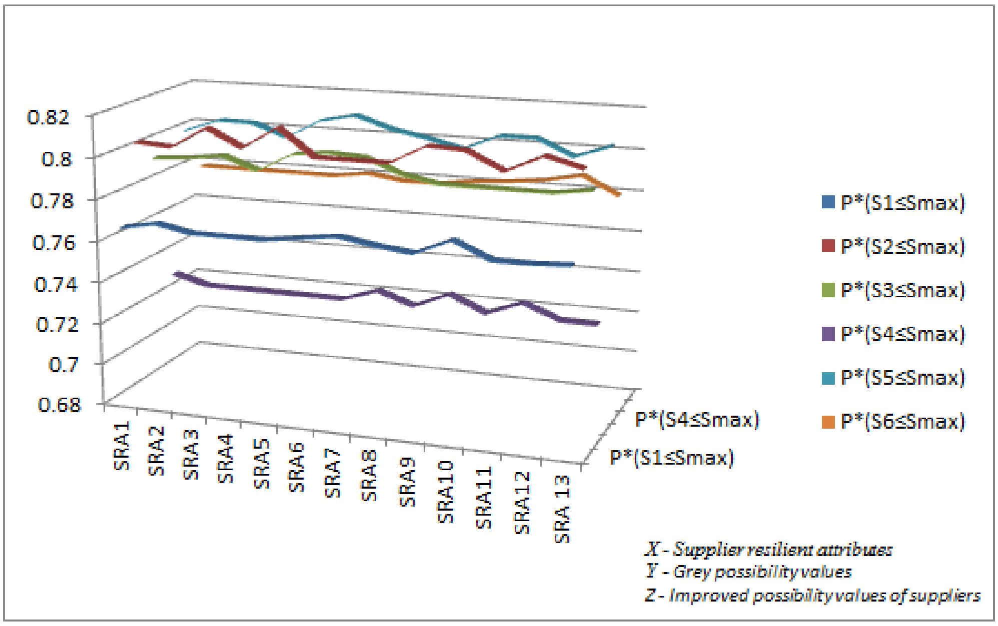


Figure 5.4: Sensitivity analysis of suppliers on resilience attributes

Sustainability is another parallel theme of interest for researchers and practitioners. It is essential to achieve the dual benefits of sustainability and resilience together in a network and the same is the topic of contemporary relevance. A conceptual study in this direction has been proposed and presented in the next chapter.

CHAPTER 6

ON SUSTAINABILITY, RESILIENCE AND SUSTAINABLE- RESILIENT SUPPLY NETWORKS: AN ANALYSIS OF THE DECOUPLING POINT

6.1. Evolutionary Sequence of Supply Chains

Supply chain resilience and sustainability are notions and the exact evaluation of the same is a bit complicated as there are many behavioral and intangible elements in it. How the benefits can be achieved is a continuing debate among practioners and the need for resilience or sustainability is based on the strategic focus and needs of the demanding firm or its supply chain. The topic is of discussion in the chapter and from the study it is concluded that strategic focus differ with respect to a particular point in a supply chain and a collection of such points in case of a supply network. The study paved the way for the concept of both sustainability and resilience oriented supply networks, referred to as the sustainable- resilient supply networks. The categories of supply chains considered the paradigm shift observed and the model cases for constructing sustainable- resilient supply networks are discussed in this chapter.

Generally, supply chains are classified according to the differences in their core strategic objectives (Mason-Jones, et al., 2000; Green Jr, et al., 2012; Dües, et al., 2013; Seuring, 2013; Vinodh, et al., 2013; Govindan, et al., 2015). In this research, major categories of supply chains as found in literature were observed and analyzed from time to time. By cautiously observing the evolutionary sequences of supply chains that we have arrived at certain concluding remarks and are commented under corresponding sections as corollaries. *Six* of those categories of supply chains with wide industrial applicability and practitioners' acceptability are elaborated as follows;

6.1.1. Lean supply chains

Lean supply chains are generally intended to reduce wastes in all forms as far as possible to construct a level schedule assuming a certain market demand. They are efficient supply chains implemented when the demand for variability in production and variety of products are generally low (Naim & Gosling, 2011). In general, lean is all about doing more with fewer inputs. Lean practices are usually adopted for a pull type production system and are generally seen in association with JIT flows and certain quality practices. Reduced buffers in terms of inventory and capacity could be appreciated as an enhanced feature of lean supply chains. When the target focus is on the reduction of non-value added processes, the lean supply chains are said to be efficiency focused. Information sharing enhances the capabilities of being lean and this also helps to reduce the complexity of the supply chain to the maximum end possible. The building principles of a lean supply chain and the related literatures are shown in Table 6.1.

6.1.2. Agile supply chains

Agile supply chains are a class of supply chains responsive and flexible enough to handle market fluctuations. An agile supply chain focuses on the enrichment/ satisfaction of customers (Lin, et al., 2006). Thus, being agile means the supply chain should possess the ability to respond appropriately to changing business environments. Flexibility is built throughout the supply chain by incorporating flexible product, process and pricing strategies. Flexibility enables the supply chain to be competitive enough to capture market attention and allows the supply chain to reconfigure quickly incorporating robust changes. The principles associated with agility in supply chains and the related literatures are elucidated in Table 6.2.

Table 6.1: Building blocks of lean supply chains

Sl No.	Core Aspects of Lean Supply Chains	Relevant Literature	Why to Consider?	When to Consider?
LSCA1	**Waste reduction**	(Dües, et al., 2013)	Reducing non-value added activities	Cases of stable demand
LSCA2	**Level schedule**	(Zhou & Ji, 2015)	Developing a value stream	Cases of stable demand
LSCA3	**Lead time reduction**	(Chen, et al., 2013)	Incorporating quick responses over stages	Cases of competitive markets
LSCA4	**Buffer reduction**	(Yang & Yang, 2010)	Reducing the holding costs of inventory	Cases of stable demands
LSCA5	**Focus on efficiency**	(Lee, et al., 2009)	Products with higher utility	Cases of competitive markets and stable demands
LSCA6	**Process streamlining**	(Dües, et al., 2013)	Working for common goals	Focus on product features
LSCA7	**Information sharing**	(Martínez-Jurado & Moyano-Fuentes, 2014)	Replace inventory by information	Focus on visibility
LSCA8	**Complexity reduction**	(Cudney & Elrod, 2011)	Reducing the levels of interaction among sc elements	Cases of stable demands and endorsement for level schedules

Table 6.2: Building blocks of agile supply chains

Sl No.	Core Aspects of Agile Supply Chains	Relevant Literature	Why to Consider?	When to Consider?
ASCA1	**Responsive supply chains**	(Vinodh, et al., 2013)	Increase number of customer accounts	Cases of volatile markets
ASCA2	**Focus on competency**	(Gligor & Holcomb, 2012)	Increase market share	Cases of volatile markets and uncertain demand
ASCA3	**Flexibility**	(Pan & Nagi, 2013)	Quicker incorporation of changes	Cases of volatile markets and uncertain demand
ASCA4	**Virtual co-operation**	(Gligor, et al., 2015)	Increase the level of trust among partners	Incorporating robust changes
ASCA5	**Integration**	(Agarwal, et al., 2007)	Quicker incorporation of changes	Incorporating robust changes
ASCA6	**Marketing sensitivity**	(Yusuf, et al., 2014)	Utilize volatile markets	Cases of competitive markets

Sl No.	Core Aspects of Agile Supply Chains	Relevant Literature	Why to Consider?	When to Consider?
ASCA7	**Rapid reconfigurations**	(Gligor, et al., 2015)	Products with shorter lifecycles	Cases of volatile markets and uncertain demand
ASCA8	**Robustness**	(Chiang, et al., 2012)	Deal with fluctuations in supply and demand	Cases of volatile markets and uncertain demand

The core principle of *building efficiency* in supply chains adopting lean practices contradicts with the core principle of *building flexibility* in agile supply chains; since flexibility is always associated with a cost. At the same time, the theme of *process streamlining* contradicts with the provision for *rapid reconfiguration* in agile supply chains, as it is difficult to change the product configurations quickly in a lean supply chain. Also, the concepts of *reducing complexity* in supply chains as practiced in lean supply chains contradicts with the principle of concentrating on *market competency* as in agile supply chains; since for maintaining market competency, the supply chain has to improve the level of interactive complexities (Mason-Jones, et al., 2000). A comparison of the principles of both is as shown in Figure 6.1.

Corollary 1*: The core principles of lean supply chains; like building efficiency, process streamlining and reducing complexities controverts the core principles of an agile supply chain like building flexibility, rapid reconfigurations and enabling market competency.*

6.1.3. Leagile supply chains

Naylor et al. (1999) investigated the notions of agility in supply chains and considered how the benefits of leanness can be harvested in an agile supply chain. This lead to the concepts of leagile supply chains. Later, Mason-Jones et al. (2000) gave concrete evidence for positioning the boundaries of separation of lean and agile paradigms in a leagile supply chain. These supply chains generally adopts lean principles in the upstream supply chain up to the decoupling point and adopts principles of agility from the decoupling point to the downstream of the supply chain. Leagile supply chains have a dual focus on waste reduction as well as uncertainty reduction and are responsive enough to reduce the lead times of delivery. The principles and practices associated with leagile supply chains and the related literatures are explicated in Table 6.3.

Table 6.3: Building blocks of leagile supply chains

Sl No.	Core Aspects of Leagile Supply Chains	Relevant Literature	Why to Consider?	When to Consider?
LASCA1	**Uncertainty reduction**	(Agarwal, et al., 2006)	Increase the level of risk sharing among partners	Incorporating change strategies
LASCA2	**Lead time reduction**	(Naim & Gosling, 2011)	Shorter lifecycle products	Cases of volatile markets
LASCA3	**Flexibility**	(Olhager, 2012)	Adapting better with changes	Cases of volatile markets and uncertain demand
LASCA4	**Focus on integration**	(Purvis, et al., 2014)	Quicker incorporation of changes	Incorporating robust changes
LASCA5	**Focus on competitiveness**	(Roh, et al., 2014)	Increase market share	Cases of unstable demand and market instability
LASCA6	**Collaboration**	(Sukati, et al., 2012)	Increase the level of trust among partners	Improve connectedness
LASCA7	**Waste reduction**	(Olhager, 2012)	Reducing non-value added activities	Endorsement for supply chain efficiency
LASCA8	**Rapid reconfiguration**	(Christopher & Ryals, 2014)	Shorter product lifecycles	Cases of volatile markets and uncertain demand
LASCA9	**Information sharing**	(Banerjee, 2015)	Using information as a buffer	Focus on visibility

Corollary 2*: Leagile supply chains upholds the core principles of agile supply chains like building flexibilities and improving proficiencies for rapid reconfigurations, thus reducing the uncertainties associated with the supply chains along with the considerations of waste reduction as far as possible; hence can be regarded as enriched forms of agile supply chains.*

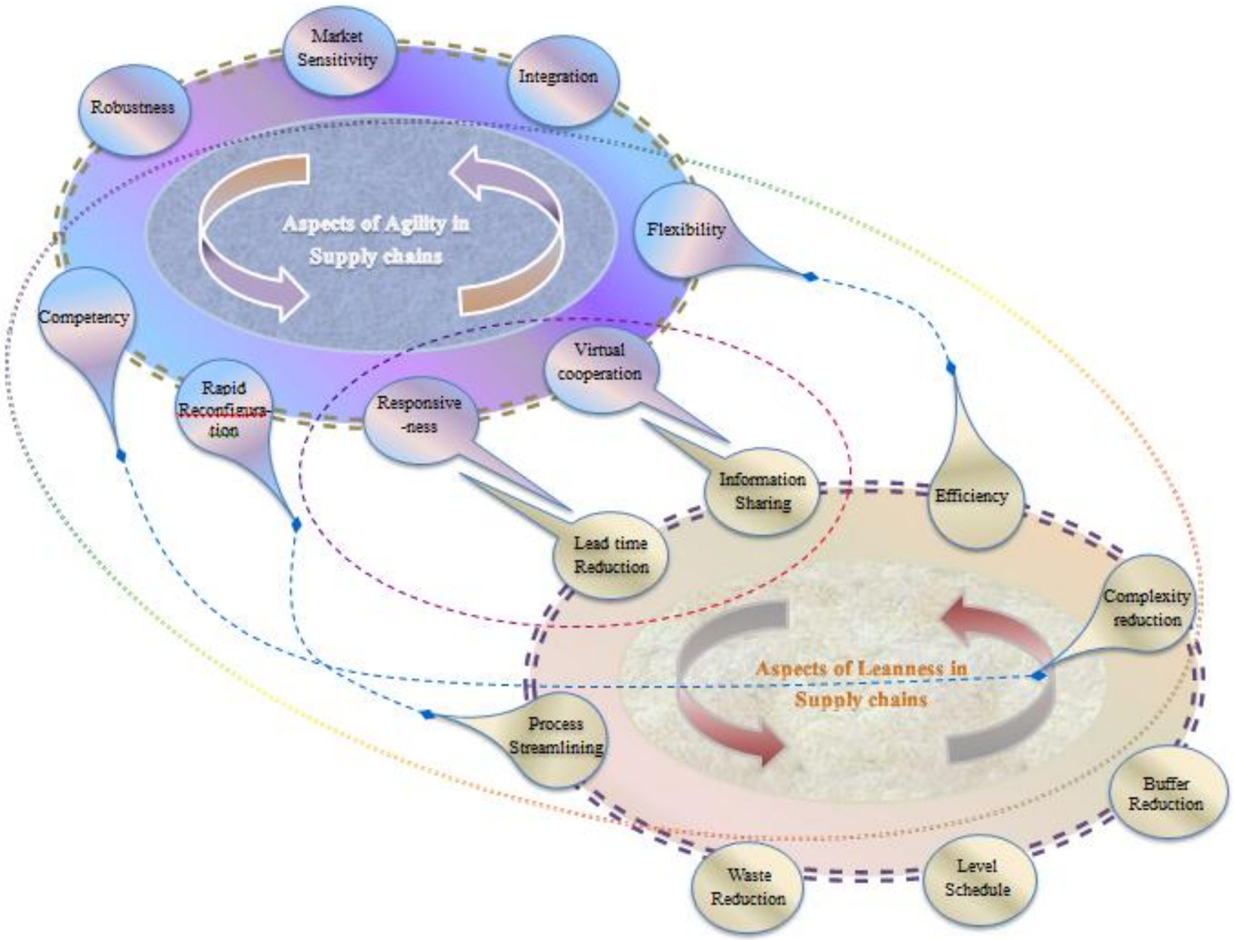


Figure 6.1: Principles contributing to agility and leanness in supply chains

6.1.4. Green supply chains

Green supply chains are a class of supply chains generally focusing on the environmental considerations of products with enhanced waste management practices adopted, but are also targeted in making good business sense, values and higher profits. Thus, in general the scope of green supply chain management practices varies from reactive monitoring of general business environment to proactive management practices for improving the activities to reduce the carbon footprints of products (Green Jr, et al., 2012). Green supply chain management extends its roots over the areas of environment management and supply chain management. The principles of *reduce, reuse, reconfigure, remanufacture and recycle* are well practiced in those supply chains and the supply chains are customarily built-in with a reverse logistics network. Inventories in any forms are mostly reduced and the product life cycle assessment for costs and carbon footprints are carried out prior to the launch of any products, thereby making these supply chains efficient at the same time environmental friendly. Green principles and practices in supply chains and the related literatures are shown in Table 6.4.

Table 6.4: Building blocks of green supply chains

Sl No.	Core Aspects of Green Supply Chains	Relevant Literature	Why to Consider?	When to Consider?
GSCA1	**Responsive supply chains**	(Green Jr, et al., 2012)	Incorporating quick responses over stages	Cases of competitive markets and stable demand
GSCA2	**Waste management**	(Zhu, et al., 2013)	Utilization and reduction of wastes	Reduce ecological impacts
GSCA3	**Resource conservation**	(Shen, et al., 2013)	Reducing resource utilizations	Scarcity of available resources
GSCA4	**Reusability/ Reverse logistics**	(Guang Shi, et al., 2012)	Reduce/ reuse/ refurbish, recycle or remanufacture products	Reduce wastes over stages and its ecological impacts
GSCA5	**Environmental considerations**	(Tseng & Chiu, 2013)	Reduce the carbon footprints	Reduce ecological impacts

Sl No.	Core Aspects of Green Supply Chains	Relevant Literature	Why to Consider?	When to Consider?
GSCA6	**Product safety**	(Eltayeb, et al., 2011)	Keeping manufacturing and delivery safety of products	Customer preference for safe products
GSCA7	**Focus on efficiency**	(Kuei, et al., 2015)	Products with higher utility	Cases of competitive markets and stable demands
GSCA8	**Inventory reduction**	(Liu, et al., 2012)	Replace inventory by information	Reduce inventory over stages
GSCA9	**Lifecycle assessment**	(Green Jr, et al., 2012)	Reduce the carbon footprints	Reduce wastes over stages and ecological impacts

***Corollary 3**: Green supply chains can be considered as advanced forms of lean supply chains with improved focus on environmental considerations while upholding the core principles of inventory reduction, resource conservation and efficiency as seen in lean supply chains.*

Leagile supply chains uphold the principles of *flexibility* alike as seen in agile supply chains, which contradict the focus on *reduction of inventory* in green supply chains. Reducing inventories will eventually reduce the redundancies and in turn tamper the flexibility of the supply chain. Similarly the focus on *rapid reconfigurations* to maintain market buoyancy as seen in leagile supply chains contradicts the principles of *resource conservations* for greening the supply chains, since rapid reconfigurations are possible with the availability of resource buffers. At the same time, the focus on *reducing uncertainties* in leagile supply chains contradicts with the focus on *building efficiency* in green supply chains. Efficiency is generally achieved through reduced buffers that eventually increases the uncertainties associated with supply chains (Bruce, et al., 2004). A comparison of the principles of both is as shown in Figure 6.2.

***Corollary 4**: The essential principles of building flexibilities, enabling provisions for rapid reconfigurations and reducing the associated uncertainties as seen in a leagile* *supply chains conflict with the staple principles of inventory reduction, resource conservation and building efficiencies as seen in green supply chains.*

6.1.5. Resilient supply chains

Resilient supply chains are robust supply chains to deal with any sudden supply/ demand fluctuations or even disruptions. They are utilizing the power of flexibility in dealing with major supply chain risks. Supply risks are managed through flexible supply strategies either through multiple suppliers or through flexible supply contracts. Process risks are managed by adopting flexible processes using flexible manufacturing systems. Demand risks are more or less uncertain and are managed by adopting flexible product strategies via postponement and through flexible pricing strategies via responsive pricing (Tang & Tomlin, 2008). Resilient supply chains are not only having the ability to manage risks, but are potentially able to position better than competitors to deal with and even gain advantages from disruptions (Sheffi & Rice Jr, 2005). High levels of collaborative working can also be seen as a superior feature in those supply chains. The principles and practices generally seen in association with supply chain resilience and the related literatures are presented in Table 6.5.

Corollary 5*: Resilient supply networks are robust supply networks, which can be considered as advanced diversities of leagile supply networks with inbuilt capability for managing potential vulnerabilities by reducing complexities and are grounded on the core principles of agility and flexibility.*

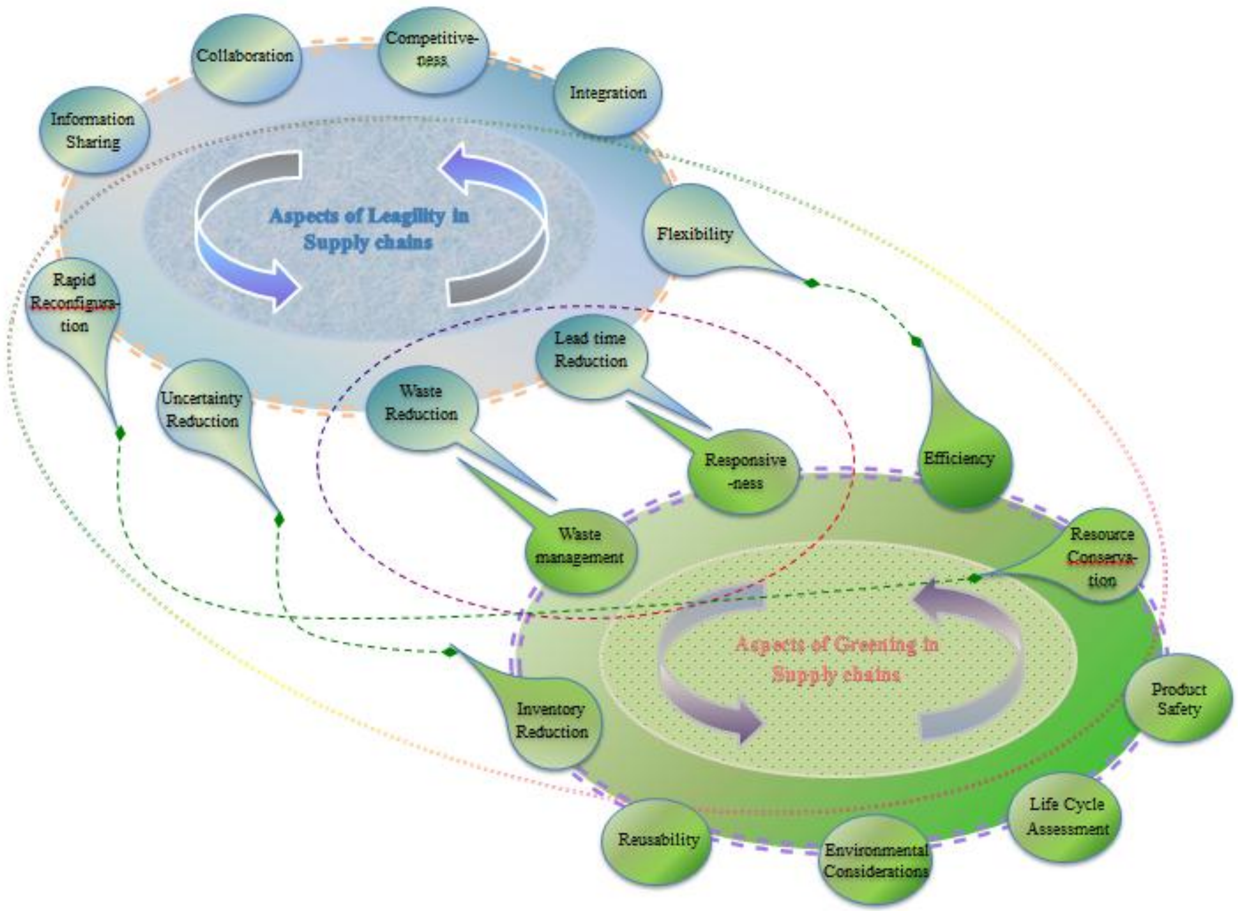


Figure 6.2: Principles contributing to leagility and greening in supply chain

Table 6.5: Building blocks of resilient supply chains

Sl No.	Core Aspects of Resilient Supply Chains	Relevant Literature	Why to Consider?	When to Consider?
RSCA1	**Agility**	(Ambulkar, et al., 2015)	Rapid response towards changing conditions	Cases of unstable demand and supply
RSCA2	**Responsiveness**	(Govindan, et al., 2015)	Incorporating quick responses over stages	Customer preference for fast deliverables
RSCA3	**Visibility**	(Azevedo, et al., 2013)	Increase trust among partners	Cases of vulnerable supply chains
RSCA4	**Redundancy**	(Yang & Yang, 2010)	Building buffers against supply/demand fluctuations	Increased bullwhips and volatile markets
RSCA5	**Flexibility**	(Sodhi, et al., 2012)	Deal with dynamic market conditions	Cases of vulnerable supply chains and volatile markets
RSCA6	**Reduction of uncertainty**	(Azevedo, et al., 2010)	Increase the accuracy of demand forecasts	Cases of vulnerable supply chains
RSCA7	**Reduction of complexity**	(Hearnshaw & Wilson, 2013)	Reduced complexities lead to reduced vulnerability	Initiatives such as business process reengineering
RSCA8	**Integration/ Operational capabilities**	(Gong, et al., 2014)	Providing integrated operating environment	End to end transaction of orders
RSCA9	**Collaboration**	(Govindan, et al., 2015)	Distributing the effects of risks by improving trust	Cases of vulnerable supply chains
RSCA10	**Transparency**	(Christopher & Holweg, 2011)	End to end interaction of orders, inventory and logistics	Increased bullwhips and volatile markets

6.1.6. Sustainable supply chains

Sustainable supply chains have to take into account of a wider range of issues and a set of performance objectives, thereby looking at a longer part of the supply chain. Sustainable supply chain management comprises of a set of managerial practices for producing sustainable products depicting focus on the entire value chain of each product as well as encompassing the entire product life cycle (Gupta & Desai, 2011; Chaabane, et al., 2012). Sustainable supply chains are eco- efficient supply chains with the base of lean management principles. Reduction of wastes and adaptability with markets are the core competencies of these supply chains. The supply chain is not merely focused on environmental issues, but also on the social and ethical issues (Seuring, 2010; Seuring, 2013). Strategic business partnerships enable the supply chain to be responsive at the same time making it robust. The principles and practices seen in association with sustainability in supply chains and the allied literatures are presented in Table 6.6.

Table 6.6: Building blocks of sustainable supply chains

Sl No.	Core Aspects of Sustainable Supply Chains	Relevant Literature	Why to Consider?	When to Consider?
SSCA1	**Lean management**	(Walker & Jones, 2012)	Reducing all wastes across stages	Cases of competitive markets and stable demand
SSCA2	**Delivery speed**	(Seuring, 2013)	Incorporating quick responses over stages	Customer preference for quick deliverables
SSCA3	**Safety**	(Wittstruck & Teuteberg, 2012)	Keeping product safety and providing safe working conditions	Improved customer and employee satisfaction levels
SSCA4	**Efficiency**	(Gupta & Desai, 2011)	Products with higher utility	Cases of competitive markets and stable demands
SSCA5	**Adaptability**	(Tobescu & Seuring, 2015)	Adaptable to various external changes	Respond to changing market conditions
SSCA6	**Labor equity**	(Wang & Sarkis, 2013)	Reduce functional silos and improve worker satisfaction	Processes are focused and aligned
SSCA7	**Reusability/ Reverse logistics**	(Chaabane, et al., 2012)	Reduce/ reuse/ refurbish, recycle or remanufacture products	Reduce wastes over stages and ecological impacts
SSCA8	**Strategic partnerships**	(Seuring & Müller, 2008)	Increase the level of trust among partners	Improve the effectiveness of change management
SSCA9	**Environmental concerns**	(Chaabane, et al., 2012)	Reduce the carbon footprints of products/ bi-products/ wastes	Reduce ecological impacts of products
SSCA10	**Social issues**	(Golicic & Smith, 2013)	Improve social and societal living conditions	Govt. regulations and CSR

Corollary 6*: Sustainable supply chains can be stared as improved forms of green supply chains with enhanced focus on environmental as well as social issues adopting core principles of lean management for reducing wastes and enabling likely reuse of all items in the supply chain, thus keeping an efficient and sustainable market place.*

The principle of *agility* adopted in resilient supply chain contradicts the principles of *lean management* as seen in sustainable supply chains; following the same objective contraction as stated for lean and agile principles. The principles of *building redundancy* for managing vulnerabilities in resilient supply chains directly contradict the *focus on efficiency* as seen in sustainable supply chains. Also, emphasis on *reusability of products* and building reverse logistic networks increases the network complexity and thus tampers the principles of *reducing interactive complexities* as practiced in a resilient supply network. A comparison of the principles of both is as shown in Figure 6.3.

Corollary 7*: The core competencies of agility, redundancy and reduction of complexities as seen in a resilient supply network contradicts the central principles of lean management, building efficiency and increasing reverse logistics practices as seen in a sustainable supply network.*

6.2. Paradigm Shift in Supply Chains

6.2.1. Lean, green, sustainable supply chains

Mollenkopf et al. (2010) conducted vast literature survey to connect lean, green and global supply chain strategies and concluded that several internal and external drivers have contributed to the integration of lean processes and environmental practices. Dües et al. (2013) piloted literature examinations to link lean processes with green practices and have recognized that lean practices are catalysts for greening the supply chains. Green supply chains are classically focused on reducing environmental impacts.

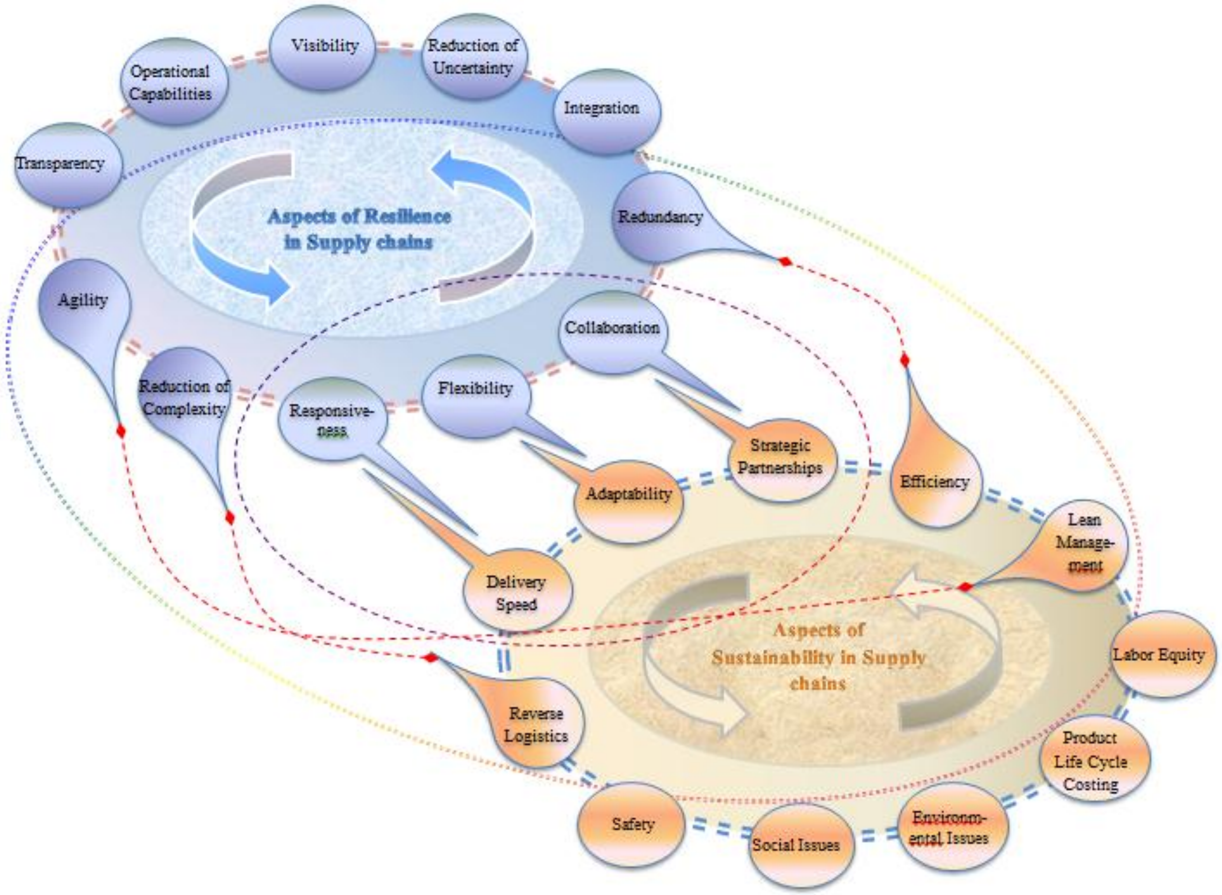


Figure 6.3: Principles contributing to resilience and sustainability in supply chains

Generally this is achieved through reducing the wastes over stages in supply chain that sequentially emanates as the primary focus of lean supply chains. Green supply chains consider the principles of waste reduction on a wider scope than what the lean paradigm essentially does. In that manner, we can conclude that green supply chains are innovative types of lean supply chains. Sustainable supply chains take into consideration of a wider set of performance objectives compared to green supply chains and are looking generally into the environmental as well as social dimensions of sustainability (Tobescu & Seuring, 2015). Research efforts in sustainable supply chains were dedicated mostly in the direction of understanding those vital technical and managerial contemplations while implementing different dimensions of sustainability into practice (Gupta & Desai, 2011). From these we can comment that sustainable supply chains are progressive sorts of green supply chains with wider set of performance objectives.

Corollary 8*: The capability of the supply chain to reduce wastes on a long run, thereby setting a constant market place increases as the supply chain transforms from lean to green and then to sustainable supply chain.*

6.2.2. Agile, leagile, resilient supply chains

Being agile means the supply chain is capable to exploit profitable opportunities in a volatile market using market knowledge and virtual cooperation (Mason-Jones, et al., 2000). The waste in lean production is an essential buffer in agile supply chains. So the concepts of leagile supply chains were introduced; in which the supply chain adopts a lean manufacturing approach upstream and once the leanness is achieved, it follows the principles of an agile supply chain in the downstream that is capable of delivering to an unpredictable market place. Thus leagile supply chains are progressive forms of agile supply chains, with optional buffer levels available.

Resilience can be primarily achieved through redundancy and flexibility. Redundancy is built through buffers in the supply chain and flexibility is achieved through standardization, postponements and through aligning strategies with supply chain objectives (Sheffi & Rice Jr, 2005). Thus resilient supply chains can be remarked as leagile supply chains with broader set of performance objectives. One among those major objectives is the proper utilization of buffers in the network. There are *three* major types of buffers in supply chains; capacity, inventory and time. Building flexibility in supply chains enable the usage of the proper combination of these buffers.

Agile supply chains provide options for rapid reconfiguration and will eliminate as much waste as possible. But waste elimination is not considered as a prerequisite in agile manufacturing (Naim & Gosling, 2011). Lean supply chains are designed to be flexible as much as possible, but flexibility is not considered to be a prerequisite in lean supply chains (Naylor, et al., 1999). Reducing buffers could reduce waste in all forms, but will eventually make the supply chain less robust and on wider latitude makes it vulnerable. In this context, the need of resilient supply chain systems is enhanced. The paradigm shift as observed in the nature of supply chains is represented in Figure 6.4.

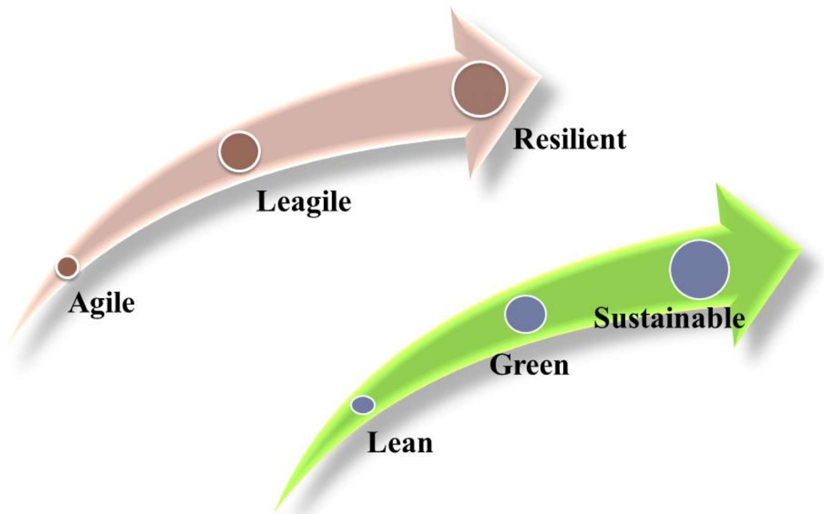


Figure 6.4: Paradigm shift in supply chains

***Corollary 9**: The ability to manage disruptions, thereby reducing vulnerability increases when the supply chain transforms from agile to leagile and then to the resilient supply chain.*

The principles and practices of various categories of supply chains are acknowledged and a comparison table is made as shown in Table 6.7.

Table 6.7: Comparison table for principles of categories of supply chains

Sl No.	Core Aspects of Supply Chains	Lean	Agile	Leagile	Green	Resilient	Sustainable
CA 1	Waste reduction	✓		✓	✓		✓
CA 2	Waste management				✓		✓
CA 3	Lead time reduction	✓	✓	✓	✓	✓	✓
CA 4	Resource conservation	✓			✓		✓
CA 5	Inventory reduction	✓			✓	✓	✓
CA 6	Buffer reduction	✓				✓	✓
CA 7	Responsiveness	✓	✓	✓	✓	✓	✓
CA 8	Level schedule	✓					
CA 9	Focus on efficiency	✓			✓		✓
CA10	Focus on competency		✓	✓		✓	
CA11	Virtual cooperation	✓	✓	✓		✓	✓
CA12	Focus on integration		✓	✓		✓	
CA13	Collaboration	✓	✓	✓	✓	✓	✓
CA14	Strategic partnerships	✓	✓	✓	✓	✓	✓
CA15	Process streamlining	✓					

Sl No.	Core Aspects of Supply Chains	Lean	Agile	Leagile	Green	Resilient	Sustainable
CA16	Information sharing	✓	✓	✓	✓	✓	✓
CA17	Complexity reduction					✓	
CA18	Flexibility		✓	✓		✓	
CA19	Market sensitivity		✓	✓		✓	
CA20	Rapid reconfiguration		✓	✓		✓	
CA21	Robustness		✓	✓		✓	✓
CA22	Uncertainty reduction					✓	
CA23	Reusability of products				✓		✓
CA24	Environmental considerations				✓		✓
CA25	Product safety						✓
CA26	Lifecycle assessment				✓		✓
CA27	Visibility	✓	✓	✓	✓	✓	✓
CA28	Redundancy			✓		✓	
CA29	Transparency					✓	
CA30	Adaptability					✓	✓
CA31	Labor equity						✓
CA32	Social issues						✓

* CA- Core Aspects

6.3. Role of Partition Line in a Sustainable/ Resilient Supply Chain

Multiple DPs exist in a supply network which when connected together form a partition line which divides the supply network running on an MTS strategy from that running on an MTO strategy at multiple points in the network. The time for production increases as the partition line is shifted to the left and there are lesser amounts of available buffer in the network. The time for production is condensed as the partition line is shifted to the right and there are more buffers available in the network to handle augmented demand uncertainties. The supply network transforms from an efficient network to a responsive network as the partition line shifts from the left towards the right.

The major factors influencing the positioning of DP are the estimated demand volume (EDV) and the relative demand volatility (RDV) (Teimoury, et al., 2012). Positioning of CODP plays a significant role in determining the right product delivery strategy. When the concept of supply chain advances to the concept of a supply network, there would be multiple CODPs positioned across the network. The partition line separates the network into forecast driven and demand driven fragment networks (Olhager, 2003).

Within the supply network there are *three* types of buffers as, capacity, inventory and time. Inventory buffers helps to manage variability in demand by utilizing the available stocks. Capacity buffers allow replenishing stocks quickly and time buffers usually allow the network to replace inventory by information. There exist *two* major pipelines to ensure availability of product in a network as; *material pipelines* and *information pipelines*. Material pipelines utilize capacity and inventory as buffers to deal with the fluctuations in demand and information pipelines utilize information to replace inventory and shift the point of delivery across time through postponement.

Naylor et al. (1999) suggests that lean management principles should be applied upstream of the supply chain and the agile management principles in the downstream of the supply chain. As perceived from the above section, the lean principles have been evolved into the concept of sustainability and the agile principles into the concepts of resilience. Also, it is worthy to notice that not a single point divides the modern supply networks into *two* broader objective fragment networks, but is actually a collection of points forming the partition line.

The partition line divides the entire network into a more waste reducing, sustainability oriented network upstream and the downstream, a more vulnerability reducing resilience oriented network. The entire supply network transforms into a *sustainable- resilient* network with operations primarily oriented for bringing sustainability applied upstream and those operations customarily targeted in bringing resilience applied downstream of the network, separated by the partition line. Before bringing resilience into the supply networks for handling uncertainties and for managing disruptions, the supply network must have well established processes for reducing possible wastes and working in an operationally stable environment implying sustainability. In that way, we can conclude that sustainability precedes resilience in a *sustainable- resilient* network.

Corollary 10*: The partition line divides sustainability oriented upstream supply network from the resilience oriented downstream supply network, which opens insights into the concept of a sustainable- resilient supply network.*

The reflections of the partition line in a supply network at each level of buffer are either visible in the form of handling capacity and inventory buffers by utilizing the material pipeline or could be realized in the form of handling time buffers by utilizing the information pipelines. The imaginary line connecting the buffer levels in a supply network, utilizing the information pipelines represents points of information order decoupling points (IODP) and the imaginary line linking the buffer levels, utilizing the material pipelines epitomizes points of material order decoupling points (MODP).

Corollary 11*: The reflections of the partition line at each level of buffer in a supply network represents imaginary lines connecting information order decoupling points (IODP) or material order decoupling points (MODP) or a combination of both.*

6.4. Model Case Analysis

We have extended the case of multiple DPs in a supply network, as proposed by (Sun, et al., 2008) to the distinctive cases of production systems and have critically analyzed *eight* alternative cases of interest; in order to position DP in a network. For better understanding of the concepts of sustainable- resilient networks, a sample case manufacturing network with *five* operations, ***A, B, C, D and E*** was taken under consideration. Raw materials are taken as inputs for a series of transformation operations ***A*** and ***B*** at one chain and ***C*** and ***D*** at the other, establishing *two* parallel branches of the network. Operation ***E*** is an assembly operation. For the network, *eight* separate cases for positioning the partition line in the network were analyzed. Out of them, *two* are analogous cases of interests. In effect we have *six* unalike cases for analysis which are metaphorically signified in Figures 6.5 to 6.10. Operations are represented as circles and the associated buffers are denoted as triangles. *Three* different set of buffers are considered in the network, the inventory buffer, the capacity buffer and the time buffer; that are differentiated using varying colors in the figures. The utilizations of these buffers vary when the nature of the network alters. The information feed backs for the utilization of buffers is shown as dotted lines. The detailed analysis of the cases is as follows,

6.4.1. Case 1

This is a case of manufacturing network consisting of all MTO operations; hence it is worthwhile to adopt strategies for resilience. Flexible operations reduce the vulnerability of the supply chain. Flexibility is imparted through the adoption of postponement strategies by dealing with time buffer. The buffers are exploiting the information pipeline more willingly than the material pipeline. Complexity is abridged through reduced inventory and capacity by providing tight coupling, as seen in postponement. CODPs in this case are placed at the first upstream operations and the Sustainable/ Resilient (S/ R) boundary is located at the upstream end. Since this is a case of all MTO operations, the reflections of CODP on both sides of the S/R boundary represent IODPs. The detailed view of the Case 1 network can be perceived from Figure 6.5.

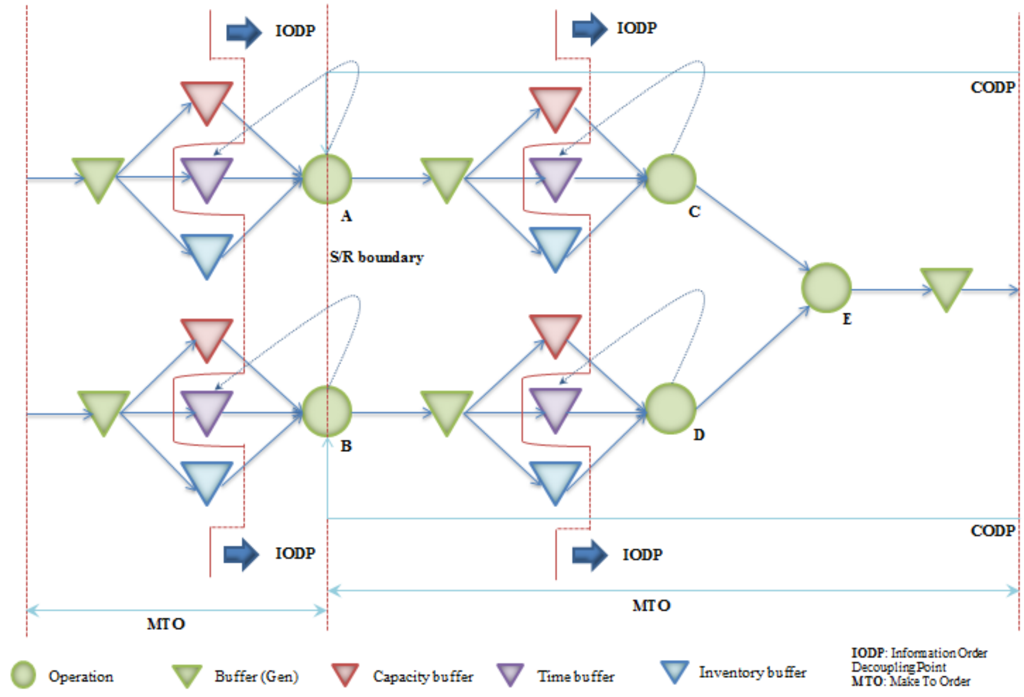


Figure 6.5: Case 1: All MTO processes

6.4.2. Case 2

This is a case of supply network consisting of all MTS operations. Sustainability is primarily achieved through lean operations by minimizing inventory and utilizing capacity to the maximum extent possible, thereby improving the operational efficiency of the supply chain. Sustainable supply chains enhance delivery speed through strategic partnerships and improved adaptability. Reusability and reverse logistics are considered for efficient and environmental friendly products. This increases the complexity of supply networks. Unlike as seen in postponement, flexibility is built through capacity and inventory buffers; thus the network provides a loose coupling, but with an advantage of managing more interactive complexity as seen from a complexity perspective view of supply chain. CODP in this case is placed at the last downstream operation and the S/R boundary is placed at the rear end downstream of the network. The reflections of S/R boundary on either side represent points of MODPs. A detailed view of Case 2 can be realized from Figure 6.6.

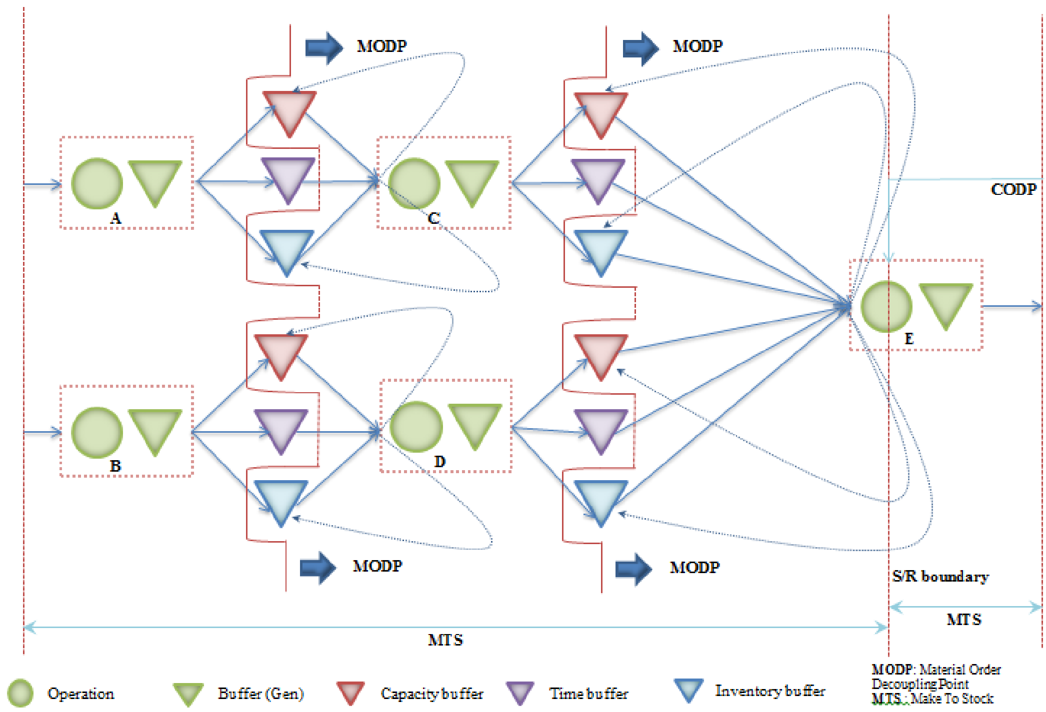


Figure 6.6: Case 2: All MTS processes

6.4.3. Case 3

This is an extension of Case 2, where the final operation is a MTO operation which gives the flexibility of Assemble To Order (ATO) systems. Finished goods inventory is reduced and resilience is imparted by having the advantage of an MTO operation. CODP is placed at the last operation and the S/R boundary is located at the end downstream. This network explores the possible advantages of a *sustainable-resilient* network. The network generally provides a loose coupling state with more interactive complexity among the elements taking insights from the normal accident theory (NAT) view in supply chain. Buffers generally utilize the material pipelines in view of the previous order information. The reflection of S/R boundary at each level of buffers, which largely utilizes the material pipeline, represents points of MODPs. The details are presented in Figure 6.7.

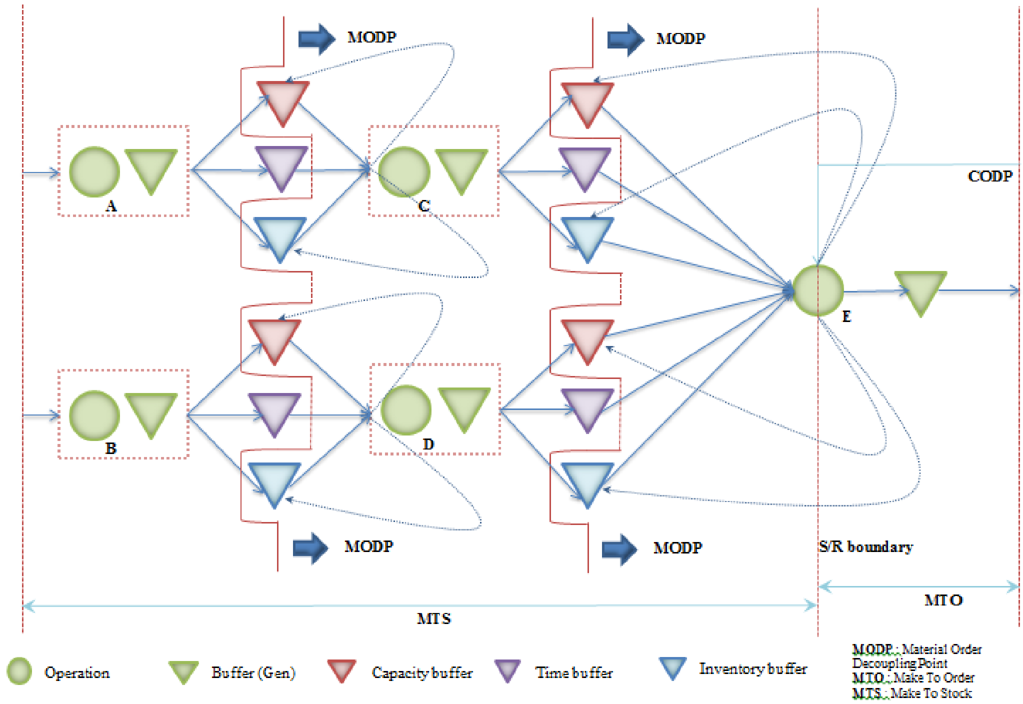


Figure 6.7: Case 6.7: ATO/ CTO processes *(A, B, C, D- MTS; E- MTO)*

6.4.4. Case 4

This is a pure combination of sustainable- resilient network. S/R boundary is virtually located in the middle of process network, where the upstream follows a MTS strategy where flexibility is imparted through strategic stocking and by utilizing excess capacity. The downstream follow MTO operations, utilizing visibility of capacity and inventory through information pipelines and by adopting postponement decisions, giving flexibility through time. This case is interesting, as the CODP is located at the middle operations and the S/R boundary separates the buffer levels of MODPs and IODPs. Upstream reflection of the S/R boundary involves the buffer utilizations through material pipeline representing MODPs at the coupling level and the downstream reflection involves the buffer utilizations through information pipeline showing IODPs at the coupling level. Case 4 is as detailed in Figure 6.8.

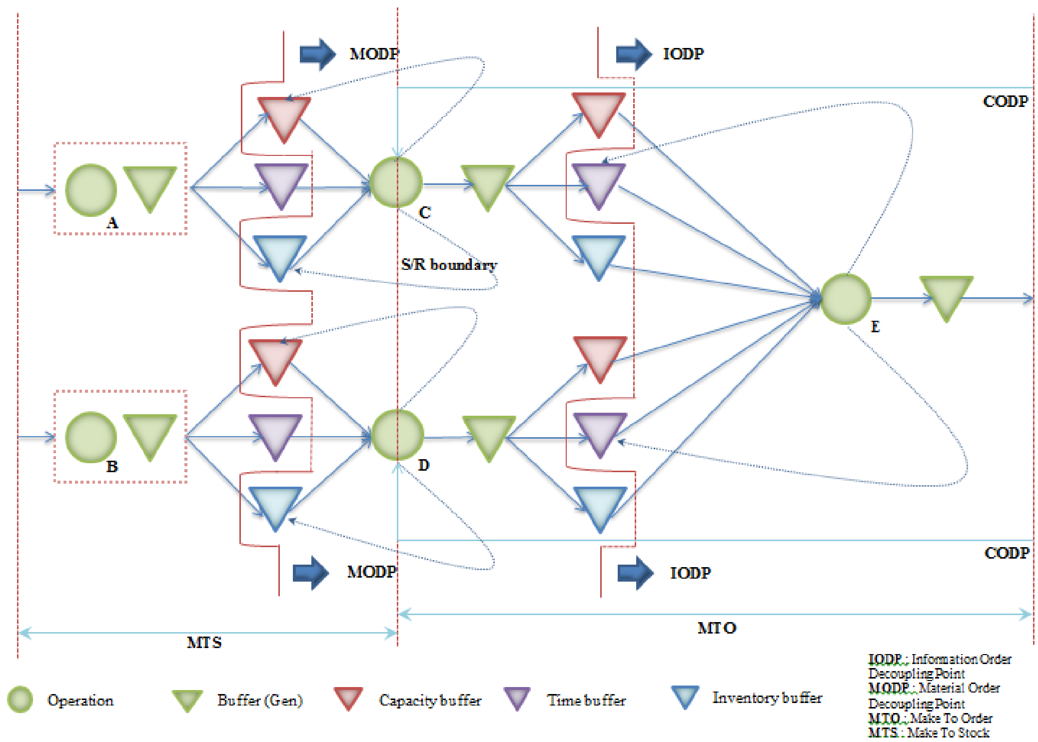


Figure 6.8: Case 4: ATO/ CTO processes *(A, B - MTS; C, D, E- MTO)*

6.4.5. Case 5 and 6

These are complicated cases of multiple decoupling points with a skewed S/R boundary. CODP is positioned at operations ***C***, ***E*** for case 5 and ***D***, ***E*** for case 6, which are representations of analogous cases. The buffer for operations ***C*** and ***D*** differ as one of them utilizes capacity and inventory and the other utilizes time. The reflections of the S/R boundary in the downstream appear to be a combination of IODPs and MODPs and in the upstream as points of MODPs. The points between ***C*** and ***E*** adopt a combination of MTS and MTO operations. On a complexity perspective, the points in between ***C*** and ***E*** are having a high interactive complexity with moderate coupling available, making the network vulnerable to disruptions. High visibility of capacity and inventory along with collaborative partner relationships are needed to tackle this vulnerability. The detailed view of case 5 and 6 is shown in Figure 6.9.

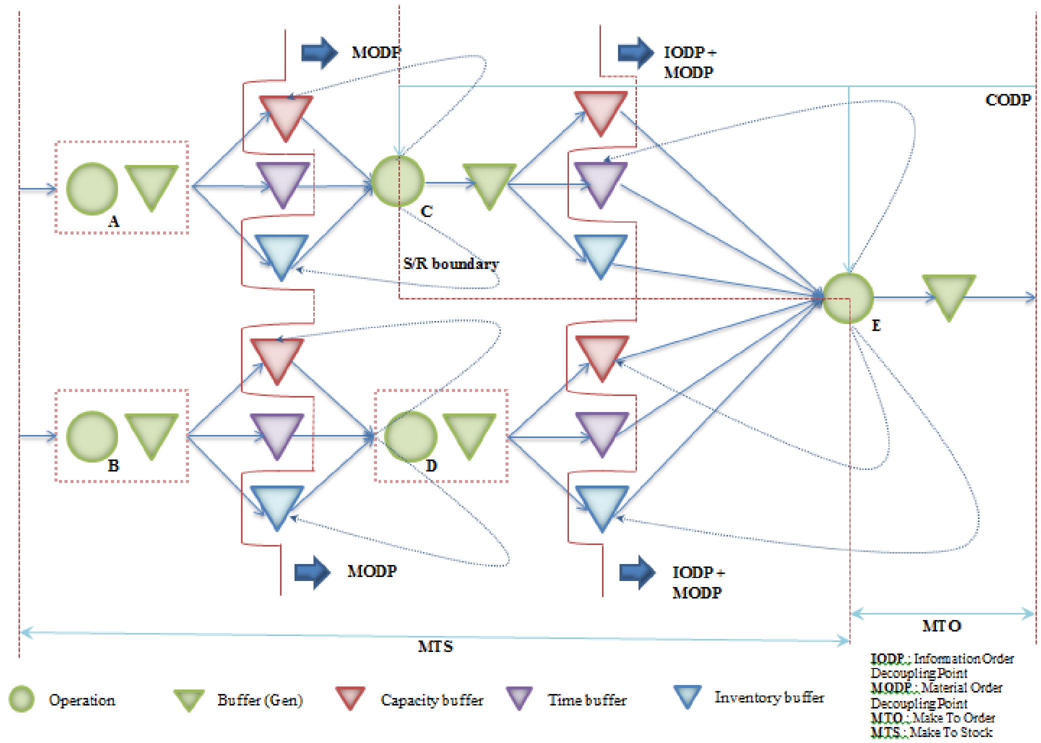


Figure 6.9: Case 5: ATO/ CTO processes *(A, B, D - MTS; C, E- MTO)*
OR Case 6: ATO/ CTO processes *(A, B, C - MTS; D, E- MTO)*

6.4.6. Case 7 and 8

These *two* analogous cases represent further complicated networks of multiple CODP, where the CODPs are placed far apart. Operations ***A***, ***C*** and ***E*** are MTO as seen in Case 7 or operations ***B***, ***D*** and ***E*** are MTO as seen in Case 8. The S/R boundary is critically skewed and a vast majority of operations comes in the *sustainable- resilient* region. The reflections of the S/R boundary on both upstream and downstream represent combinations of IODPs and MODPs. The coupling levels on both cases are either time or a combination of capacity and inventory. Collaborative practices such as vendor managed inventory benefits to reduce the chances of potential vulnerabilities. As viewed from a complexity perspective, the interactive complexity of the network is very high, so proportionately high level of coupling is needed. Cases 7 and 8 are represented in Figure 6.10.

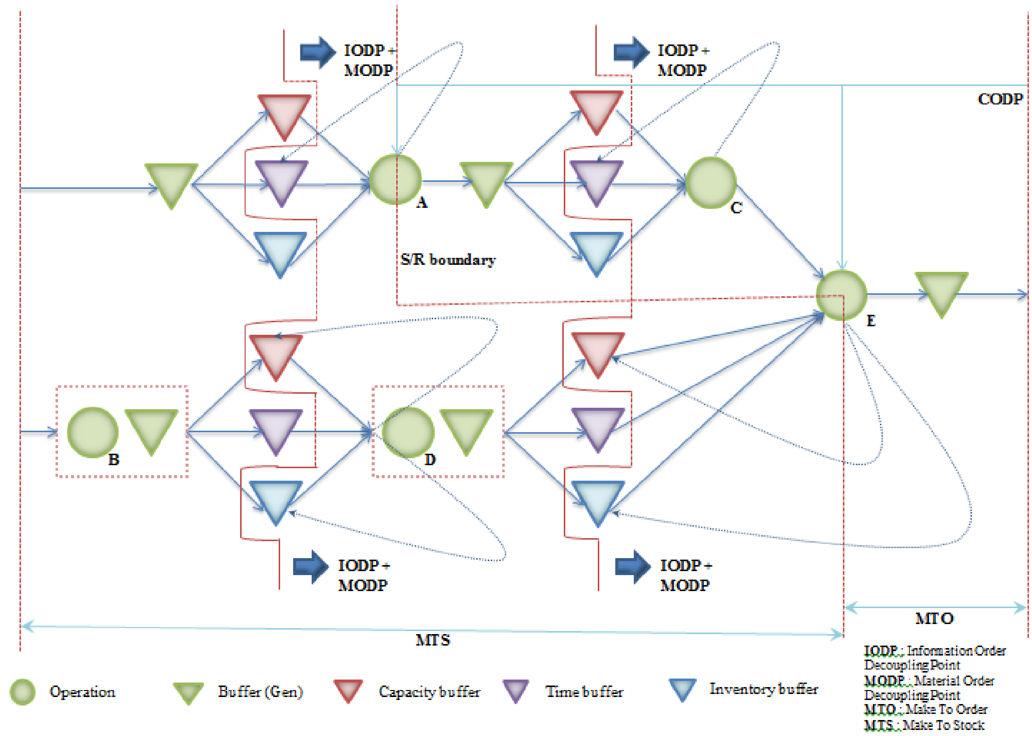


Figure 6.10: Case 7: ATO/ CTO processes *(B, D - MTS; A, C, E- MTO)* OR Case 8: ATO/ CTO processes *(A, C - MTS; B, D, E- MTO)*

6.5. Real Case Examination

An Indian electronic gadget manufacturer, *XYZ* (presently denoted so, due to security reasons) especially in the smart phones and tablet segments is achieving an extra ordinary market share through the launch of its new smart phone model, *ABC*. Let us have a cross examination of the production and sales strategies with respect to the *'eight' sample cases* as proposed in this research. The company adopts a special case of *all MTS process* (*Case 2*), where the products are *made to stock* assuming a very certain demand. The plant is set for its full capacity to produce models for every week delivery. The sales through internet allow the customers *not to pay* for any intermediaries. During the fall of *2014*, *XYZ* launched its evolutionary smartphone named *ABC* in the price segment of *less than ₹10000 (~149$)* in India. *ABC* models went on sale with an overwhelming response with a few lakhs of registrations in a week of time.

They conducted flash sale, every weekend online through one of the leading online sales sites. If the first come buyer fails to complete the order procedures within a stipulated time, the smartphone will be available to the customer in the waitlist. Only limited models would be available for sale in a week and the demand is massive, the online purchase has been well maintained to minimize any delay in purchase. Priced at *less than ₹10000* in the competitive segment, it competes with almost all leading models in the market including several foreign competitors in the related price segments. These descriptions clearly make us understand how well the company has managed to deal with sales without intermediaries and how effectively the company manages its inventories (in a batch).

The demand fluctuations and vulnerabilities are highly reduced as the customers have to register and are willing to wait for the product, which can be seen as a striking resemblance to *Case 1*. Capacity and inventory are the major buffers involved as the demand information is already known and the customers are ready to wait. Sustainable operations are practiced right at the operational level from production to assembly to packaging, thereby reducing the overall wastes and carbon foot prints. Thus in general, the manufacture and delivery of *ABC* can be made analogous to *Case 2* as explained in the model with an additional element of *customers who are willing to wait* considering a reasonably higher benefits out of costs.

6.6. Analysis of Findings

The research problem is to apprehend the general nature of the supply chains by analyzing the shift in their chief strategic objectives time to time. Several categories of supply chains in literature were analyzed and a paradigm shift in their general strategic objectives has been observed. Sustainable supply chains and resilient supply chains are the most evolved type supply chains with wider focus and broader set of performance objectives. Even though the core principles of sustainability and resilience are a bit contradictory, there are some similarities in their general strategic objectives. It is a subject of discussion to bring together sustainability and resilience in a single supply chain.

The lean- agile boundary has been extended to the case of supply networks and a study of positioning several decoupling points in a supply network has been conducted in this research. By observing the core focus of supply chains time to time, we have arrived at certain conclusions and are marked as corollaries. One among the remarkable observation is that sustainable supply chains are evolved from the principles of lean supply chains and resilient supply chains are evolved forms of agile supply chains, as supported from the literature.

Along with that, the lean- agile boundary can be extended for the case of a supply network as an advanced sustainable- resilience boundary. This opens research into a new category of supply chains called the *sustainable- resilient* supply chains, which follows a more sustainability oriented upstream network and a more resilience oriented downstream network separated by a partition line. Right from the supplier selection process, considerations should be taken for the environmental and social aspect of sustainability for the effective evaluation of suppliers. Once sustainability is achieved, the focus can be shifted in order to handle demand fluctuations and to make the supply network more resilient.

In this manner, the advantageous of a sustainable supply chain as well as a resilient supply chain can be harvested in a *sustainable- resilient* supply network by carefully positioning the partition line. For the critical analysis of positioning the decoupling point, we have considered *eight* separate cases of interest with different positions of S/R boundaries in diverse production networks. It is observed that, soon after the partition line, there is a rich visibility of inventory and capacity as seen in case of a general resilient supply network. Hence, the information pipelines are principally utilized with time as the major buffer. This is realized by adopting postponement decisions to the maximum possible extend.

For the practical implementation of a *sustainable- resilient* supply network, it is essential to effectively position the partition line in the network. Thus, supply chain managers may follow the *five* step procedure elaborated as follows;

(i) Identify the specific focus of the network from a strategic level to an operational level,

(ii) Locate points until clear visibility of product information is available and fix partition line,

(iii) Determine suitable buffer levels and its level of utilization at stages with practical insights,

(iv) Align strategies of sustainability and resilience on either sides of the network, successively, and

(v) Gradually improve the capabilities of the supply chain for managing vulnerabilities and for reducing carbon foot prints of products.

The details of the *five* problems addressed are elaborated in chapters 2, 3, 4, 5 and 6. The present study has certain limitations and practical constraints. The conclusions derived out of the present study along with limitations and scope of future works are discussed in the coming chapter.

CHAPTER 7

CONCLUSIONS, LIMITATIONS OF THE STUDY AND SCOPE OF FUTURE WORKS

Quantification of vulnerability, supply chain risks and risk mitigation practices need immediate managerial attentions. Supply chain risks and vulnerabilities should be identified and assessed to reduce their effects as well as the mitigation practices should be gauged for its true effectiveness. Relating to this, this research was done to address some of the major gaps in literature. The research was to address some of the critical problems in the domain of supply chain risk management and supply chain resilience. The related issues were considered in an Indian context by taking representative case studies. *Five* problems were addressed in this research and suitable methodologies were developed for addressing the same. Conclusions from the study and the delimitations along with directions for further research are presented in the subsequent sub-sections.

7.1. Problem 1

First problem was to effectively quantify supply chain risk management strategies based on their net influences. A methodology using a combination of grey theory and digraph- matrix methodologies were employed to address the same. Reading from the results of the solution to *first* problem, it can be inferred that risk mitigation strategies have positive as well as negative effects over risks and on quantification of this, both the effects should be taken into consideration. The net positive effects determine the true efficacy of these strategies.

The research has attempted to identify the major risks in electronic supply chains and most important risk mitigation strategies, which can be implemented to prevent, curb or to mitigate supply chain risks. The mitigation strategies were ranked based on its overall effectiveness on risks by making use of a combined grey theory and digraph-matrix approaches. A real case application of the model was also conducted in an Indian electronic manufacturing industry, *XYZ*. The results were also subjected through sensitivity analysis.

The proposed methodology conglomerates the benefits of grey theory and graph theory to deal with human judgments to be converted into a set of numerical values which makes the decision making easy for managers. The approach is advantageous as it considers importance relations and influence relations simultaneously, so that the net effect of each risk mitigation strategy over risks can be clearly appreciated. The net positive influence values (*NPIV*) of risk mitigation strategies, proposed in this research have a lot of managerial implications.

Top management can ascertain the best risk mitigation strategies by simply considering strategies with higher *NPIV* values. By plotting digraphs, it is easy to represent the importance relations among various supply chain risks. Risk mitigation strategies *RMS11* and *RMS12* (*reducing bullwhips* and *using insurance*) were identified as most effective mitigation strategies for the case electronic supply chain. By implementing the model, it is also possible for managers to take proactive initiatives to tackle supply chain risks by implementing suitable mitigation strategies and to deal with the vulnerability of supply chain as a whole.

The proposed methodology needs three sets of input parameters as, importance relations, positive influence relations and negative influence relations, for effective ranking of risk mitigation strategies. This makes the process mentioned in *Step1* (Chapter 2), a tedious job. The grey importance ratings among various supply chain risks and the grey influence rating of risk mitigation strategies over risks were given by supply chain analysts. Thus, their biasing towards some of the variables might have slightly influenced the results.

In this research, we have considered only *twelve* of the predominant supply chain risks in an electronic supply chain. The permanent function for an $M \times M$ matrix contains *M!* (factorial *M*) terms to be computed. Thus, a 12×12 matrix permanent function in this research contains *12! (47,90,01,600)* terms. Increasing the number of considered risks will increase the complexity of the model. Also, the time required for computation of the results increases radically. Future research could focus on varied application of the model considering more supply chain risks and mitigation strategies. The proposed model is quite generic in nature and with marginal changes can be made applied to different types of industries as well. Efforts could also be made for building user friendly software on the basis of proposed model.

7.2. Problem 2

Second and *third* problems are complementary problems of interest to practitioners. These problems were addressed to fill the gap from the effective implementation of supply chain risk management practices towards achieving supply chain resilience. In effect, there are critical entangled cause- effect relations existing among the drivers of risks as well as among the enablers of risk mitigation. These cause- effect relations were quantified to identify the critical causal driver of supply chain risk as well as to identify the most influential enablers of risk mitigation. A representative case evaluation was conducted and the solutions were obtained using a combined methodology using grey theory and DEMATEL methodologies.

This research has attempted to identify the major supply chain risks and corresponding risk drivers with primary emphasis on electronic supply chains. The implementation of the proposed model as a test case in an Indian electronic manufacturing company throws insights into some of the practical applications and managerial implications of the model. The proposed methodology can be incorporated into the planning phase of any strategy implementation, so that each strategic decision could be checked for vulnerabilities based on the evaluation model. This could enable the company to sort out the root causal risk drivers associated with a particular strategy.

The constructed cause–effect relations have helped to identify *fluctuating exchange rates (C3)*, *loss of information system (E2)* and *supply failures (C2)*, as the most vulnerable causal supply chain risk drivers. We have obtained the following conclusions for the case and have recommended that the managers should focus on the most vulnerable drivers of risks, recognized as *C3, E2* and *C2*. Company should prevent the chances of occurrence and propagation of the effects of these risk drivers in the burgeoning stage itself for improving their resilience capabilities. For that, high levels of visibility and collaboration should be practiced to handle those unforeseen risk drivers and their associated vulnerabilities.

The research has a dual scientific contribution to the literature and practice of supply chain risk management. Firstly, it identifies and confirms the existence of pronounced causal relations among various drivers of supply chain risk drivers. This could generate interest to researchers and practioners in risk management to explore more on the causal relations from a rudimentary level. Second is the managerial implications generated in this research. Managers can infer from the results of the research that efforts to reduce the effects of most influential drivers of risks could enable the reduction of the effects of other drivers of risk that are resultant to them. This can be observed in practice to ensure better implementation of SCRM practices. The results can be extended to other supply chains considering the drivers of various risks in those supply chains.

Also, the results of the proposed case have wide applicability in practice of SCRM. It is healthier for managers to deal with the drivers of supply chain risks instead of addressing the subsequent risk events. Amongst the drivers of supply chain risks, some are predominant being causal, showing wider effects and having serious impacts over the supply chain; while some others are effect drivers commenced in consequence of other risk drivers. Drivers of supply chain risks are generally interconnected and this is the primary reason for the propagation of risk events leading to the disruption of the entire supply chain. The obtained results agree with the conclusion that the risk drivers are interconnected and that one risk driver can be the cause for another, as evidenced from the prominent digraph plots. Thus this model could enable managers to take proactive initiatives for tackling supply chain risks by implementing suitable strategies to deal with those causal drivers as evinced in the digraph plots.

From the results, it can be inferred that the drivers of risks and the enablers of risk mitigation have critical causal relations among themselves. It is essential for managers to concentrate on the critical causal driver as well as the chief enablers of risk mitigation to gain considerable benefits. Reading from the results of the complimentary problems some major inferences were remarked. Those scope of future works and delimitations were as discussed in this section and section 8.3.

Firstly this research is conducted on a macro level basis. An analysis of the factors influencing the drivers of risks at micro levels could generate more idea into the existence of influential relations. *Secondly*, in this research we have considered only *six* of the major risks predominant in an electronic manufacturing supply chain and *fourteen* supply chain risk drivers. More risks and their drivers can be incorporated at the cost of complexity. *Thirdly*, the results are dependent on the ratings given by supply chain analysts for various risk drivers and this might have also influenced the conclusions. The analysts need to have an exhaustive knowledge about the firm, its practices and the possible risk events associated with their supply chains from the past data to deliver those ratings. *Finally*, we have considered those significant causal relations that are higher than a particular threshold. More causal relations can be plotted for critical analysis of the model by lowering the threshold.

A micro level analysis of the factors influencing the drivers of supply chain risks could be considered as a scope of future work. This requires careful analysis and critical interpretations involving strenuous effort and time. Future research could also focus on the occurrences of *two* way relations to identify those risk drivers representing a mutual cause and effect among themselves, by subsequently lowering the threshold value. For managers, it is easy to propose general mitigation mechanisms to deal with those paired risk drivers. Extending this methodology for each risk driver and their supporting causes, it is also possible for managers to identify the root cause of each risk driver through causal relationship diagrams. This could benefit them in ascertaining and categorizing those root causes of risk drivers that demands imperative managerial attentions.

Also, future research could concentrate on adding more supply chain risks and the associated drivers to identify and plot their effects on the existing causal relations. Efforts could be attempted in the direction of validating the recommended model. The research need to be extended for different electronic manufacturing industries to isolate those drivers found to be critical for a vast majority of the industries. Along with that, the study can be extended to different industries taking a number of cases and the results obtained can be compared to find the variation in chief causal drivers for different firms. A comparative study can also be conducted among partners to isolate chief driver contributing to supply chain vulnerability, as a whole. User friendly software packages could also be built on basis of the proposed model. Using those packages, different prominent causal relations can be plotted by setting different threshold values and the analysis could be made easy for managers.

7.3. Problem 3

The research has attempted to identify the major enablers of supply chain risk mitigation with typical focus on electronic supply chains. A representative case study of the model was conducted in an Indian electronic manufacturing company, *XYZ*. Enablers of supply chain risk mitigation are usually interconnected. Cause–effect relationships plotted can facilitate managers to identify primary causal enablers for addressing the vulnerability issues of supply chain. The obtained results agree that enablers of risk mitigation are interrelated. Managers can take proactive steps to address primary causal enables of risk mitigation up in the strategic level to reduce total risk impacts of supply chains.

For this organization, we found that even though they have implemented a number of enablers, their focus was relatively argumentative and the vulnerability of the supply chain was snowballing. We also found, through sensitivity analysis that the managers have a common judgment of the enablers in prioritizing them. These insights were achieved from the initial and sensitivity analysis portion of the study. The managerial implications and usefulness of the technique are vivid and managers are able to determine which enabler for supply chain risk mitigation need more attention (high cause, high importance) and which among those might be given relatively less priority.

It is also possible for the managers to complete sensitivity analyses in ways that allow them to determine the stability of their observations. Managers can also plan the future direction of implementation of strategies by determining how particular enabler influences the other ones. For instance, if they wish to further expand supply chain risk mitigation plans or other programs for risk reduction, the digraphs provide clear relationships on '*which enablers*' should be emphasized to ensure greater success of such programs. Primary emphasis must be given for the investments and prioritization for the implementation of more foundational and prominent enablers coming under *third zone (Z3)*.

The tool employed is also helpful for researchers for either a broad study of the causal- effect relations, or similar as in our case, for a single comprehensive analysis. Other electronic manufacturing companies may have similar general relationships. The causal relationship diagrams can also be found useful in identifying and classifying the risk mitigation strategies for various structures and relationships among different companies based on the type, size, process, product or any other characteristics, which can be directly used for the comparative analyses of cases. The results are subjective to change depending on the strategic prominence of the organization.

The major limitations remain the same as discussed for problem 2. *Firstly* this research is conducted on a macro level basis. Enablers of risk mitigation need to be analyzed at micro levels to generate more idea into the existence of influential relations. *Secondly*, in this research we have considered only *fifteen enablers of* supply chain risk mitigation. It is possible to incorporate more at the cost of increasing complexity of the model. *Thirdly*, the results relied completely on the ratings given by analysts and the human factors of error on the ratings for various enablers of risk mitigation might have influenced the conclusions.

It is essential to have experienced analysts with exhaustive knowledge about the firm, its practices and the possible risk events associated with their supply chains to deliver those ratings. *Finally*, the value of threshold was determined on basis of an interpretive logic of the relations and hence those significant causal relations that are higher than a particular threshold were only considered for the study. Increasing the number of causal relations in the plotted digraph can help in critical analysis of the relations and could assist in the appearance of two way influential relations needing immediate attentions.

As discussed above, this research we have piloted contemplation among *fifteen* enablers of supply chain risk mitigation. Future works could concentrate on increasing the number of enablers for analysis and critical analysis of the causal relations by varying the threshold values. The case study considered was a representative case study and generalization of the results may not be always possible. Future efforts could be made for validating the proposed model. User friendly software could also be built on basis of proposed model.

7.4. Problem 4

Fourth problem is in consideration of the upstream supply chain as most of the critical disruptions are supply related. A resilient supplier chain selection problem was formulated and solved for a representative case supply chain. The *fourth* problem enables managers to adopt a model and methodology for the selection of suppliers for resilience. The upstream supply chain has to be dealt with adequate importance and the concept of resilience should be implemented even from the selection of suppliers. The inferences from the results of the application of proposed model, the scope of future works as well as the delimitations are mentioned in section 8.4. The conclusions to problems are detailed as follows;

Ultimate objective of this supplier selection problem is to select appropriate suppliers matching with resilient capabilities of the company's supply chain. As suppliers are the vital sources of vulnerability, better supplier selection helps in building resilience thereby reducing the risks in supply chain as a whole. Till date, no study has been seen for selection of suppliers in case of a resilient supply chain. Grey relational analysis has been employed in this study to select suppliers by considering attributes of resilience typically seen in an electronic supply chain. This method is advantageous as any new supplier could easily be incorporated in the evaluation process. The proposed attributes for supplier selection used in this research are quite generic and thus with minor modification can be used in case of other industries also. The choice of parameters for supplier selection and determination of weightings for each parameter depends on the degree of resilience needed.

Companies are benefitted by using the proposed methodology for reducing potential vulnerabilities associated with their supply chains, as it results in selection of a resilient supplier. Also, there is no limitation for the number of suppliers that can be compared. In addition, it is possible to vary weightings given to attributes so that priorities for attributes can be varied at any point of time to fit with current market requirements. By using simple linguistic scales for comparison grey relational analysis could successfully end up with a set of possibility values for supplier selection in numeric figures, which makes the selection process easier for managers. Despite all, managers are better benefitted with the approach by finding the qualities of an ideal referential supplier so as to get indication on how better a supplier can perform in comparison.

There are a few limitations of this research too. The weightings and rating of attributes by committee members are subjective and depends upon their knowledge and expertise with the firm, its processes, etc. Future research could extend the proposed model into a multi stage model, considering the sub-attributes of each attribute that imparts resilience. The resilience parameters can be combined with a number of green parameters for supplier selection to address the sustainability issues of suppliers. Efforts could also be undertaken to make a tradeoff between attributes imparting sustainability and resilience for the selection of appropriate suppliers.

7.5. Problem 5

Fifth problem is to study the strategic level objectives of supply chains and the periodical shifts in their focus. Major objective is to identify the sequence of evolution of supply chains and to devise the exact location of positioning of partition line in a network to achieve complementary strategic objectives from the same supply network. A concept of sustainable- resilient supply network is proposed and the positioning of partition line to achieve sustainability and resilience together in a network was studied. A model case analysis was conducted and the results were also discussed. This study has certain limitations. Albeit, the concepts are derived from the supply chain practices found in literature, scrupulous implementation of a *sustainable- resilient* network into practice needs extended research and practitioners expertize in the field. It is challenging for an existing supply chain to amend its strategic level objectives all of a sudden. The principles can be incorporated progressively in the network.

The positioning of decoupling point is a chief strategic level decision affecting the supply chain performance and its market share. In a supply network, there exists a set of decoupling points which when connected together forms a partition line in the network, which was of discussion through addressing the problem. Literature on supply chains has made the understanding of different strategic level objective focused supply chains in general. Lean, agile, leagile, green, resilient and sustainable classes of supply chains contribute to a vast majority of strategy focused supply chains with various sets of performance objectives.

The study included the similarities and dissimilarities in their objectives and paved the way for many concluding remarks. The paradigm shift observed in the general nature of strategic objectives in supply chains have made the understanding that the focus of supply chains become eclectic when it either transforms from lean to green and to sustainable supply chains or from agile to le-agile and to the resilient supply chains. It is significant for managers to fix the meticulous location of the partition line in their supply chains to apprehend the exact strategic focus at various echelons of the supply network. It is advantageous to implement strategies focusing on sustainability in the upstream of the supply network, whereas those focusing on resilience suits best in the downstream of the network.

Managers are advised to align suitable strategies matching the fundamental focus of a speculative and a realistic network on either sides of the partition line. At the tactical and operational levels, managers are advised to keep sufficient inventories and utilize capacities to act as buffers in the upstream network up to the partition line. In the downstream network soon after the partition line, time can be used as a major buffer to deal with demand variability by adopting maximum postponement of operations or by implementing delayed differentiations. Thus, by spending expertize, managers can bring the advantageous of sustainability and resilience together in a supply network.

The major difficulty in the implementation of a *sustainable- resilient* network arises as the partition lines are imaginary and are subject to change in a real case supply network. This is a conceptual work and further research is needed to implement the concepts into practice. High level managerial rethinking and engineering reconfigurations are needed for constructing the *sustainable- resilient* supply networks into practice. Further research can be extended by analyzing the supply chain practices of today's companies to gain some insights for the applicability of the principles of sustilience for diverse supply networks. Thus future works can also be engrossed on the analysis of a real time supply network and to pinpoint the exact position of partition line in the network. An exact blending of theoretical and practical research is needed for the implementation and widening the scope of the concept of *sustainable- resilient* supply chains. Sustainable-resilient supply chains, the concept proposed as the *fourth* objective could be the future of supply networks that can imply sustainability, while being resilient.

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LIST OF PUBLICATIONS BASED ON THE THESIS

Refereed International Journals

1. Rajesh, R. and Ravi, V. (2015) 'Supplier selection in resilient supply chains: a grey relational analysis approach', ***Journal of Cleaner Production***, Vol. 86, pp.343-359. (©TR Impact Factor- **5.715**)

2. Rajesh, R., Ravi, V. and Venkata Rao, R. (2015) 'Selection of risk mitigation strategy in electronic supply chains using grey theory and digraph-matrix approaches', ***International Journal of Production Research***, Vol. 53, No. 1, pp.238-257. (©TR Impact Factor- **2.325**)

3. Rajesh, R. and Ravi, V. (2015) 'Modeling enablers of supply chain risk mitigation in electronic supply chains: A Grey–DEMATEL approach', ***Computers & Industrial Engineering***, Vol. 87, pp.126-139. (©TR Impact Factor- **2.623**)

4. Rajesh, R. and Ravi, V. (2017) 'Analysing drivers of risks in electronic supply chains: a Grey- DEMATEL approach', ***International Journal of Advanced Manufacturing Technology***, (DOI 10.1007/s00170-017-0118-3). (©TR Impact Factor- **2.209**)

Conference Proceedings

1. Rajesh, R., & Ravi, V. (2015) 'An integrative decision making model for sustainable supply chains in Indian industries', ***Proceedings of XIX Annual International Conference of the Society of Operations Management***, IIM Calcutta, pp. 150.

APPENDIX

Annexure 1: Sample calculation of the methodology implemented in chapter 2

From Table 2.4, a small sample of importance relation matrix considering three supply chain risks and three risk mitigation strategies were taken for the present analysis. i. e.,

X= (2.30)

	SCR1	SCR2	SCR3
SCR1	0	0.795	0.83
SCR2	0.205	0	0.512
SCR3	0.17	0.488	0

Also, from Tables 2.5 and 2.6, sample matrices of positive influence relations and negative influence relations were formulated respectively as,

Y= (2.31)

	SCR1	SCR2	SCR3
RMS1	0	0.864	0.5
RMS2	0.04	0.509	0.991
RMS3	0.04	0.311	0.85

Z= (2.32)

	SCR1	SCR2	SCR3
RMS1	0.951	0	0
RMS2	0	0	0
RMS3	0	0	0

Tables 2.7 and 2.8 represent the positive strategy selection and negative strategy selection matrices, respectively. For this sample case, these matrices are constructed by replacing the diagonal elements of X matrix by row elements of matrices Y and Z, separately for each risk mitigation strategies. i.e. for example, the positive and negative strategy selection matrices for the risk mitigation strategy, RMS 1 can be represented as,

A=		SCR1	SCR2	SCR3
	SCR1	0	0.795	0.83
	SCR2	0.205	0.864	0.512
	SCR3	0.17	0.488	0.5

(2.33)

B=		SCR1	SCR2	SCR3
	SCR1	0.951	0.795	0.83
	SCR2	0.205	0	0.512
	SCR3	0.17	0.488	0

(2.34)

Then, the permanent functions of these matrices were calculated for each case, which is the determinant expansion of a matrix considering all the terms to be positive. The same is calculated as,

$per(A) = 0 \times (0.864 \times 0.5 + 0.488 \times 0.512) + 0.795 \times (0.5 \times 0.205 + 0.512 \times 0.17) + 0.83 \times (0.488 \times 0.205 + 0.17 \times 0.864) = 0.355628$

$per(B) = 0.951 \times (0 \times 0 + 0.488 \times 0.512) + 0.795 \times (0 \times 0.205 + 0.512 \times 0.17) + 0.83 \times (0.488 \times 0.205 + 0.17 \times 0) = 0.389843$

The net positive influence values (NPIV) were calculated as the difference of $per(A)$ and $per(B)$ values. For this sample, $NPIV = per(A) - per(B)$ = -0.03422. This implies that the risk mitigation strategy, RMS 1 has more negative effects in consideration of its influence over three risks, i. e., SCR1, SCR2 and SCR 3.

Annexure 2: Sample calculation of the methodology implemented in chapter 3

Table 3.8 represents the crisp relation matrix of influence relations among various supply chain risk drivers. A sample of influence relations of three risk drivers is taken for the demonstration of the methodology. i. e.,

A^*=	FRER	BWEF	CCPY
FRER	0	0.726	0.285
BWEF	0.733	0	0.783
CCPY	0	0.325	0

(3.14)

The above matrix is normalized by multiplying the elements with M as shown in equation (3.9). Thus for this case $M = 1.516$ and the normalized matrix is represented by R, synonymous to the normalized direct crisp relation matrix as in Table 3.9.

R=	FRER	BWEF	CCPY
FRER	0	0.4789	0.188
BWEF	0.4835	0	0.5165
CCPY	0	0.2144	0

(3.15)

Then for the sample, an identity matrix of appropriate dimensions is formulated and the total relation matrix is formulated using equation (3.11) i.e.

I=	FRER	BWEF	CCPY
FRER	1	0	0
BWEF	0	1	0
CCPY	0	0	1

(3.16)

$$T = R \times inv(I - R) \tag{3.17}$$

T=	FRER	BWEF	CCPY
FRER	0.3933	0.8135	0.6821
BWEF	0.7576	0.5668	0.9517
CCPY	0.1624	0.3359	0.2040

(3.18)

Let r_i represents the sum of row elements and c_j represents the sum of column elements of this sample matrix. Then for all $i = j$; $r_i + c_j$ represents the effects given by the driver to the system and $r_i - c_j$ represents the effects received by the driver. For the sample considering the cause-effects of the first driver FRER, $r_i + c_j = 3.3022$ and $r_i - c_j = 0.5756$. Since $r_i - c_j$ is positive, considering the cause- effects over three drivers, we can say that the considered driver is a causal driver. Digraphs are plotted showing the relations from the causal drivers to the effect drivers.

Annexure 3: Sample calculation of the methodology implemented in chapter 5

The ratings from experts were collected and the same were converted into grey values. Average grey performance ratings were calculated and the grey decision matrix D is calculated. The average weightings for attributes were determined using equation (5.4). A sample average grey rating matrix is taken considering three attributes and three suppliers only. i.e.,

D= (5.35)

	FRER	BWEF	CCPY
FRER	7.8 / 9.6	5.2 / 7.0	7.2 / 9.4
BWEF	6.6 / 9.2	5.6 / 7.8	5.0 / 6.4
CCPY	5.8 / 8.4	4.0 / 5.0	5.6 / 7.8

This matrix is normalized to obtain the normalized rating matrix. Since the attributes were rated based on their benefits, the normalization is done as per equation (5.12). i.e., for the sample it is represented below;

D^*= (5.36)

	FRER	BWEF	CCPY
FRER	0.813 / 1	0.667 / 0.897	0.766 / 1
BWEF	0.688 / 0.958	0.718 / 1	0.532 / 0.681
CCPY	0.604 / 0.875	0.513/ 0.641	0.596 / 0.83

The weighted normalized grey matrices were obtained by multiplying with corresponding weightings as in equation (5.16). So by considering the sample, the weighted matrix is obtained as;

$$D^{**} = D^{*} \times W \tag{5.37}$$

$D^{**}=$ (5.38)

	FRER	BWEF	CCPY
FRER	0.683 / 0.98	0.520 / 0.861	0.552 / 0.94
BWEF	0.578 / 0.939	0.56 / 0.96	0.383 / 0.64
CCPY	0.507 / 0.858	0.4/ 0.615	0.429 / 0.78

The ideal referential supplier alternative is formed as per equation (5.19) as,

$$S^{max} = \left\{\frac{0.683}{0.98}, \frac{0.578}{0.96}, \frac{0.507}{0.858}\right\} \tag{5.39}$$

Thus for the sample case, the grey possibility values for the first supplier is calculated as;

$$P(S_1 < S^{max}) = \frac{1}{3}\sum_{j=1}^{3} \frac{\max(0, L_j{}^{*} - \max(0, \overline{V}_{ij} - \underline{G}_j{}^{max})}{L_j{}^{*}} \tag{5.40}$$

For this sample, $L_1{}^{*}$ is calculated based on equation (5.23) as;

$$L_1{}^{*} = \big((0.98 - 0.683) + (0.98 - 0.683)\big) = 0.594 \tag{5.41}$$

Similarly, $L_2{}^{*} = 0.782$; $L_3{}^{*} = 0.739$

Considering equation (5.21), the grey possibility value of first supplier is calculated as;

$$P(S_1 < S^{max}) = \frac{1}{3}\left(\frac{0.293}{0.594} + \frac{0.499}{0.782} + \frac{0.306}{0.739}\right) = 0.515$$

The decreasing *P* values shows increasing preference of selection of the suppliers.