Supply chain risk management: models and methods

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Abstract: This paper consolidates various research outputs in supply chain risk management (SCRM). It presents the techniques employed for managing and modelling supply chain risk drivers in an encapsulated form to aid the risk related decision making in industries. This review paper proposes a hybrid of systematic and descriptive review approach. Initially, the authors apply a systematic literature review approach to study the current research directions and subthemes in SCRM. The information thus obtained is also utilised to shortlist the research papers for the descriptive review that identifies the various models and methods applied in SCRM research. A software tool known as BibExcel is employed for data mining and analysing. Another software tool called Pajek is used to visualise the BibExcel outputs. Furthermore, this review paper identifies and discusses the significant gaps in SCRM research studies and proposes some unique and promising areas for future research.

Keywords: supply chain management; SCM; supply chain risk management; SCRM; literature review; meta-analysis; risk modelling; risk mitigation.

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1 Introduction

Supply chain is the network of firms organised to meet customer demand. This network basically includes the supplier, manufacturer, distributor, retailer and even customers themselves. Supply chain management (SCM) can be defined as the process of strategically managing the procurement, movement, and storage of materials, parts and finished inventory (and related information flows) through the organisation and its marketing channels in such a way that current and future profitability is maximised through the cost-effective fulfilment of orders. During this seamless operation, organisations have to confront and overcome many barriers (i.e., risks) for sustaining in this competitive globalised market. Some of these barriers are demand uncertainty, internal uncertainty, supply uncertainty and supply chain disruptions. The unplanned and unanticipated events that prevent the normal material and information flow through the supply network denote supply chain disruptions. The disruption causing events can be either mitigated entirely or the effects of those events can be controlled up to some extent by framing a proper contingency plan (Poirier and Quinn, 2003; Kim et al., 2015). Mitroff and Alpasan (2003) state that only between 5% and 25% of Fortune 500 companies are prepared to handle disruptions. A major example is the impact of 2011 tsunami in Japanese automotive industry resulting in Toyota losing their top position as global car producer in 2011, handing over the title back to general motors.

Adding to this vulnerability, the increased level of competition as a result of globalisation forces industries to follow business practices such as lean manufacturing, just-in-time systems, Omni-channel marketing, increased outsourcing, centralised distribution system, clustering and concentration, reduction in supplier base, etc. that involve a considerable amount of risk. Supply chain risks result in either mismatch between supply and demand or affect the supply chain functioning, efficiency, output and even end up in company closure. Considering this situation, World Economic Forum (WEF) has highlighted supply chain disruptions and vulnerability as one of the four

emerging risk issues that will affect the world's economy and society during this decade. The WEF considers supply chain vulnerability to have an impact potential as high as systematic financial risks, food security or energy supply (Hubner et al., 2014). Therefore, the relevance of adopting supply chain risk management (SCRM) practices in everyday business has gained widespread attention from both the industries and academia over the past decade. As a result, the number of research publications in this domain has exponentially increased. In the early 21st century, supply chain practitioners claimed that studies published in this area are chaotic and disorganised (Jüttner et al., 2003; Trkman and McCormack, 2009). However, now the research on SCRM is slowly approaching a saturation level with different methods and tools employed giving new insights to the problem. Hence, there lies scope for review papers that consolidates the results of research happened in SCRM to identify the potential areas for further investigation. To cater to this need, there is a significant number of review papers in SCRM published in reputed journals in the last five years. The review papers of Sodhi et al. (2012), Ho et al. (2015), Fahimnia et al. (2015) and Heckmann et al. (2015) are the most significant review papers published in SCRM domain. However, the present review paper is different from the above publications and the rest of the review papers in SCRM in the following aspects.

- A framework is proposed for conducting an integrated approach of systematic (meta-analysis) and descriptive methods for reviewing the literature. This integrated methodology for literature review is followed to highlight the salient features of research in SCRM.
- Emphasis has been given to models and methods employed in different phases of SCRM. The tabulated list of models containing the description of its application will be useful to managers for identifying the most appropriate method for risk assessment and modelling. In addition to this, the table also depicts the scope for extending the models, thus enhancing industrial applicability.
- Methods applied in SCRM are classified according to the purpose it served, i.e., risk identification, risk assessment, risk modelling and risk mitigation.
- More significant gaps in the current literature are identified and discussed in detail including that of risk interrelationship study, Omni-channels, medium and small scale industrial applications, data analytics in SCRM, Impact of people's behaviour in SCRM, etc.
- A novice in SCRM research will be able to visualise the contributions that have been made by his/her predecessors more clearly.

Thus, these aspects make the present review paper quite significant to researchers and practitioners in SCRM.

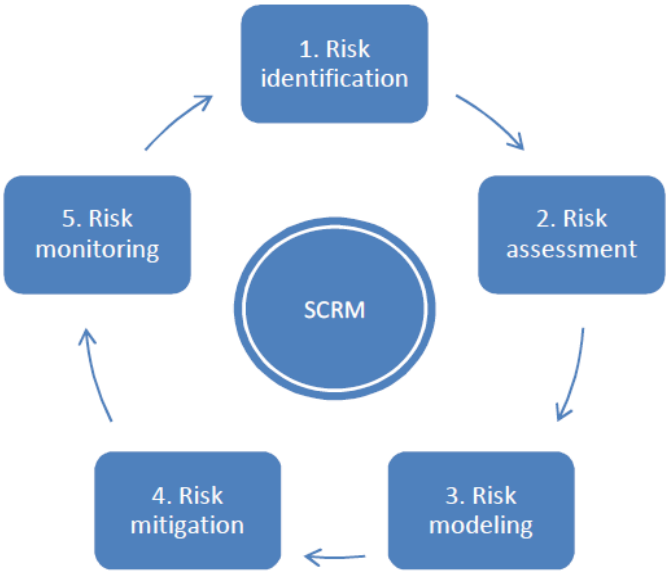
The rest of the paper is organised as follows: Section 2 discusses the definition of SCRM. Meta-analysis reports of research papers in SCRM are presented in Section 3. Section 4 deals with research articles that identify different supply chain risks. Section 5 describes various assessment methodologies followed by researchers and practitioners, while Section 6 enumerates different risk modelling techniques. Sections 7 and 8 illustrate various strategies to control and monitor supply chain risks. Gaps in the current

literature and directions for future research are discussed in Section 9 and finally, concluding remarks are provided in Section 10.

2 Supply chain risk management

Risk management philosophy is finding applications in different domains and contexts including project management, finance, occupational safety and in healthcare management. The definition and notion of the term 'risk' vary significantly across the above research domains. Interestingly, unlike other domains, uncertainty is also considered as a major sub-component of risks in SCRM (Norrman and Jansson, 2004). In SCM, risks can be defined as any factors that result in interruptions in the flow of materials, information and funds in a supply chain that result in undesirable consequences and vulnerability. In fact, vulnerability is termed as points of weakness prevailing in supply chains or the susceptibility of the supply chain to the likelihood and consequences of severe interruptions (Christopher and Peck, 2004; Svensson, 2000). These interruptions can be due to disruptive events such as natural disasters, breakdown of supply chain components, delays or even uncertainty pertaining to supply chain operations. These risks create a mismatch between supply and demand, affect the supply chain functioning, efficiency and output, or create situations leading to company closure.

Figure 1 SCRM process (see online version for colours)



SCRM is a branch of study in SCM for efficiently managing disruptions and uncertainty in supply chain operations. More precisely, SCRM is to work collaboratively with partners in a supply chain or independently apply risk management process tools to deal

with risks and uncertainties caused by or impacting on logistics related activities or resources in the supply chain (Brindley, 2004). Thus, SCRM determines the capability of a supply chain to synchronise supply and demand. It is a multi-step process consisting of identifying the potential sources of risks, defining the risk concept, identification of risk drivers and finally mitigating the risk (Jüttner et al., 2003; Manuj and Mentzer, 2008) as illustrated in Figure 1 and Table 1.

Table 1 Steps followed in SCRM

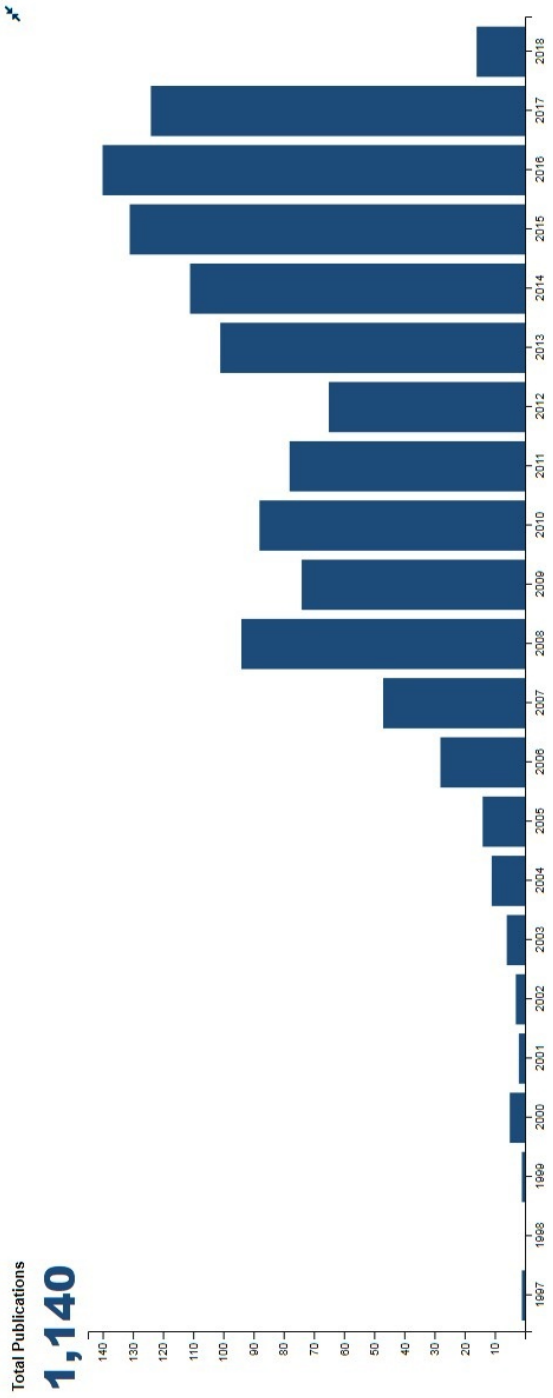
Steps	*Description*	*Major references*
Risk identification and classification	Identifying various risk sources and classifying according to its severity	Jüttner et al. (2003) and Rangel et al. (2015)
Risk assessment	Measuring the magnitude of various risks quantitatively either using historical data or by expert survey	Sudeep and Srikanta (2014), Pujawan and Geraldin (2009) and Samvedi et al. (2013)
Risk modelling	Modelling optimisation mathematical models. Will become useful in framing mitigation strategy.	Kim et al. (2015), Klimov and Merkuryev (2008) and Aqlan and Lam (2015)
Risk management	Framing robust strategies to mitigate risk.	Tang (2006b)
Risk monitoring	Continuous monitoring and updation of strategies	Hallikas et al. (2004)

This state-of-the-art literature review paper studies and classifies significant works in the area of SCRM into five classes based on the above macro-process involved in SCRM. The research papers that identify potential supply chain risk factors form the first class, succeeded by sections on risk assessment, risk modelling, risk mitigation and monitoring respectively. Before proceeding to this classification, a meta-analysis is carried out using the data from web of science (WoS) to study the present direction of research in SCRM and to shortlist the research papers that propose different tools and techniques in SCRM. The procedure followed for the meta-analysis is discussed in the succeeding section.

3 Meta-analysis of research papers in SCRM

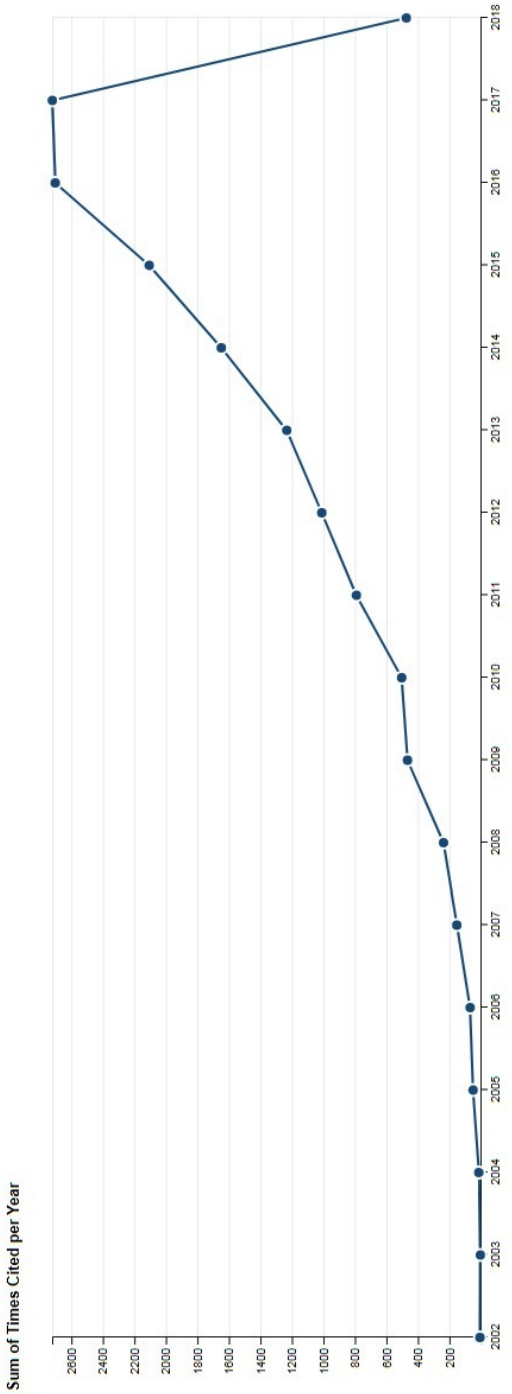
There have been tremendous excitements all over the world to understand and manage supply chain risks better. This enthusiasm has been motivating a large number of researchers to pursue various studies related to SCRM. As a result, SCRM research is slowly approaching a saturation level with a large body of research articles. For example, WoS database (after proper refining) suggests 1,140 research articles directly connected with the keyword ‘supply chain risk’ as on March 2018. The collection includes 556 journal articles, 565 conference proceedings, 22 reviews, six editorial materials, etc. The year wise distribution of papers is illustrated in Figure 2.

Figure 2 Year wise distribution of research papers in the SCRM domain (see online version for colours)



Source: Web of Science

Figure 3 Citations achieved by the research papers in the SCRM domain (see online version for colours)



Source: Web of Science

This massive volume of articles makes it difficult to provide a simple narration and critical review of each research article. To overcome this common issue in conducting a literature review, Glass et al. (1981) introduced a new approach known as meta-analysis. Meta-analysis is a methodology used to integrate research findings from a large body of articles using statistical analysis and sophisticated measurement techniques (Krishnaswamy et al., 2007). Bhosale and Kant (2016) utilised this methodology in the area of knowledge management in supply chains very effectively, and this research methodology is taken as the primary reference to carry out the analysis of the literature in the present paper. To accomplish the objective of this review paper, statistical techniques are employed to the data retrieved from a pool of research papers extracted by data mining using BibExcel software tool (Persson et al., 2009).

To identify potential research papers and journals that had published articles in SCRM areas, we utilised the keyword 'supply chain risk' to search the database of major research publishers such as Elsevier, Taylor and Francis, Emerald, Springer, Wiley, Inderscience and IEEE Explore. These publishers were selected due to their wide coverage of industrial, management and engineering journals. The number of papers appeared in these databases suggests that in the last few years, SCRM and supply chain agility have started attracting major attention from academia. WoS core collection database reports an exponential increase in the number of citations achieved by research papers which used the keyword 'supply chain risk' (Figure 3). As per the latest statistics, papers authored by Tang (2006a) and Kleindorfer and Saad (2005) are the most cited research papers in SCRM with citations from all databases counting 679 and 593 respectively as on March 2018, followed by Christopher (2000), Chopra and Sodhi (2004) and Tomlin (2006) (Source: WoS).

Meta-analysis of papers was carried along with systematic literature review procedure to;

- know the sub-themes related with SCRM research
- obtain the first-hand data for the selection of final papers for descriptive review.

A software tool called BibExcel is employed to carry out the statistical analysis on the citation and bibliographical information of textual nature such as the title of the paper, author, source, keywords, cited references, etc. This free software tool also allows modifying and adjusting data that can be imported from various databases including Scopus and WoS (Fahimnia et al., 2015).

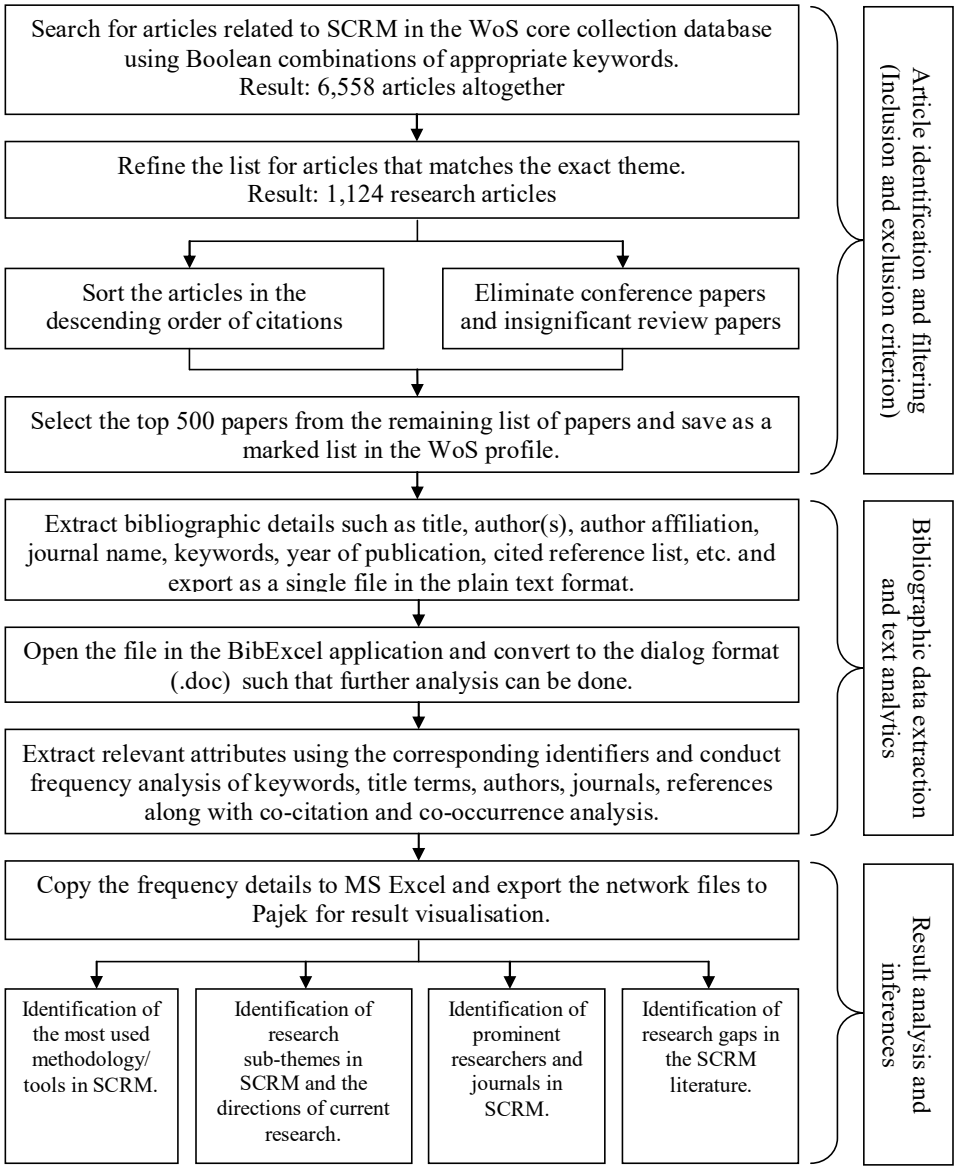
3.1 Meta-analysis procedure

The systematic literature review methodology followed in the present research consists of three broader stages namely;

- article identification and filtering
- bibliographic data extraction followed by text analytics using BibExcel
- analysis of results and deriving inferences

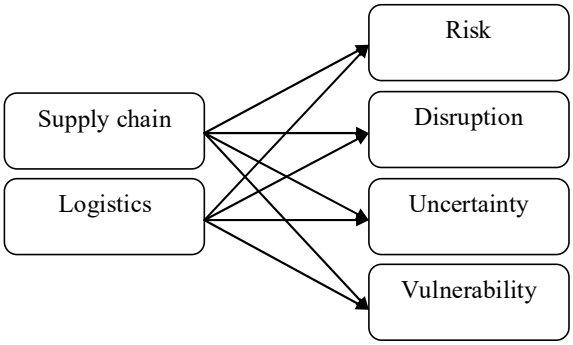
Each stage constitutes activities performed sequentially to fulfil the objectives of the individual phase. Altogether, the procedure involves 12 interconnected activities summarised as a flowchart in Figure 4.

Figure 4 Systematic literature review procedure



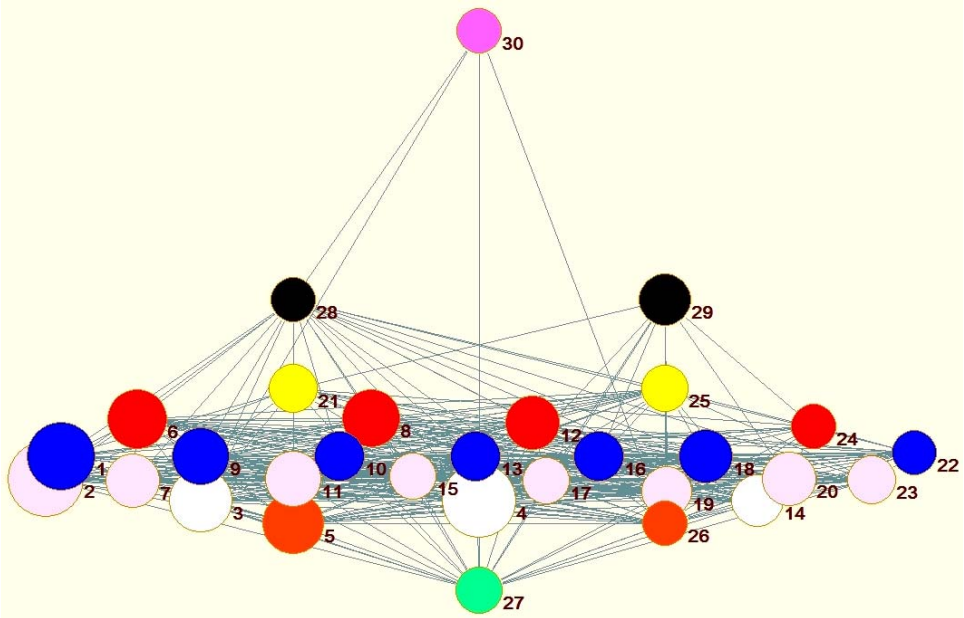
Initially, technical alternates to the keyword 'supply chain risk' are identified to be used as the search parameter in WoS core collection database. Figure 5 shows the combination of terms that build up the meaningful keywords utilised to search for potential research articles in SCRM domain. In total, we utilised eight keywords combined with the Boolean operator 'OR' to filter relevant papers in a single search process.

Figure 5 Keyword combinations for paper identification



The results were filtered for journal articles by excluding insignificant conference proceedings, review articles, and book chapters. The resulting list is sorted by citations achieved by the corresponding article. These activities are carried using the tools available in WoS platform. A WoS outfile is created in plain text format that contains relevant information of top-cited 500 research papers in SCRM domain, to be used as input for BibExcel. Keyword frequency analysis, co-citation analysis, and co-occurrence analysis have been carried out to study the present research direction of SCRM using BibExcel. Co-occurrence denotes the presence, frequency, and proximity of similar keywords across various research papers. Co-occurrence logically includes keywords that are topically relevant, but not exactly the same. In the present research, the keyword co-occurrence analysis is conducted to identify the aspects in SCRM already explored.

Figure 6 Co-citation analysis report (see online version for colours)



Co-citation occurs between two research papers when a third research paper cites both these papers. In co-cited papers, there is a strong content-driven connection between two documents due to their mutual appearance in a third research paper and not because of any actual links between the documents. In short, co-citation refers to the process of link building without real links.

The Bibexel co-citation and co-occurrence output file in '.net' format is exported to another data visualisation software tool called Pajek to plot the network diagram (Figure 6, Table 2 and Figure 7).

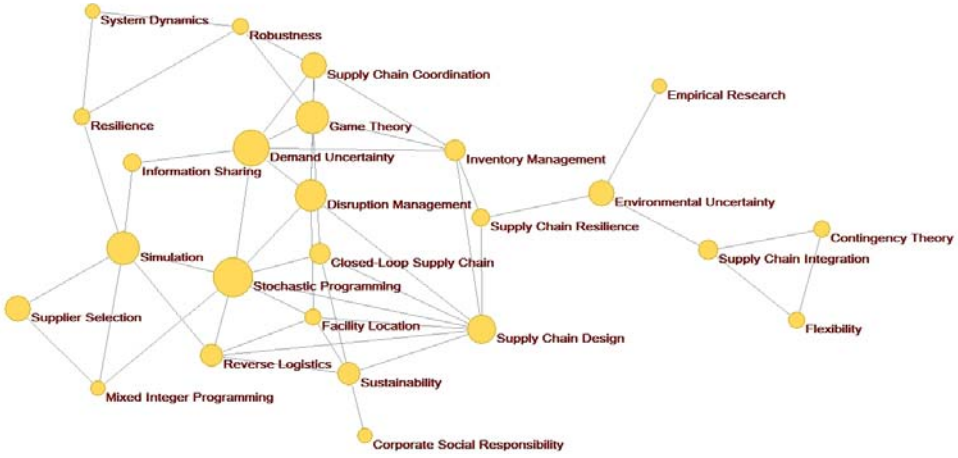
Table 2 Co-cited paper details

Label no.	*Authors (year)*	*Journal/books*	*Theme*
1	Chopra and Sodhi (2004)	*MIT Sloan Management Review*	Risk management
2	Kleindorfer and Saad (2005)	*Production and Operations Management*	Disruption risk management
3	Tomlin (2006)	*Management Science*	Risk mitigation and contingency strategies
4	Tang (2006a)	*International Journal of Production Economics*	Supply chain risk management
5	Craighead et al. (2007)	*Decision Sciences*	Design characteristics and disruption mitigation capabilities of supply chains
6	Harland et al. (2003)	*Journal of Purchasing and Supply Management*	Risk in supply networks
7	Jüttner (2005)	*The International Journal of Logistics Management*	SCRM in practitioner perspective
8	Jüttner et al. (2003)	*Int. J. of Logistics: Research and Applications*	Framework for future research in SCRM
9	Norrman and Jansson (2004)	*Int. J. of Physical Distribution & Logistics Management*	Case study on Ericson company
10	Hallikas et al. (2004)	*International Journal of Production Economics*	Risk management processes
11	Hendricks and Singhal (2005a)	*Production and Operations Management*	Relation between supply chain risks and stock price performance
12	Hendricks and Singhal (2003)	*Journal of Operations Management*	Relation between supply chain risks and share holder wealth
13	Christopher and Peck (2004)	*The International Journal of Logistics Management*	Supply chain resilience
14	Tang (2006b)	*Int. J. of Logistics: Research and Applications*	Strategies for mitigating disruptions
15	Sheffi (2005a)	*MIT Sloan Management Review*	Supply chain resilience
16	Zsidisin et al. (2004)	*Int. J. of Physical Distribution & Logistics Management*	Supply risk assessment techniques
17	Sheffi (2005b)	*MIT Press Books*	Supply chain resilience

Table 2 Co-cited paper details (continued)

Label no.	*Authors (year)*	*Journal/books*	*Theme*
18	Christopher and Lee (2004)	*Int. J. of Physical Distribution & Logistics Management*	Risk mitigation
19	Blackhurst et al. (2005)	*International Journal of Production Research*	Research issues for managing supply-chain disruptions
20	Santoso et al. (2005)	*European Journal of Operational Research*	Supply chain network design under uncertainty
21	Tsiakis et al. (2001)	*Industrial & Engineering Chemistry Research*	Supply chain network design under demand uncertainty
22	Spekman and Davis (2004)	*Int. J. of Physical Distribution & Logistics Management*	Risk management in extended enterprise
23	Hendricks and Singhal (2005b)	*Management Science*	Risks and operating performance.
24	Gupta and Maranas (2003)	*Computers & Chemical Engineering*	Managing demand uncertainty
25	Sheffi (2001)	*The International Journal of Logistics Management*	SCRM due to international terrorism
26	Goh et al. (2007)	*European Journal of Operational Research*	Stochastic model for risk management
27	Klibi et al. (2010)	*European Journal of Operational Research*	Review on designing robust supply chain
28	Lee et al. (1997)	*Management Science*	Role of information in minimising bullwhip effect
29	Birge and Louveaux (1997)	*Springer Science and Business Media LLC*	Book on stochastic programming
30	Pasternack (1985)	*Marketing Science*	Perishable supply chain

Figure 7 Keyword co-occurrence report (see online version for colours)



Different colours in Figure 6 indicate the year of publication. Accordingly, the articles are arranged in the chronological sequence in the vertical direction. The difference in the size of the node is an indication of the frequency of citation achieved by the article. The details of the corresponding top 30 cited articles are listed in Table 2. The keyword frequency output file is exported to MS Excel to plot the frequency plot of keywords appeared in this database after removing apparent keywords such as 'supply chain', 'risk', etc. Furthermore, a linguistic morphological analysis is conducted for adequately combining words with same morphemes before plotting the frequency diagrams. Titles of the papers and frequency of journals are also analysed in a similar fashion to find out the most recurring items. The output of the analysis is exported to MS Excel to obtain the frequency chart of different elements. The sub-themes of SCRM research are identified based on the results of the title term frequency analysis and the keyword frequency analysis.

3.2 Inferences from meta-analysis

The theoretical foundation of SCRM was laid in the early 21st century by eminent academicians located principally in the Europe and North American region. The co-occurrence, co-citation analysis, and author frequency analysis reveal other significant researchers in SCRM besides researchers such as Tang (2006a) and Kleindorfer and Saad (2005). Accordingly, the major contributions to SCRM knowledge base was also provided by researchers such as Martin Christopher, Uta Juttner, Yossi Sheffi, Jukka M. Hallikas, Jennifer Blackhurst, Kevin B. Hendricks, Mark Goh, Sunil Chopra, Manmohan S. Sodhi, George A. Zsidisin, Christopher W. Craighead, M. K. Tiwari, Ila Manuj, John T. Mentzer, Tadeusz Sawik, Srinivas Talluri, Ravi Shankar, Tiaojun Xiao, etc. The co-cited articles described in Table 2 are the papers that can be considered as the theory building articles in the domain of SCRM.

The keyword frequency analysis (Figure 8) and co-occurrence (Figure 7) analysis suggest that stochastic programming is the most used tool for modelling supply chains exposed to uncertainties. Game theory, simulation and system dynamics are the other prominent methodologies utilised by researchers for investigating risk management aspects such as coordination, supplier selection, and resilience/robustness respectively. It is also noted that supplier risk or the inbound risk is the most researched area in SCRM. Network design, integration, information sharing, inventory management and facility location are the other supply chain aspects extensively studied in risk mitigation perspective. The frequency analysis of title terms (Figure 9) discloses the research sub-themes in risk management that focus on different strategic capabilities of a supply chain which facilitates it to contain the negative consequences of risky events.

These research sub-themes include the following:

- Agility/adaptability/responsiveness: ability of a supply chain to quickly adapt to disruptions in the operations and fluctuations in the market (Lee, 2004).
- Reliability: in supply chain context, reliability is the probability that a supply chain function will perform its intended purpose for a specified period under stated standard conditions. The reliability of a supply chain function can be measured for performance in different dimensions, i.e., lead time, quantity, quality, cost and proportion of order met.

- Flexibility is the amount of variation (in terms of demand, supply) that a supply chain can tolerate without compromising other performance measures. The less flexible an organisation in the chain is, the more lead-time variability it will display in meeting the orders (Chopra et al., 2011; Vickery et al., 1999). Slack (1987) defined range and response as two spectra of flexibility. Range refers to the number of states the system can achieve, whereas, response indicates the cost and time associated with transitioning between the states. In addition to this, Upton (1994) incorporated uniformity as the third dimension that defines the ability to deliver consistent performance throughout the range.

- Resilience: ability of a system to return to normal/desired conditions quickly after a disruptive event (Sheffi and Rice, 2005).

- Robustness: ability of a system to continue the operations in the presence of internal and external disruptive events without compromising fundamental performance attributes of the original system (Sawik, 2014).

Figure 8 Frequency of appearance of keywords in top-cited papers in SCRM (see online version for colours)

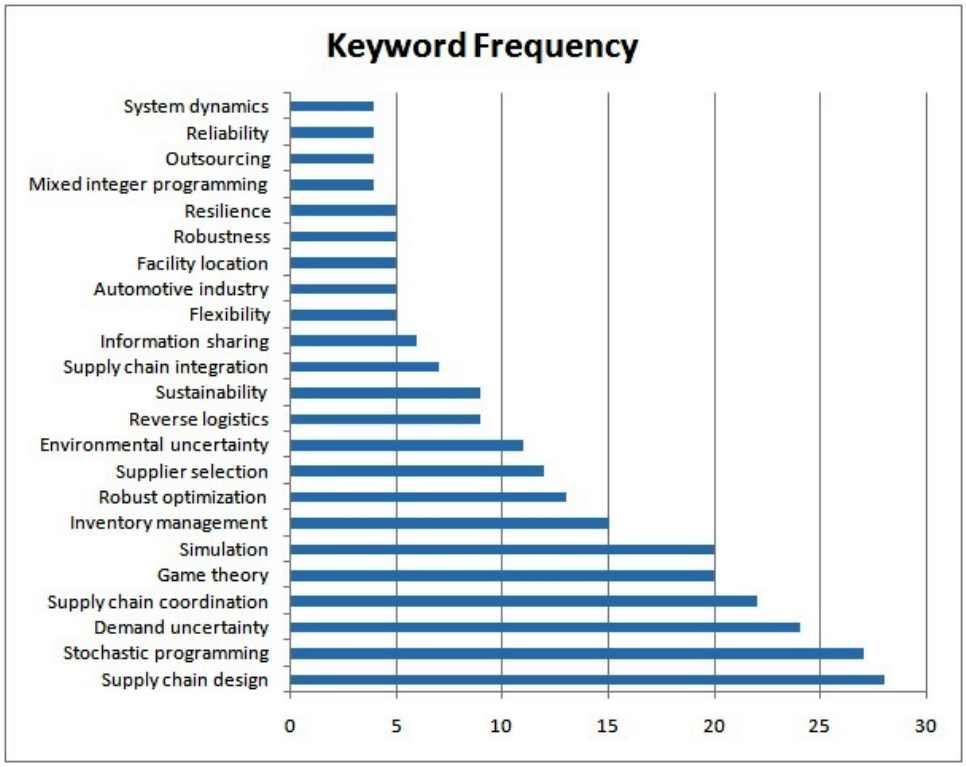
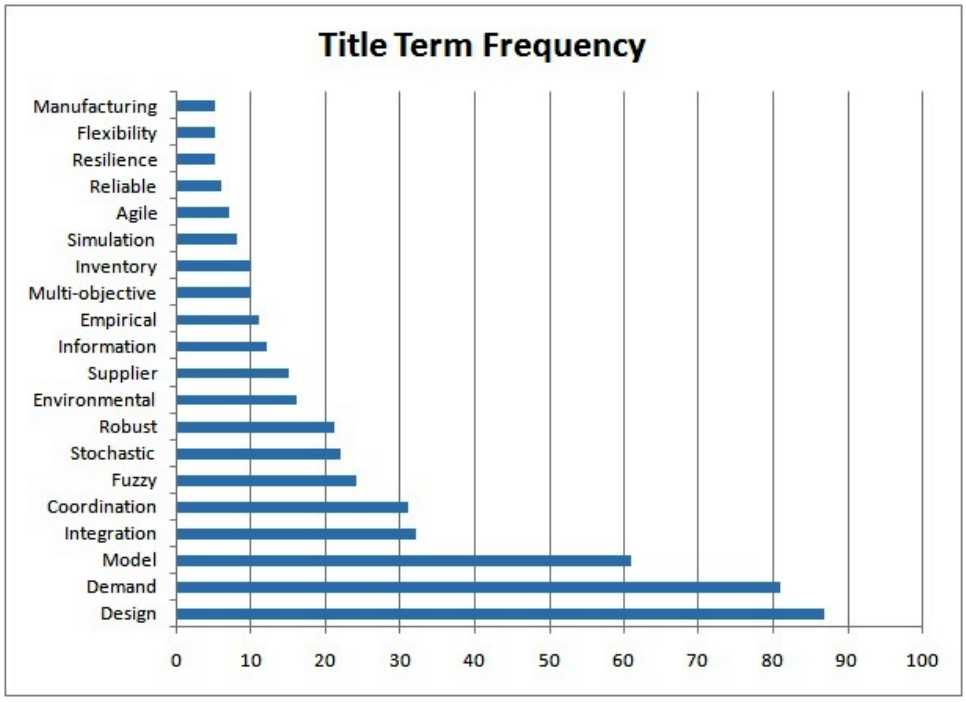


Figure 9 Frequency of appearance of title terms in SCRM (see online version for colours)



Even the definition and the concept of these capabilities were also found to be varying from article to article. Among these definitions and concepts, the most accepted definitions are the ones illustrated in the above sub-themes. It is interesting to note that all the above sub-themes assist the supply chain to restrain different risk factors in different ways. Moreover, most of the research work focused only on a single capability at a time. Table 3 shows the number of research articles indexed in WoS core collection that dealt with the above strategic capabilities as on March 2018.

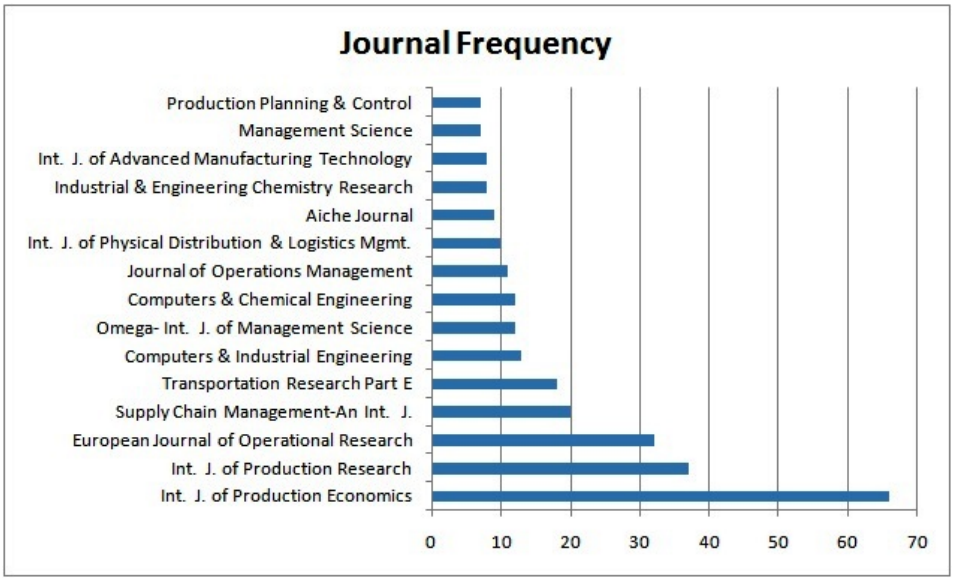
Table 3 Frequency distribution of research papers in SCRM sub-themes

Sl. no	*Sub-theme*	*Journal articles*	*Conference proceedings*	*Reviews*	*Total*
1	Flexibility	104	82	7	193
2	Resilience	82	45	6	133
3	Agility	72	38	4	114
4	Reliability	41	52	0	93
5	Robustness	16	8	1	25

Source: Web of Science

The frequencies suggest that supply chain flexibility is the most researched sub-theme in SCRM, followed by resilience and agility. Since the number of research papers on supply chain robustness is comparatively low, future research can be focused in this direction. Finally, essential sources of top quality articles in SCRM can be identified from the journal frequency analysis depicted in Figure 10.

Figure 10 Frequency analyses of journals (see online version for colours)



This information will benefit researchers working in the area to continuously monitor the imminent risk related articles in those journals to continuously update themselves with the advancements of global research. In addition, the researchers may select one or more focal premise of SCRM such as risk identification, assessment, modelling, mitigation or even monitoring for their research as described in the succeeding sections.

4 Supply chain risk identification and classification

The process of SCRM starts by identifying and classifying various sources of risk or risk drivers in a supply chain. March and Shapira (1987) define supply chain risk as the variation in the distribution of possible supply chain outcomes, their likelihood, and their subjective values, while supply chain vulnerability can be defined as exposure to serious disturbance arising from risks within the supply chain. Vulnerability is therefore seen as a combination of a disturbance and the resulting negative consequence.

According to Jüttner et al. (2003), the sources of risk are environmental, organisational or supply chain related variables that have the potential to compromise supply chain performance factors. Furthermore, these risk factors cannot be predicted with certainty. They classify risk sources into three major categories such as environmental risks, network related risks and organisational risks. These categories of risks includes

- political risk
- market risk
- economic risk
- customer risk

- supplier risk
- environmental risk
- human/labour risk (Zsidisin and Ellram, 2003; Wagner and Bode, 2008; Sydow and Frenkel, 2013).

Rao and Goldsby (2009) identify factors pertaining to supply chain risks as environmental factors, industry factors, organisational factors, problem-specific factors and decision-maker related factors.

Apart from the above, classifications based on the level of decision making in a supply chain or the level of risk mitigation strategy are also meaningful. Viewing from this point, supply chain risks can be classified into

- operational level risk
- tactical level risk
- strategic level risk.

This classification will enable the decision makers to visualise the impact of various risks more precisely and thus to frame mitigation strategies more effectively.

If we now turn to the methodologies adopted, Chaudhuri et al. (2016) and Rangel et al. (2015) conducted a literature survey to identify various supply chain risk drivers. Rangel et al. (2015) proposed 56 risk types under 16 levels. These risk types were sorted according to existing conceptual similarities and then related to the five management processes intrinsic in a functional supply chain (i.e., plan, source, make, deliver and return), which are mainly advocated by the supply chain operations reference model. On the other hand, Chaudhuri et al. (2016) identified risk drivers such as perishability, product traceability, etc. that are predominant in the food industry. Furthermore, Adhitya et al. (2009) adopted a HAZard and OPerability (HAZOP) analysis for risk identification. To perform HAZOP analysis, they developed a supply chain flow diagram analogous to process flow diagram that depicts all the elements in the supply chain and their interactions in the form of material and information flows pictorially.

Supply chain disruption is one of the major forms of supply chain risk. Shah (2009) identifies six major sources of supply chain disruption as follows:

- natural calamities like tsunami, flood, etc
- manmade issues like strikes, riots, terrorism, etc., (Sheffi, 2001)
- failure of machine/equipment or other technical failures/shutdowns
- disruptions within the suppliers of raw materials
- reduction in inventories, shorter clock speeds
- limited supplier base resulting from just-in-time and lean practices leading to more opportunities for disruption.

These disruptions cause failures in different modes such as

- disruption in supply
- disruption in transport
- disruption in facilities

- freight breaches like delay in customs clearance or other law enforcement
- disruption in communication
- disruption in demand.

Table 4 provides the consolidated supply chain risk drivers and the appropriate level of decision making required for mitigation.

Table 4 Types of supply chain risk drivers

Sl. no.	*Supply chain risk*	*Type of risk*	*Level of decision making required*
1	Production halt due to machine/equipment failure	Disruption risk	Strategic level
2	Power failure	Disruption risk	Strategic level
3	Communication/information system failure/internet failure	Disruption risk	Strategic level
4	Logistics failure	Disruption risk	Strategic level
5	Inventory management failures	Disruption risk	Strategic level
6	Capacity mismatching with demand	Disruption risk	Strategic level
7	Quality mismatch with demand	Disruption risk	Strategic level
8	Natural calamities	Disruption risk	Operational level
9	Plant safety failures/accidents	Disruption risk	Strategic level
10	Labour strikes	Disruption risk	Operational level
11	Terrorism	Disruption risk	Operational level
12	Climatic conditions	Disruption risk	Operational level
13	Freight breaches like delay in customs clearance	Disruption risk	Tactical level
14	Public strikes	Disruption risk	Operational level
15	Cyber security breach	Disruption risk	Tactical level
16	Supplier delays	Supply uncertainty	Tactical level
17	Raw material shortage	Supply uncertainty	Tactical level
18	Supply quality	Supply uncertainty	Tactical level
19	Supplier relationship	Supply uncertainty	Strategic level
20	Outbound delays	Demand uncertainty	Strategic level
21	Inertia: lack of company response to market changes	Demand uncertainty	Strategic level
22	Demand fluctuation	Demand uncertainty	Tactical level
23	Consumer price index changes	Demand uncertainty	Tactical level
24	Outbound firm relationship	Demand uncertainty	Strategic level
25	Forecast errors	Planning challenge	Tactical level
26	Technology change	Planning challenge	Strategic level
27	Lack of innovation	Planning challenge	Strategic level
28	Globalisation/elevated competition	Planning challenge	Tactical level
29	Economic crisis	Planning challenge	Tactical level

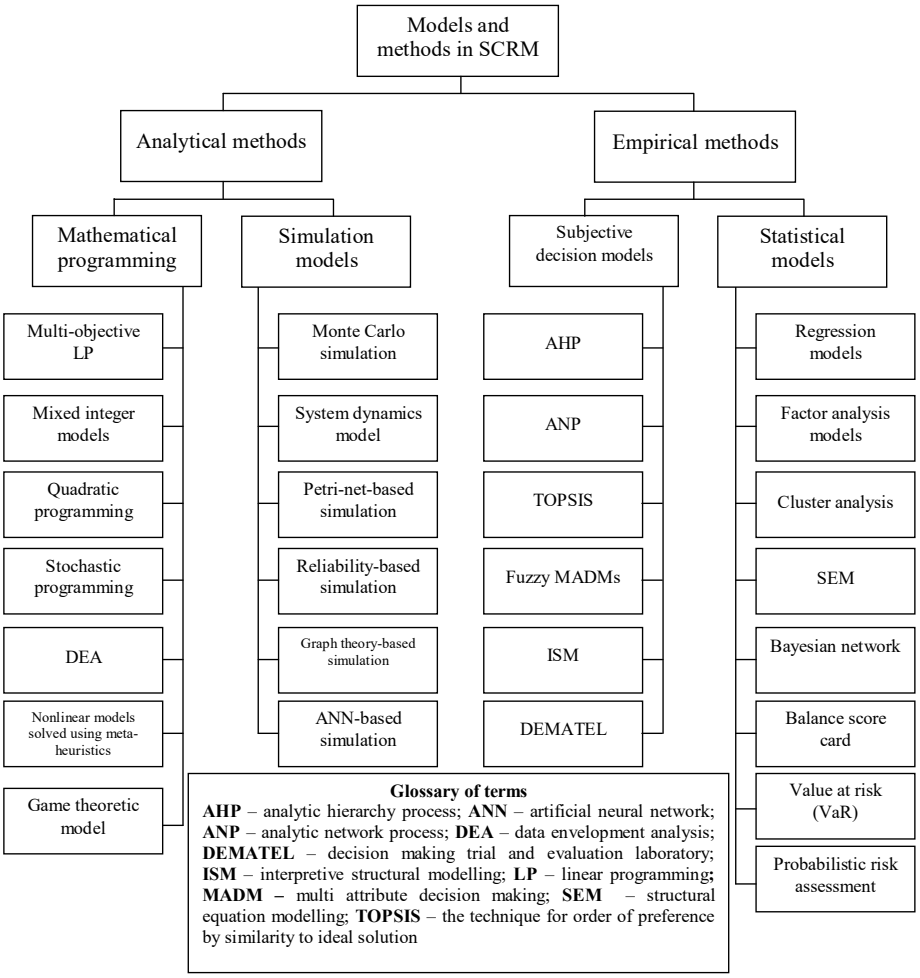
Table 4 Types of supply chain risk drivers (continued)

Sl. no.	*Supply chain risk*	*Type of risk*	*Level of decision making required*
30	Mistrust between firms in the supply chain	Planning challenge	Strategic level
31	Community mistrusts/misbelieves	Planning challenge	Strategic level
32	Product/raw material characteristics (i.e., perishables, hazardous, brittleness, etc.)	Planning challenge	Strategic level
33	Product traceability	Planning challenge	Strategic level
34	Employee attitudinal issues	Planning challenge	Tactical level
35	Supply chain strategies (i.e., JIT, Omni-channels, etc.)	Planning challenge	Strategic level
36	Political uncertainty	Institutional risk	Tactical level
37	Corruption issues	Institutional risk	Tactical level
38	Delays in clearances of projects	Institutional risk	Tactical level
39	NGO's and social interest groups	Institutional risk	Tactical level
40	Regulatory risks (antidumping, taxes, etc.)	Institutional risk	Strategic level
41	Voluntary export/import restrictions	Institutional risk	Tactical level
42	Environmental regulations	Institutional risk	Tactical level
43	Centre-state policy contradictions	Institutional risk	Tactical level
44	Intellectual property infringements	Institutional risk	Strategic level
45	Instability in fuel price	Financial risk	Tactical level
46	Elevating labour charge	Financial risk	Tactical level
47	Foreign exchange rate policies	Financial risk	Tactical level
48	Tax rates	Financial risk	Tactical level
49	Interest rates	Financial risk	Tactical level
50	Credit risk	Financial risk	Tactical level
51	Asset impairment	Financial risk	Tactical level
52	Insurance security risk	Financial risk	Tactical level
53	Share market instability	Financial risk	Tactical level
54	Increasing inflation rate	Financial risk	Strategic level

5 Supply chain risk assessment

Turning now to the risk assessment stage, managers measure the magnitude of various risk quantitatively either by using historical data or by conducting an expert survey. Many researchers have employed a variety of tools and techniques for modelling and measuring supply chain risks as illustrated in Figure 11.

Figure 11 Models and methods in SCRM



Generally, the methodology employed in industry is based on three primary disciplines: probabilistic risk assessment using fault trees or failure mode and effect analysis (FMEA) (Sudeep and Srikanta, 2014; Käki et al., 2015); vulnerability assessment by an expert team constituted from all major departments of the organisation using any multi-attribute decision making tools; and decision analysis. Firstly, Kleindorfer and Saad (2005) introduced a framework for risk assessment by formulating a set of ten principles derived from the industrial risk management and supply chain literature. Secondly, Macdonald and Corsi (2013) conducted an intercompany survey among managers to identify and measure the impact of significant risks faced by the respective firms. Furthermore, Alvarez et al. (2011) and Dalziel (2011) propose an expert choice-based methodology for risk assessment in food industry prone to terrorism. Finally, Gualandris and Kalchschmidt (2015) developed a model of congruence based on empirical survey and hypothesis testing for the management of supply risk. The consolidated list of techniques in risk assessment is provided in Table 5.

Table 5 Supply chain risk assessment techniques

Risk assessment methodology	*Major references*	*Description*
Probabilistic risk assessment (PRA)	Käki et al. (2015)	A two step methodology based on PRA and simulation is proposed to analyse disruption risks in realistic sized random supply networks.
Failure mode and effect analysis (FMEA)	Sudeep and Srikanta (2014)	Collected historical data and employed (FMEA) for the assessment of supply chain risk and its various impacts.
	Pujawan and Geraldin (2009)	Adopted quality function deployment (QFD) technique along with FMEA to identify various risk sources.
Analytical hierarchy process (AHP)	Gaudenzi and Borghesi (2006), Wu et al. (2006) and Lee (2014)	Based on suggestions from the experts in the field of SCRM.
Fuzzy AHP and fuzzy TOPSIS	Samvedi et al. (2013), Radivojevića and Gajovićb (2014) and Mangla et al. (2015)	Based on suggestions from the experts in the field of SCRM.
Multi grade fuzzy approach	Vinodh and Prasanna (2011)	Identified five agile supply chain (ASC) enablers, 20 ASC criteria, and 86 ASC attributes.
Grey theory and modified TOPSIS	Hui-Min (2008)	Develops an evaluating index system from the standpoint of the core enterprise in fuzzy environment for supply chain overall risk assessment.

Even though there are many tools available as demonstrated in Table 5, the most preferred method in supply chain risk assessment is multi-criteria decision making employing tools such as analytical hierarchy process (AHP), analytic network process (ANP) and its variants. Chand et al. (2015) conducted a comparative study of multi-criteria decision making approaches like ANP and a multi-objective optimisation by ratio analysis (MOORA) technique to identify the most appropriate method. In addition, Hallikas et al. (2002) proposed two approaches: internal audit, and computer-aided cause and effect analysis as instruments for the assessment of risk.

6 Supply chain risk modelling

Beamon (1998) identifies and tabulates different models and methods employed in design and analysis of multi-echelon supply chains. This paper has enabled various researchers in the field to determine the best method for their study in supply chains. However, a comprehensive review paper that tabulates models and techniques used in SCRM are only a few. Furthermore, the review paper of Fahimnia et al. (2015) on quantitative models in supply chain risks classifies and tabulates various journals publishing articles in the area, without mentioning various models and methods adopted by the researchers. The present review paper is intended to fill this gap. Major articles in supply chain risk modelling are reviewed and tabulated in Table 6.

Table 6 Types of modelling methods employed in SCRM

Modelling methodology	*Researchers*	*Type of risk*		*Description*	*Scope for future research*	*Other works employing similar methods*
		Internal	*External*			
Multi objective programming	Aqlan and Lam (2015)	X	X	Propose a Bow-tie analysis-based hybrid optimisation model. Give consideration to risk correlation and root cause. Altogether ten types of risks are considered for analysis.	Assume that the mitigation strategies are independent from each other. Furthermore, They may affect other areas of the supply chain	Alborzi et al. (2011), Costantino et al. (2012) and Yu and Goh (2014)
Graph theory-based simulation	Kim et al. (2015)	X	X	Differentiate supply chain disruption at node/arc level and network level.	Equal probability of failure is assumed for every node and arc	Wagner and Neshat (2010)
Data envelopment analysis (DEA)-based Monte Carlo simulation	Olson and Wu (2011)	X	X	A risk-adjusted cost concept is proposed utilising tools such as DEA and Monte Carlo simulation.	Study supply chain risk for vendor selection and to frame outsourcing strategy	Izadi and Kimiagari (2014) and Vilko and Hallikas (2012)
Petri net-based simulation technique	Wu et al. (2007)	X	-	Disruption analysis network (DA_NET) modelling approach is proposed as an extension of Petri nets.	Study a single stage supply chain. Root cause of the risk and mitigation strategy not specified	Blackhurst et al. (2004) and Li and Yi (2014)
Discrete event system simulation based on reliability theory	Klimov and Merkuryev (2008)	X	X	Reliability theory-based simulation using ProModel. Also distinguish between uncertainty and risk.	A simple supply chain model is constructed. Simulation result is not validated	Lukinskiy et al. (2014) and Taghizadeh and Hafezi (2012)
Mixed integer programming (MIP) model	Claypool et al. (2014)	X	X	Consider the combined effect of risk to product development and the supply chain design in parallel to designing a new product.	Scope to consider more significant risk factors. The supplier selection decision already in the DFSC risk model could be modelled as well.	Wang et al. (2016), Vidal and Goetschalckx (2000), Claypool et al. (2015) and Khalifehzadeh et al. (2015)

Table 6 Types of modelling methods employed in SCRM (continued)

Modelling methodology	*Researchers*	*Type of risk*		*Description*	*Scope for future research*	*Other works employing similar methods*
		Internal	*External*			
System dynamics	Sidola et al. (2011)	X	-	Here four echelon supply chain is designed to investigate two different policy alternatives i.e., visible and conventional supply chains.	Information sharing is the only risk mitigation strategy studied.	Towill (1996) and Keilhacker and Minner (2017)
Stochastic programming	Sahay and Ierapetritou (2015)	X	-	A hybrid simulation-based optimisation framework that uses two-stage stochastic programming in a rolling horizon framework is proposed.	Different sources of uncertainty and flexibility can be considered instead of just demand uncertainty.	Baghalian et al. (2013), Goh et al. (2007) and Jabbarzadeh et al. (2018)
Integer quadratic programming model	Gaonkar and Viswanadham (2004)	X	X	A framework to classify supply chain risk management problems and approaches for the solution of these problems is proposed with two separate mathematical models.	Optimal partner selection is suggested as the one and only risk mitigation strategy.	Sheffi (2001)
Game-theoretic model	Yue and You (2014)	X	-	Interactions among the supply chain participants are captured through a single-leader-multiple-follower Stackelberg game under the generalised Nash equilibrium assumption.	Uncertainty between entities in the chain is the only risk factor captured in the model (non-cooperative supply chains).	Zamarripa et al. (2013), Chen and Xiao (2015), Song and Zhuang (2017), Wu et al. (2017) and Zhou et al. (2018)
Bayesian networks	Badurdeen et al. (2014)	X	X	This approach is capable of analysing the conditional relationships between risk events.	The work emphasises the need of generic, customisable software tool to apply the Bayesian approach for capturing risks.	Lockamy and McCormack (2012), Lockamy (2014), Abolghasemi et al. (2015) and Qazi et al. (2018)

Table 6 Types of modelling methods employed in SCRM (continued)

Modelling methodology	*Researchers*	*Type of risk*		*Description*	*Scope for future research*	*Other works employing similar methods*
		Internal	*External*			
Grey decision making trial and evaluation laboratory (DEMATEL)	Rajesh and Ravi (2015)	X	X	Depicts the cause and effect relationships among enablers of supply chain risk mitigation in the electronic supply chains.	Piloted contemplation among 15 enablers of supply chain risk mitigation. Additional enablers can be incorporated at the cost of complexity.	Ya-Feng and Qi-Hua (2009) and Rajesh and Ravi (2017)
Multi objective nonlinear programming model solved using genetic algorithm	Yildiz et al. (2015)	X	X	Total reliability of a network is quantified by using reliability indices and cost components to model the impact of upstream supply chain on the reliability of individual entities.	Reliability measure can be treated as probabilistic function instead of constant single value.	Neureuther and Kenyon (2008)
Balanced scoring card and back propagated neural networks	Qinghua et al. (2008)	X	-	An early-warning model for supply chain risk is constructed based on three evaluation criteria namely SC financial, SC internal business process and SC customer criteria's.	Risk mitigation measures are not proposed. Early warning criteria can be further expanded.	Xu et al. (2010) and Li et al. (2015)
BP neural networks	Wang and Huang (2009)	X	-	The BP neural network is utilised to avoid subjectivity factors in the risk assessment process.	Limitations in the sample size and the difficulty in testifying the correctness of the sample	Zhao et al. (2007)
Interpretive structural modelling (ISM) along with MICMAC analysis.	Agarwal et al. (2007)	X	-	Interrelationships of the variables influencing agility of supply chains are derived.	Sector wise study can provide more accurate results than a sector independent study.	Diabat et al. (2012), Srivastava et al. (2015) and Chaudhuri et al. (2016)

Table 6 Types of modelling methods employed in SCRM (continued)

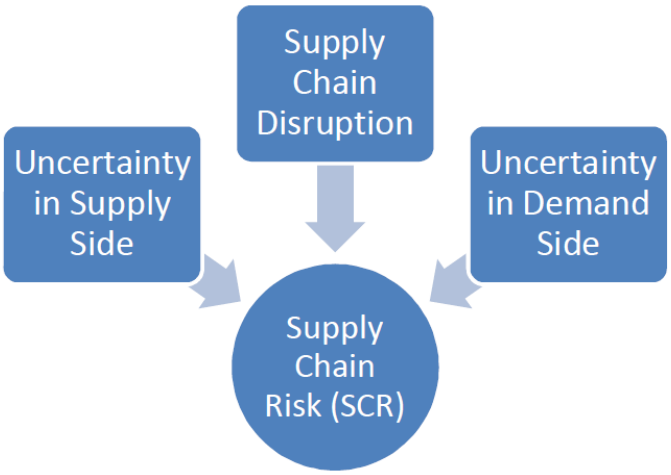
Modelling methodology	*Researchers*	*Type of risk*		*Description*	*Scope for future research*	*Other works employing similar methods*
		Internal	*External*			
Analytic network process (ANP)	Agarwal et al. (2006)	X	-	Investigates the dependence among service level, cost, quality, lead-time, the leanness and agility of a supply chain operating in FMCG sector	Variables like Inventory level, Product variety, customer loyalty, speed etc can also be considered.	Fazli et al. (2015), Fazli and Masoumi (2012) and Rokou and Kirytopoulos (2014)
Value at risk (*VaR*)	Lim et al. (2013)	X	X	Presents a practical method for SCRM using *VaR*, a technique to identify, assess and mitigate these disruption risks.	In case of insufficient data, Monte Carlo simulation can be used in computation of *VaRs*.	Zhang et al. (2013)
Structural equation modelling (SEM)	Braunscheidel and Suresh (2009)	X	X	Investigated the impact of three major organisational practices like flexibility, internal/external integration and two cultural antecedents that determines agility of a supply chain.	Interrelationship between supply chain risk factors can also be investigated.	Zhang et al. (2003), Sreedevi and Saranga (2017) and Truong and Hara (2018)
Cluster and factor analysis	Hallikas et al. (2005)	X	X	Investigates the relevance of collaborative risk management through a good supplier relationship.	Can investigates other risk mitigates strategies using same methodology.	No similar works identified
Vibrations analogy	Sharma and Lote (2013)	X	X	Study how supply chain disruptions causes demand volatility in onion supply chain.	Can be extended to other supply chains to investigate the relationship between disruptions and demand variability.	No similar works identified

It is evident from Table 6 that researchers working in the area of SCRM have employed a wide variety of tools such as mathematical modelling, simulation modelling and statistical modelling techniques for modelling supply chain risk. However, most of the papers propose conceptual models when compared to empirical models. This trend may be the reason behind the incapability of SCRM models that restrict the application of the models in a real industrial scenario.

7 Supply chain risk mitigation

Risk mitigation means controlling the effects of the three major components of supply chain risks, i.e., supply-side uncertainty, supply chain disruptions and demand-side uncertainty as depicted in Figure 12.

Figure 12 Supply chain risk components (see online version for colours)



In the risk mitigation phase, risk assessment and modelling results are analysed to frame appropriate strategies to either avoid or to mitigate the effects of each supply chain risk. This decision-making activity involves selection of the most appropriate strategy or choice from a group of alternatives based on some predetermined conditions. The proactive approach suggests that risk management activities should begin at the supply chain design stage itself (Tsiakis et al., 2001). This activity is acclaimed as a complicated task since there is no historical data available for risk assessment at the design stage of the supply chain. Therefore, firms usually can conduct a pilot study in risk management during the supply chain design phase to frame proactive strategies. These strategies should be monitored and improved along with the availability of data which comes up in the operation stage of a supply chain.

According to Diabat et al. (2012), some of the classic techniques of risk mitigation include the following:

- Prevention or lowering of risks through understanding.

- Controlling the impact of risk, so that even if an adverse event occurs, the impact is minimised.
- Mitigating risk by transferring it to another party i.e., by insurance, contracts, etc.
- Diversification of products.
- Risk pooling.

Practitioners in this field have pointed out many strategies that are proved successful. Tang (2006a) illustrates some robust strategies to mitigate supply chain disruptions with their success stories. Some of the commonly mentioned strategies are as follows:

- Physical backup or redundancies. Adopting this strategy will offer the firm sufficient freedom to withstand the failure of critical components. However, this practice violates the philosophy of lean methodology since increasing redundancy level increases the inventory level as well.
- Knowledge backup along with standardisation of process. For example, Salmon Smith Barney rolled back to their business after 12 hours of shutdown following World Trade Centre terrorist attack 11 September 2001, by following this strategy.
- Multi-location sourcing: adopting this strategy along with following modular product design approach, Nokia suffered less compared to its competitor Ericson when their main semiconductor supplier Philips's plant caught fire.
- Location of secondary source
- Pricing strategy: during Taiwan earthquake Dell computers faced a shortage of some components along with their competitor Apple computers. Dell substituted the parts with less expensive components and reduced their final product price and thus retained customers without letting them know about the shortage, while Apple failed to convince their customers to accept slower versions of G4 computers.

Other risk mitigation strategies are postponement (Cheng et al., 2010), insurance (Eggert and Hofmann, 2016), collaboration (Marqui et al., 2013), trust building, strategic stock, flexible supply base, make and buy, economic supply incentives, flexible transportation (multimodal), revenue management, dynamic assortment, silent product rollover (Tang, 2006b; Laeequddin et al., 2012; Manuj and Mentzer, 2008; Lee, 2014). Furthermore, supply chain risk due to natural disasters can be minimised by

- enhancing visibility of supply chain by identifying n-tier suppliers and determining interdependencies
- mapping key risk areas associated with n-tier supply chain
- engaging and sharing global best practices with suppliers
- preparing emergency preparedness plans for business continuity, etc. (Kohli, 2016; Normann and Jansson, 2004; Zsidisin et al., 2000).

In addition to the above strategies, society relationship management is necessary to avoid communal mistrusts in and around the supply chain facilities. This strategy can be executed by establishing public schools, hospitals, public transit systems, etc. Even

providing jobs to local people will enhance the image of the firm. Thus, mitigating the issues of community mistrusts to a more significant extent

Habermann et al. (2015) through an empirical study emphasise the importance of supplier location in designing a disruption-free supply chain. The authors found that supplier co-location is negatively associated with the duration of the disruption, which means that co-location is one of the keys to the resolution of disruptions. The authors also investigated supply chain disruption risk as it relates to differing supply chain design strategies namely

- The dispersion of supply chain partners and its relation to supply chain disruption risk.
- The co-location of supply chain partners and its relationship to supply chain disruption risk.

Emphasising on the methodology instrumented in risk mitigation strategy selection, Ellis et al. (2011) propose a conceptual unified decision-making framework in SCRM based on enactment theory. Additionally, Hult et al. (2010) offer a decision-making approach following real options theory. The study extends real options theory from a firm focus approach to the supply chain context and found evidence that several options operate differently for supply chain decisions than they do for individual firms involved in the supply chain. Finally, Chang et al. (2015) present a conceptual framework by building a basic rubric for selecting risk mitigation strategies. The paper classifies risk mitigation strategies into two broad categories namely, redundancy and flexibility, based on how each of the alternative approaches reduces uncertainty.

All the strategies mentioned above have a significant effect on risk reduction. On the contrary, the exact performance of each approach is difficult to analyse unless the firm or the expert has prior experience in implementing those risk mitigation strategies. Manuj et al. (2015) address this issue and investigate the effectiveness of different risk management approaches in a supply chain by examining how performance varies when these approaches are applied under different risk conditions. The study was based on systems design theory (SDT), and the research utilises a two-method approach. First, a conceptualisation of key SCRM opportunities is developed based on results of field-generated research to portray the relationships between the applications of different supply chain risk approaches under varying supply chain risk circumstances. Next, a simulation model is applied to investigate the relationship between overall net profit and the four approaches in risk management such as hedging, assuming, postponement, and speculation.

In addition to the above study, Talluri et al. (2013) compute the efficiency of risk mitigation strategies. This study combines an empirically grounded simulation methodology with data envelopment analysis and nonparametric statistical methods to analyse and rank alternative mitigation strategies. The authors found that strategies focusing on flexibility are more efficient compared to those on redundancy for supply chain failures. Alternatively, Rajesh et al. (2015) propose a combination of grey theory and digraph-matrix methodologies for quantifying various supply chain risk mitigation strategies. The study is based on 12 major supply chain risk categories and 21 risk mitigation strategies with a typical focus on electronics manufacturing supply chains. However, risk mitigation strategy is selected considering their relative importance and level of influence on other risk factors only. Thus, the above study can be further

elaborated by considering other important factors like cost of implementation, commitment requirements from other firms in the supply chain, change management, etc. Also, Talluri et al. (2013) considered only seven different risk mitigation strategies for managing all types of risk factors. This again motivates further research in this area.

Apart from the above, the criteria followed in mitigation strategy selection will differ from firm to firm or even person to person. The relative weight distribution of different selection attributes is a function of the firm's vision, mission, and objectives. The decision will also be affected by the operating environment, competition and many other critical factors and operating elements of SCM that effectively integrate partner-firms in a supply chain. Dath et al. (2009) has identified such elements in a developing economy environment like India that can be used as a reference. Generally, attributes that determine the selection of mitigation strategies are as follows:

- cost of implementation
- involvement of other firms in the strategy implementation process
- relevance of risk factor addressed by the strategy
- level of impact on the identified risk factor i.e., prevention, mitigation of effects, etc.
- level of impact on other risk factors (positive/negative)
- change management required for implementation
- level of improvement required after implementation
- benefits to other firms in the supply chain
- evidence of successful implementation of the strategy in other firms.

8 Supply chain risk monitoring

A regular risk monitoring practice should be adopted to make sure that the possible adverse impacts are controllable. Failure data analytics is considered the crucial activity in monitoring major supply chain risks quantitatively. In this method, each disruption event is recorded in the computer database with details like its occurring time, impact potential score, recovery time, etc. Using these data, reliability parameters are calculated so as to plot the failure/reliability curve of every activity in the chain. This plot will provide the first-hand idea regarding the health of the supply chain component.

It is interesting to note that research studies in risk monitoring practices are very few when compared with the volume of research papers in the other macro processes of SCRM, i.e., risk identification, assessment, and mitigation. Zhang et al. (2011) and Fang and Xiao (2014) proposed an early warning model for monitoring risk in supply chains. While Zhang et al. (2011) studied food supply chains, Fang and Xiao (2014) emphasised on a dual-channel cycle quality chain by following a multi-objective mathematical programming approach to design supply networks. These two papers are the only comprehensive research papers that addressed the requirement for risk monitoring in supply chains.

9 Areas for future research

Based on the analysis of the literature on SCRM, the following are found to be the most promising areas for future research.

9.1 Hybrid models

Every modelling tool/method has capabilities to address some issues and incapability with respect to some other parameters at the same time. These issues always induce some assumptions in the analysis that leads to shortcomings in the results and inferences made from the study that in turn compromises the applicability of the models. To overcome this drawback, nowadays researchers have started combining various methods in a meaningful manner to offset the incapability of a single method. Major examples being AHP-QFD clubbing done by Dai and Blackhurst (2012) in their study of supplier assessment whereas, Purvis et al. (2014) introduced a new approach by combining the concepts of lean and agility to frame leagile supply network taxonomy. This new practice will lead to more realistic solutions and can be adopted in SCRM domain as well.

9.2 Context specificity

Even though there are many quantitative models in SCRM, there is a significant gap between theory and practice, as most of the models fail to prove applicability in industry. The major reason behind this failure is their generalised framework that does not consider complexity pertaining to individual sectors in industry. Since the risk factors and their behaviour depends on the type of industry and even the geographical location (Rogers et al., 2015), it is more appreciated to build models for different individual sectors independently. The major scope of this context-specific study lies within healthcare and food supply chain as they are more critical sectors especially in developing and under-developed countries. For this purpose, empirical research studies are appreciated rather than a generalised approach or hypothetical models. This is due to the reason that empirical studies are more concerned with what is happening in industry whereas analytical models try to explain what should happen in an ideal industry.

The service quality perspectives presented by Padma et al. (2009) in healthcare, demand variation study of Sharma and Lote (2013) and risk propagation study of Chaudhuri et al. (2016), both in food supply chain can be used as benchmarks for the assessment of risks. They calculated risk as deviations in the quality attributes. In addition, dynamic urban supply chain network design model proposed by Friesz et al. (2011) can also be considered as a benchmark paper where uncertainty factor is quantitatively measured as variance in operations.

9.3 Reliability and flexibility

The firms that have configured their supply chain design and operations to handle high levels of demand uncertainty effectively are known as responsive supply chains, whereas firms that have configured their supply chain design and operations to effectively handle high levels of demand uncertainty along with disruptions are known as agile supply chains (ASC) (Shah, 2009). Therefore, to resolve the issue of supply chain risks, traditional supply chains should be updated to ASCs by improving reliability and

flexibility. However, robust methodologies to upgrade conventional supply chains to ASCs are comparatively found to be fewer. Along with reliability and flexibility, researchers have also identified responsiveness, competency, alignment, adaptability, interconnectivity, information sharing and quickness as the closely related performance parameters of ASCs (Christopher, 2000; Lee, 2002).

Taghizadeh and Hafezi (2012) and Lukinskiy et al. (2014) propose methods to evaluate supply chain reliability. However, these studies assume the reliability of a supply chain subsystem or component as static, rather than considering its stochastic nature. The mathematical model proposed by Yildiz et al. (2015) for the design of a reliable supply chain network design is another notable contribution in the domain. A compounding mechanism is presented in this paper to compute the reliability of the entire supply chain without considering the actual network configuration, i.e., series/parallel relationships of echelons. This assumption results in compromising the applicability and accuracy of the models in a real case. In addition, these models did not consider failure recovery time and cost of failure in the analysis. Furthermore, methodologies to improve the reliability of the supply chain system are also an area of future research. Methodologies like ARINC (designed by ARINC Research Corporation, a subsidiary of Aeronautical Radio, Inc) and Advisory Group on Reliability of Electronic Equipment (AGREE) methods for reliability improvements applicable in technical systems can be modified in this regard (Ebeling, 2011).

9.4 Risk interrelationships

The interrelationship between various supply chain risk factors has not received much attention in the studies, instead most of the papers assume risk factors to be independent. On the contrary, one can see that in the real world, many risk factors are interrelated. For example, the industrial scenario during the 2015 Chennai flood reveals how a single supply chain risk factor called natural calamity raises issues of various other supply chain risks. Major supply chain risk factors that arose as a result of Chennai floods were

- production halts
- power failures
- communication system failures
- logistics failures
- inventory management failures
- supplier delays
- outbound delays
- human resource unavailability's
- environmental regulation risk
- credit risk
- asset impairment
- insurance security risk

- share market depression
- inertia: lack of firms response to market changes (Vishnu and Sridharan, 2016).

In addition, there are many risk factors that prevent other risk factors from happening. Therefore, future studies in this area should also consider how one supply chain risk factor is related to other factors.

The study of interrelationships between various risks will assist the managers to cluster and classify risks based on various aspects such as the impact strength, the frequency of occurrence and cost of containing/mitigating risk. This process can again lead to the ranking of various risk factors based on their criticality. Furthermore, the information thus revealed can be utilized for prioritizing the execution of mitigation strategies and to frame the business continuity plans. Pfohl et al. (2011) and Pramod and Banwet (2010) are some of the notable contributions in this regard. Pfohl et al. (2011) studied the inter-relationships between 21 disruption risks in a supply chain, while Pramod and Banwet (2010) analysed 13 supply chain inhibitors in a service supply chain. Both these papers proposed distinct interpretive structural models that classify the risk factors into a hierarchical structure based on subjective/cognitive inputs. However, the results of the above studies cannot be generalised to industries around the globe were the significance of each risk factors varies. Furthermore, the statistical validation of the results based on a geographic specific study also promises a good research possibility.

9.5 Sustainable SCRM

Studies in sustainable supply chain management (SSCM) are attracting significant attention from both academia and industry since the last decade. Researchers are concentrating primarily on carbon emissions in different aspects of the supply chain with a prime focus on transportation-related emissions (Liao et al., 2009, 2011, Das and Jharkharia, 2018) and reverse supply chain design/analysis. However, researchers are still finding difficulties in proving the likelihood of long-term success of companies that follow sustainable practices. Giannakis and Papadopoulis (2015) argue the need for considering the future risks imposed by sustainable strategies in supply chains. This scenario advocates more research to concentrate on SSCRM, where risk analysis is unavoidable, to test the above hypothesis on long-term success. On the other hand, Rostamzadeh et al. (2018) argue for incorporating sustainability criteria in decisions related to risk management. They proposed a framework for SSCRM by deploying a hybrid TOPSIS and criteria importance through inter-criteria correlation (CRITIC) methodology. Hence, there exists a twofold research opportunity based on the primary objective set for investigation. First, to examine sustainable practices in the risk management perspective and second, to analyse the robustness of risk mitigation strategies from sustainability standpoint.

9.6 Service supply chain risk

Unlike manufacturing, supply chain risk factors and their behaviour in service supply chains are significantly different. Choi et al. (2016) provides the challenges in planning and exercising risk management activities in a service supply chain. In some service supply chains such as banks, insurance, telecommunication, etc. no physical entity or material flow is happening through the chain. In these systems, the types of flow involved

are information and money that are hard to visualise and measure when compared to materials flow in manufacturing supply chains. In addition, services produced are mostly intangible and perishable; these characteristics aggregate the complexity of risk analysis in service supply chains. Future research can be directed to these promising and unexplored areas.

9.7 Supply chain risk in small and medium scale industries

Most of the research papers in SCRM domain framed their models focusing mainly on multinationals and large supply chains. On the other hand, small and medium scale industries are also prone to supply chain risks where the scenario is different. Strategies that apply to an established large supply chain may not be appropriate for small and medium supply chains in their growing stage. For this purpose, risk mitigation strategies should align with the company vision and must consider the critical success factors of a small firm in the sector. This gap should also be addressed to build a minimum risk market environment that will be appreciated by start-up ventures, especially in a country like India where the government is motivating start-ups through different schemes. To identify the critical success factors of small enterprises, the case study conducted by Gunasekaran and Ngai (2003) on a third-party logistics company can be a roadmap in this direction.

9.8 Impact of people behaviour in supply chains

The impact of people behaviour in supply chain risk creation and mitigation efforts is another area where future research in SCRM can be directed. Nienhaus et al. (2006) have recognised the significance of human behavioural aspects acting as obstacles in supply chain operations. The human behavioural factors relevant in SCM include commitment, perception, honesty and trust. Panayides and Lun (2009) have highlighted the significance of trust in improving the innovativeness in supply chain that finally elevates the supply chain performance. As observed by Muduli et al. (2013), the continuously evolving and dynamic nature of human behaviour complicates the execution of conventional research methods in this area. To overcome these research issues, specialised techniques need to be borrowed from the fields of human psychology and physiology for applying in SCM research. Foreseeing these complexities, Tokar (2010) advocates the relevance of conducting controlled behavioural experiments in SCM. The researcher further presents two research frameworks for the identification and mitigation of behavioural issues in supply chain operations. Future research can employ these frameworks for analysing the positive impact of human behavioural aspects on mitigating risks. The work of Cantor et al. (2012) on human engagement and perception is a significant attempt in this direction.

9.9 Data analytics in risk mitigation

Researchers like Tsao (2017) and Niu and Zou (2017) disclose the capability of big data analytics to do wonders in mitigating risk drivers such as credit risk, forecast errors, and environmental risks. Despite these papers, there are only few research papers that focused on the application of big data in monitoring and mitigating risks. Moreover, research

papers on risk monitoring itself are very few when compared to the literature corresponding to the other macro processes in SCRM. To fill this gap, researchers in this field can think of designing a database system/module in connection with the enterprise resource planning (ERP) package implemented in the firms to monitor supply chain risks. Data mining from a similar database will enhance visibility that further assists the company's management in monitoring and predicting supply chain risks.

9.10 Omni-channels

Multiple channel retailing is often referred to as Omni-channel retailing where customers can shop across channels (i.e., online using desktop PC, mobile or even traditional offline stores), anywhere and at any time seamlessly and effortlessly (Beck and Rygl, 2015). The companies that follow Omni-channel philosophy value customer contacts and strive to preserve these contacts by improving their customer experience. This recently developed supply chain strategy has immense application potential in healthcare, government, retail, finance, telecommunication, etc. However, this strategy is still not validated to be effective in the risk management perspective. The basic philosophy underlying this strategy is to provide customers more opportunity and power to decide on the type of transaction required, quality and features of the product (i.e., personalisation), etc.

These aspects of Omni-channels lead to elevated supply chain risks in the form of demand and procedural uncertainties. Thus, SCRM study of Omni-channel strategy considering the existing infrastructure facilities of the supply chain is inevitable to identify possible vulnerabilities that may arise when traditional supply chains start following this strategy. If the SCRM study does not support the implementation of Omni-channel strategy with the current infrastructure, then firms can develop additional facilities to support the implementation of this strategy. For example, Barnes (2016) clearly identifies challenges (however, not in the risk management perspective) in employing Omni-channel strategy in the food and beverage industry. Also, Barnes (2016) emphasises on the innovation that will be required in packaging to ascertain the effective implementation of the Omni-channel strategy and the survival of the firm in the competitive market.

9.11 Influence of technological trends in risk reduction

The world around is evolving as a 'digital mesh' constituting human beings interacting continuously with information, apps, services, devices and other people. The technological advances in connectivity and automation have initiated the fourth industrial revolution termed as industry 4.0 (Strange and Zucchella, 2017). Some of the recent technological trends behind this evolution include artificial intelligence, augmented reality, industrial-internet-of-things (IIoT), blockchain technology, cloud computing, radio frequency identification systems (RFID), etc. These recent advances are now being widely utilised to automate and simplify various activities in supply chains transforming traditional supply chains into digital supply networks. For example, augmented reality techniques are applied in picking optimisation for warehouse management, facility planning and dynamic traffic support (considered as a successor of global positioning system), whereas IIoT and block chain technologies are enhancing visibility and transparency aspects of supply chains for elevating the efficiency.

On the contrary, researchers such as Wang et al. (2010) and Helbing (2013) disclose the vulnerabilities associated with these inter-connected information and communication technologies. They state that highly inter-connected systems result in excessive inter-dependence that fuels faster propagation of risks worldwide. This scenario even raises serious concerns over personal privacy and data security of citizens involved in the system. We have already witnessed such data breach cases and cyber security meltdowns around the globe influencing business, politics, among others. Subsequently, future studies can be directed to investigate both positive and negative influence of these technologies in managing supply chain risks. These studies can adopt either analytical or empirical methods for investigation.

10 Conclusions

Globalisation has brought companies closer, more dependent and interconnected resulting in faster propagation and amplification of supply chain risks around the globe. This market philosophy has brought new challenges in SCM, thereby elevating the relevancy of SCRM over the last few decades. More reports are emerging reflecting the vulnerability in supply chains resulting in the failure of supplies in critical areas like food, healthcare, etc. Accordingly, risk management needs to be radically modified considering the changing philosophies and practices followed in the industry. However, unlike the other domains of the supply chain such as vehicle routing, scheduling, inventory management, network design, etc. research papers in the area of risk management are comparatively less, but it is slowly approaching a saturation level with respect to the SCRM issues investigated. There are several challenging research areas in SCRM requiring modelling and analysis as highlighted in the preceding section. Consequently, many supply chain practitioners believe SCRM research is still in the infancy stage and state that SCRM is one of the promising research domains in the area of SCM.

Even though there are several review papers in SCRM, there are only a few studies that emphasised on the methods and tools employed in addressing supply chain risk. This literature review started with a systematic meta-analysis of research papers in SCRM and has presented the currently used methodologies to manage and model supply chain risks in an encapsulated form. This is the significant contribution of this review paper. It is evident from the study that most of the models in SCRM are conceptual in nature that restricts the applicability of the models in the real industrial scenarios. Hence, there is a demand for developing more industry-specific empirical models that meet the requirements of SCRM practitioners. In this review paper, after understanding the current research status in SCRM, an attempt has been made to suggest some unique and promising areas where future research can be directed. Accordingly, emphasis needs to be given to the interrelationships between various risk factors rather than assuming these as independent events. Furthermore, risk analysis is inevitable for validating the efficiency and effectiveness of recently evolved supply chain concepts such as sustainable supply chains, Omni-channels, block chain technologies, digital supply networks, etc.

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