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Optimization models for supply chains under risk, uncertainty, and resilience: A state-of-the-art review and future research directions

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ABSTRACT

The study of supply chain (SC) resilience as a research perspective is in an incipient state. Nevertheless, there is a tremendous amount of literature concerning SCs under risk and uncertainty. This paper presents a review of the quantitative models for SC resilience using bibliometric and network analyses. The study identified 3672 articles and provided statistical measurements of science, scientists, and scientific activities. Additionally, the analysis highlights the inter-temporal dimensions of decision making and classifies articles based on their usability in real-world applications. Systematic mapping using co-citation and the PageRank algorithm resulted in seven key research themes, and a microlevel analysis of these themes provides prospective research directions. This involved examining the contributions of individual articles with respect to their scope, value proposition, risk-type consideration, methodology and technique used, and their industry applications. The thematic analysis and extensive future research directions leverage the insights and potential of this review article.

1. Introduction

A supply chain (SC) is "a network used to deliver products and services from suppliers of raw materials to end customers through an integrated flow of information, material, and cash" (Blackstone, 2013, p. 171). Although this act of mutual collaboration brings profit to stakeholders, the SC is exposed to various risks. Common ones, as identified by Tang (2006), Chopra and Sodhi (2004), and Ivanov et al. (2019b), are disruptions, delays, forecast failures, inventory outages, and others. Of these risks, disruption risks have a low likelihood but a high impact on business operations. For example, a fire at a Toyota supplier facility in Japan in 1997 resulted in a loss of $195 million with an opportunity cost (lost sales) of $325 million, corresponding to 70,000 cars ((Converium, 2006). In 2011, Japan's Tohoku region experienced an earthquake of magnitude 9.0, followed by a tsunami, which led to a loss in the production of at least 2,00,000 cars for Toyota, approximately 50,000 for Nissan, and approximately 46,000 cars for Honda (Kim and Reynolds, 2011). In a recent example, COVID-19 disruption has affected the SC operations of approximately 94% of Fortune 1000 companies (Sherman, 2020).

In addition to disruption risks, SCs are exposed to frequent low-impact events, such as uncertainties in demand, supply, lead time, and cost rate (Torabi et al., 2015). These are not the only challenges in SCs, but events with low likelihood and low impact such as power damages and high probability and high impact, for example, quality issues, shape business performance. The literature on SC risk management has suggested measures to minimize the impact of such events (Rajagopal et al., 2017). However, traditional

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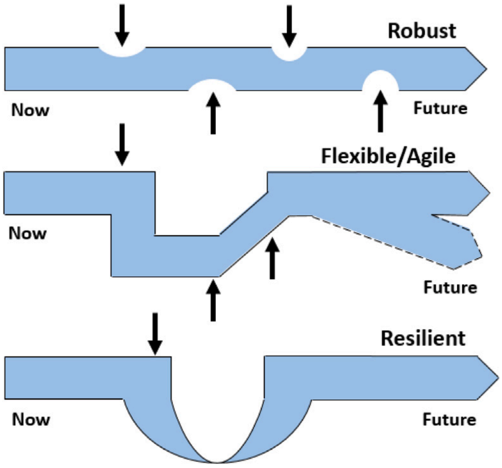

Fig. 1. Robustness, flexibility, agility, and resilience.
Source: Husdal (2009).

risk management approaches are built on hindsight understanding, failure reporting, and risk assessments that are developed based on probabilities calculated using past data. This limits the scope to deal with impacts rather than events (Hohenstein et al., 2015). Recently, practitioners have promoted strategies such as resilience to minimize the impact of such unprecedented events (BCI, 2017). Resilience provides the ability to recognize, adapt, and absorb variations, disturbances, disruptions, and surprises (Steen and Aven, 2011). In the SC context, supply chain resilience (SCR) refers to "the adaptive capability of the SC to prepare for unexpected events, respond to disruptions and recover from them by maintaining continuity of operations at the desired level of connectedness and control over the structure and functions" (Ponomarov and Holcomb, 2009, pp-131). The SC literature has perceived SCR as a proactive approach that uses a predefined set of procedures to protect against disruptions ((Klibi et al., 2010; Ponis and Koronis, 2012; Snyder et al., 2016). At the same time, SCR is promoted in terms of reactive strategies for rescuing SCs during unexpected events and maintaining balance (Knemeyer et al., 2009; Ponomarov and Holcomb, 2009; Ivanov et al., 2016a,b; Pettit et al., 2013).

A recent article in Forbes states that SCR has the capacity to improve the manufacturing throughput by 15%–25%, minimize the time required for product development by 40%–60%, and increase customer satisfaction by 20%–30% (Schatteman, 2020). Another industry-specific case analysis of transport and logistics firms implementing resilient culture guaranteed a 150% return to shareholders compared to their non-resilient counterparts (refer to Fig. 17 and Arora (2021)). The report lists some of the practical benefits of resiliently enabled models as follows: (1) they reduce the lead time, thereby improving agility, (2) they curb the impact of ripple effect, (3) they provide better signaling mechanisms for replenishing orders across SC echelons, (4) they can be used to optimally design SC networks, and (5) they ensure efficient inventory management. However, SCR as a tool for application and research has received attention lately and requires further discussion (Kamalahmadi and Parast, 2016; Ribeiro and Barbosa-Povoa, 2018; Ivanov et al., 2017; Hosseini et al., 2019a).

Moreover, resilience is not the only approach that has attracted practitioners. Robustness provides systems with the strength to fight against likely disturbances (Bundschuh et al., 2003). However, achieving only strength makes the system rigid. To minimize disruption impacts, the system also needs flexibility and agility. Flexibility offers a planned approach to deal with unanticipated events in a risky environment, whereas agility handles it in an unplanned manner (Husdal, 2009). According to Wieland and Wallenburg (2012), resilience involves both aspects, with robustness acting as a proactive and agility as a reactive dimension. The resilience strategies profoundly manage the veneer of normalcy in operations after a sudden disruption event over the other concepts of disruption management. This is illustrated in Fig. 1.

Keeping in view these benefits, this study is motivated to further understand resilience, particularly in SCs, and to that end, we perform a systematic literature review (SLR). SLR provides a more scientific, transparent, and reproducible platform for reviewing research topics (Tranfield et al., 2003). The study realized that previous reviews on risk, uncertainty, and resilience lacked a structured approach to the analyses (see, for example, Bhamra et al. (2011), Tukamuhabwa et al. (2015), Kamalahmadi and Parast (2016), Barbosa-Póvoa et al. (2018)). In contrast, this study offers a microscopic and macroscopic lens for reviewing the SC management literature to improve perception and interpretation of how SCs are designed and structured to manage risk, respond to uncertainty, minimize disruptions, and gain resilience. More information related to the fundamental terms involved in the study and the scope of the review is provided in Appendix A. We used formal modeling techniques and methodologies to analyze articles obtained from the Scopus database. Therefore, the review avoids papers involving in-depth interviews, laboratory experiments, quantitative surveys, and empirical case examples. The SLR process inspired us to address the following research questions:

- RQ1: How can the past literature be studied to provide a macroscopic view of SCR?

To answer this question, we inspected 3672 research articles and conducted a descriptive analysis. Such analysis quantifies the growth and productivity of research topics concerning scientists, institutional arrangements, and their scientific activities. For a more nuanced depiction, the research topic describes graphical presentations such as top authors, top universities, leading journals, influential keywords, and others in the beginning. While descriptive analysis shows an intermediary path for understanding the outlay of SCR, we also propose exploring SCR by digging deep into the topic. Inspired by this, we present our second research question:

- RQ2: How can the past literature be studied to provide a microscopic view of SCR?

This study adopted a bibliometric and network analysis procedure to fulfill this objective. Over 3500 published articles containing optimization tools were analyzed by investigating large citation and co-citation networks. To the best of our knowledge, there is no state-of-the-art review that covers such complex datasets to contribute to the field of SC risk and resilience. A filtering process using co-citation analysis and the PageRank algorithm was performed, which generated seven research clusters (research themes). The importance of SCR in the design and evaluation of SC networks is realized in cluster 1, particularly in the design of closed-loop and reverse SCs (cluster 4) and perishable-product SCs (cluster 5). This analysis also identified robust programming as a promising technique for building resilient SCs (Cluster 2). Other techniques to achieve SCR using quantitative modeling highlighted in the study are stochastic programming and robust optimization (Hatefi and Jolai, 2014; Jabbarzadeh et al., 2016; Govindan et al., 2017). Planning and modeling in times of uncertainty and disruptions are accounted for in Clusters 3 and 6. The study also explores the interface between sustainability, green economy, and resilience in an independent cluster (Cluster 7). These themes are synthesized in a conceptual model and are described in detail in Section 5. The model is essential for drawing generalities and combining the individual contributions of various papers to delineate the evolution and progress of SCR.

The proposed review process has the potential to yield a manual or reference guide for better decision making and to serve as a support system for practitioners. It can help in identifying the lexical shifts, substantive changes, and gravitational insights related to SCR by exploring studies published between 1996 and 2020. Most studies discussed in Section 6 were intended to solve industrial problems using strategies based on a risk-management culture as well as on SCR philosophies. Therefore, the highlighted discussions will help not only academia but also industry to manage challenges due to uncertainties and to address the contemporary issues facing the implementation of optimization tools for SCR.

For comprehension of such a vast body of knowledge, the study is organized as follows. Section 2 identifies the position of the current study with respect to past literature reviews. Section 2.1 proposes the rationale behind the research methodology and procedures for the implementation of analysis. Section 3 provides a detailed description of the research methodology introduced in Section 2.1 in terms of material collection, initial analysis of datasets, and the clustering procedure for improved visualization. It describes the SCR research field using simple graphs, charts, and tables relating to top-performing authors, affiliations, journals, and others. This section also lays the foundation for research themes by creating clusters to present common concepts using co-citation analysis and the PageRank algorithm (refer to Section 3.3.) Section 4 presents a statistical analysis of the gathered data. In Section 5, we examine the research themes, often referred to as research clusters, to investigate how SCR has emerged as a research idea in the past, its present implications, and its future perspectives. Section 6 highlights insights related to practical industrial applications. Section 7 concludes the study by identifying the limitations and proposing significant takeaways from the analysis. Finally, mathematical proofs concerning robust optimization and stochastic programming considering general industrial case understanding are presented in Appendix B.

2. Resilience in the SC literature and procedure for systematic literature review

Tracing resilience in the past identifies (Vakharia et al., 2009; Richey et al., 2009) as early but seminal contributions to SCR research, and subsequent authors have developed their research along quantitative as well as qualitative lines. Some of the recent advances in the management of SC disruptions are concerned with avoiding disruptions at the source (Schmitt and Singh, 2012), models related to inventory mitigation (Atan and Snyder, 2012), and reviews on facility location and network design in terms of disruptions (see Snyder (2006), Snyder and Daskin (2007), Snyder et al. (2016)). The structural impact and mismanaged planning of parameters across all stakeholders owing to disruptions describe what is known as the ripple effect or domino effect (Dolgui et al., 2018). This low-frequency, high-impact risk has an indirect effect on market share, company reputation, and overall SC costs (Hendricks and Singhal, 2005). The literature on the ripple effect and SC disruption is represented by Liberatore et al. (2012), Ivanov et al. (2013, 2014b), Sokolov et al. (2016), and Ivanov (2017). A graphical understanding of SCR, often depicted in the literature, is presented in Fig. 2. This highlights the performance of the SC system against unwanted disruption with reference to time. The figure also specifies the strategies of a resilient SC system on various occasions during the disruption. These strategies for effective decision making are discussed further in Sections 5 and 7.

To the best of our knowledge, quantitative and modeling-related review papers on SCR are scarce (Kamalahmadi and Parast, 2016; Ribeiro and Barbosa-Povoa, 2018). A possible reason for such disregard is the over-reliance on models in the supply chain risk management (SCRM) literature and less attention to SCR as a research topic. However, SCR has attracted significant attention in the past decade and has made contributions in terms of case studies, surveys, conceptual frameworks, theoretical work, and modeling-related papers. Some of these are listed in Table 1 for comparison with the work presented here. Note that NLR represents a narrative description of papers that are biased in the selection of articles and lack a systematic viewpoint (Petticrew and Roberts, 2008). As mentioned, studies dealing with qualitative research methods such as surveys, questionnaires, interviews, case studies, and observational trials are outside the scope of this study.

To the best of our knowledge, a review limited to formal modeling of SCR is difficult to obtain. However, numerous previous studies have reviewed SCR and considered qualitative and quantitative approaches. These include:

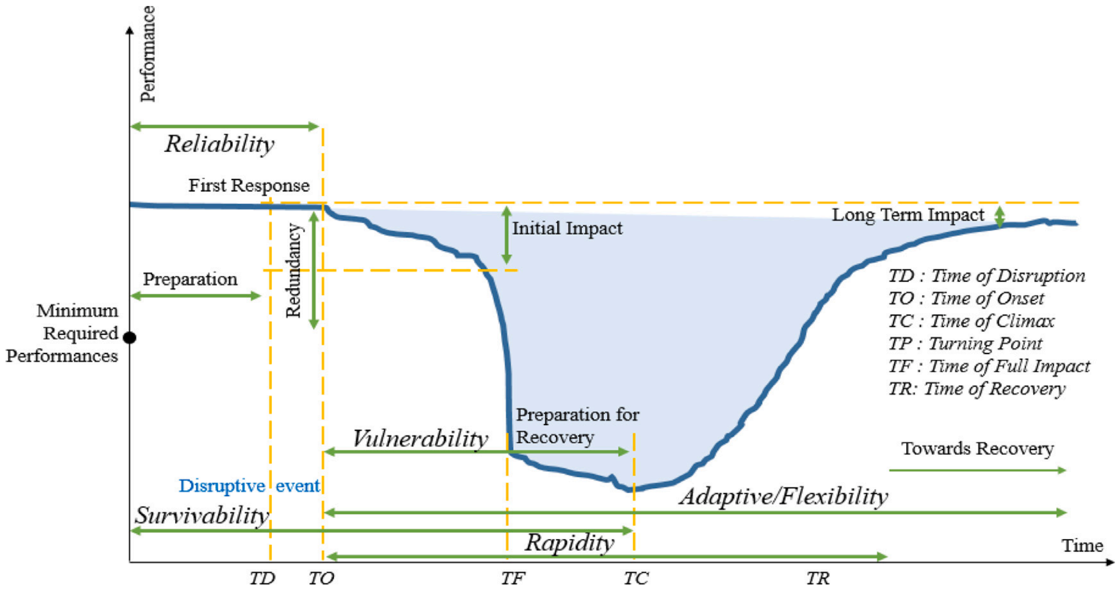

Fig. 2. Schematic diagram of the performance of a resilient SC system against disruption.
Source: Wan et al. (2018), Melnyk et al. (2014).

- Tukamuhabwa et al. (2015) proposed a comprehensive definition of SCR. The authors mentioned modeling oriented studies and provided a theoretical lens for understanding SCR.
- Hohenstein et al. (2015) realized that most of the research on SCR fails to measure resilience as a performance parameter. The authors proposed that SCR can be judged based on customer service, market share, and financial performance as metrics, and also highlighted various previously proposed definitions of SCR.
- Kamalahmadi and Parast (2016) presented a literature review on enterprises and SCR. The authors discussed the evolution of SCR and the definitions and concepts related to organizational resilience. This study also investigated the effectiveness of resilience in SMEs.
- Wang et al. (2018) advanced the utility of resilience for a holistic SC system. The authors promoted organizational resilience in an SC context and classified SCR based on estimation, awareness, and defense strategies.
- Levalle and Nof (2015a) further studied resilience within physical, digital, and service supply networks. Greater emphasis was placed on digital and service supply networks in comparison to physical SCs. Thus, the study failed to consider how resilience can benefit physical SC and the importance of management principles.
- Ivanov et al. (2017) identified tools to manage disruptions and associated recovery policies in SCs.
- Ribeiro and Barbosa-Povoa (2018) developed a review considering 39 research papers over the span of 2009–2016 to address the challenges associated with SCR modeling.

In terms of theoretical contributions, only Wilding et al. (2012a), Tukamuhabwa et al. (2015), and Ivanov (2020) presented influential review works. Wilding et al. (2012a) outlined a theoretical lens for purchasing and SC management, while Tukamuhabwa et al. (2015) studied SCR using a complex adaptive systems theory perspective. Ivanov (2020) proposed a theoretical notion about a viable supply chain (VSC); according to the author, VSC considers aspects of agility and sustainability in addition to resilience for effective SC operations. Kamalahmadi and Parast (2016) reviewed enterprise resilience and analyzed the definitions, drivers, and principles of SCR. The authors proposed an SCR principles framework, primarily based on developing SCRM culture, collaboration, agility, flexibility, and SC re-engineering.

In line with this, Hosseini et al. (2019a) developed an SCR review based on empirical and quantitative models, described the definitions and drivers, and proposed an SCR capability-building approach. Extending the study by Hosseini et al. (2016), the authors stated that resilience can be stored using agility, visibility, flexibility, collaboration, and information sharing, perhaps with the help of adaptive, absorptive, and restorative capacity. The capacity-building framework is primarily based on the union of empirical findings and systems thinking approaches, unlike the existing study. This study complements the latter by elaborating on crude OR practices performed in the past and its future implications (see Section 5). Referring to Table 1, we observed that most past studies have analyzed the literature on narrow research topics. For example, Ivanov et al. (2017), Dolgui et al. (2018) worked extensively on the impact of the ripple effect on SC performance and disruption management models using quantitative tools. Klibi et al. (2010) investigated SC uncertainty modeling, and Tang (2006), Tang and Tomlin (2008), and Pyke and Tang (2010) developed studies primarily to address SCRM issues. These studies identified different risks and their mitigation strategies; for example, Pyke and Tang (2010) developed a study on product safety risk. To the best of our knowledge, this is the only study that provides

Table 1
Papers covering quantitative models on risk, uncertainty, disruption, and SCR.

Sr No	Authors	Scope of the past studies									IA		Primary focus
		Year span	# papers reviewed	Descriptive analysis	Risk modeling papers	Network analysis	Cluster explanation	NLR(X)/ SLR(•)	CM/CF	TC	R	I	
Risk, uncertainty, and disruption related review papers													
1	Tang (2006)	1984–2005	200		✓			X	✓		✓		The paper intends to provide a unified framework on SCRM. The article creates a practical guide of reference between theory and practice on SCRM.
2	Peidro et al. (2009)	1998–2007	103					X			✓		The paper presents a quantitative models review on SC planning under uncertainties.
3	Tang and Tomlin (2008)	1991–2007	51		✓			X			✓	✓	The authors proposed an integrated approach to reduce SC risk using flexibility strategies. They identified the power of flexibility via multiple suppliers, flexible supply contracts, flexible manufacturing processes, postponement, and responsive pricing strategies.
4	Pyke and Tang (2010)	1986–2009	36		✓			X			✓		The paper was primarily developed to address questions related to product safety risk, especially the underlying reasoning, restoring mechanism, and mitigation measures.
5	Klibi et al. (2010)	1974–2008	48	✓	✓			X			✓		Focus on creating a robust SC network by building strategies to fight uncertainties.
6	Arshinder et al. (2011)	1991–2011	170		✓			•	✓		✓	✓	Primarily, the paper focus on providing a review on SC coordination for managing uncertainties.
7	Ghadge et al. (2012)	2000–2010	120		✓	✓	✓	•			✓		The paper introduces a new perspective towards modeling SC risk using systems thinking approach.
8	Wilding et al. (2012b)	1994–2010	55		✓	✓		•		✓	✓	✓	A theoretical perspective about risk management and SLR approach.
9	Chiu and Choi (2016)	1979–2013	52					X			✓	✓	The study review papers based on decision maker's attitude for managing risk. Specifically, papers based on Mean-Variance theory.
10	Fahimnia et al. (2015b)	1978–2013	1000	✓	✓	✓		•			✓		The scope of the study is to present SLR on papers based on quantitative modeling of risk for better decision-making.
11	Rajagopal et al. (2017)	2005–2016	126		✓	✓	✓	•			✓		The focus is to present papers based on mitigation strategies to manage risk.
12	Behzadi et al. (2018)	1993–2015	160	✓	✓	✓		•			✓	✓	A survey on mathematical modeling for agri-business SC risk management.
SCR related review papers													
13	Bhamra et al. (2011)	1976–2010	74					X			✓		Emphasis on definition, concepts, and perspective of resilience in general and specific in the context of SMEs.
14	Hohenstein et al. (2015)	2003–2013	67		✓			•			✓		The paper provides an SCR measurement metric and classifies SCR strategies based on the ex-ante/ex-post disruption stage.
15	Tukamuhabwa et al. (2015)	2003–2014	91		✓			X		✓	✓	✓	The paper provides little attention to modeling papers on SCR with a more considerable emphasis on providing a theoretical lens on SCR.
16	Kamalahmadi and Parast (2016)	2001–2015	100	✓	✓			X	✓		✓	✓	The focus is to provide SCR definitions, principles, and strategies and promote resilience in enterprise and organizational management.
17	Ivanov et al. (2017)	2003–2017	131		✓			X	✓		✓	✓	Survey on SC with disruptions and recovery considerations. The study focuses on providing a survey on DM considering both qualitative and quantitative articles. The authors proposed a ripple effect control framework for effective DM.
18	Barbosa-Póvoa et al. (2018)	2009–2016	39	✓	✓			X			✓		Definition of SCR and formal modeling techniques in SCR.
19	Hosseini et al. (2019a)	2002–2017	168	✓				•	✓		✓		Review on SCR describing the definitions, drivers, and capabilities of building SCR.
20	**Proposed study**	1996–2020	3672	✓	✓	✓	✓	•	✓		✓	✓	The aim is to provide a comprehensive review of the quantitative analyses of SCR, particularly on analytical studies. It also involves analysis, classifications, and identification of future research areas in the SCR context.

Dimensions includes Contextual Narrative Literature Review (NLR), Systematic Literature Review (SLR), Model/Conceptual Framework (CM/CF), Theoretical Contribution (TC), and Intended Audience (IA) as Researchers (R) and Industry(I), etc.

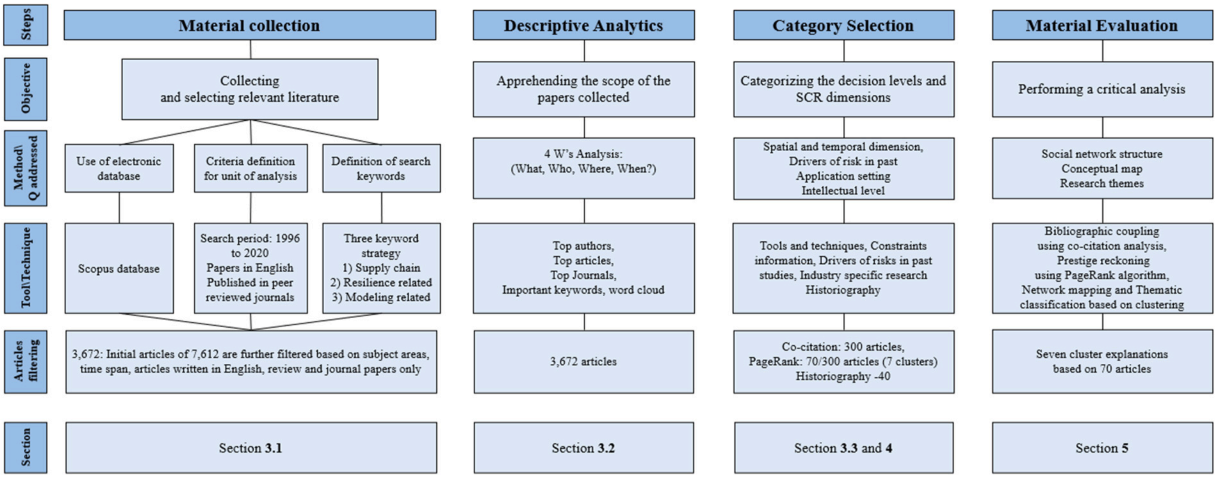

Fig. 3. Research methodology, objectives, methods, tools, and structure of analysis.

an up-to-date and well-structured overview of the literature. It analyzed the SCRM and SCR literature and covers quantitative models, frameworks, strategies, and mathematical concepts. Furthermore, the review adopts a unique approach of analyzing the literature using dimensionality reduction techniques such as multiple correspondence analysis and clustering algorithms, primarily to promote an unbiased, transparent, and reproducible research study. This review hopes to build a practical approach to help researchers navigate through the sea of research articles on topics that hold perpetual interest. In addition to these studies, which focus on formal modeling techniques in the SCR literature, we encourage readers to follow papers that describe SCR based on empirical research methods, such as Ponomarov and Holcomb (2009), Bhamra et al. (2011), Blackhurst et al. (2011), Ponis and Koronis (2012), Pettit et al. (2013), Pereira et al. (2014), Melnyk et al. (2014) and others in a similar vein. As papers based on risk, uncertainty, and disruption are inevitable in the SCR literature, Table 1 highlights the contribution of extant research based on review papers published in the past on relevant topics.

2.1. Research methodology for effective systematic literature analysis

We implemented science mapping or bibliometric mapping to reveal the conceptual, social, and intellectual structures of scientific domains or research fields in SCR. The process involves identifying major research activities, intellectual milestones in the development of the research field, and the dynamics of the transition of evolutionary research within the field of study or research specialty. Therefore, the scope of this activity is limited to a scientific discipline, a field of research, or an area defined by and limited to specific research questions (Chen, 2017). Bibliometric analysis complements the results with research vocabulary, evolutionary patterns, and research themes for future implications. Science mapping involves the following five stages to carry SLR: (1) designing the study, (2) data collection, (3) data analysis, (4) data visualization, and (5) data interpretation (Börner et al., 2003; Cobo et al., 2011). One of the major steps in science mapping is co-citation analysis and the PageRank algorithm. Co-citation is an exploratory data analysis technique used to identify generative research themes, whereas the PageRank algorithm is implemented to find trending topics (Lewis-Beck et al., 2003). Most review papers use an exhaustive search of a wide range of databases to reduce the risk of missing literature (Barnett-Page and Thomas, 2009) and to enhance the sensitivity of the review process. However, acknowledging the advantages of the Scopus database (Elsevier) over others has helped in initial online searches (Mongeon and Paul-Hus, 2016). It provides the best repository for operations and SC-related articles published by Elsevier, Emerald, Informs, Taylor and Francis, Springer, and others (Wilding et al., 2012a).

To ease the analysis process, this study was conducted using the open-source platform, RStudio. This provides a graphical user interface within the R environment, with access to the Comprehensive R Archive Network (CRAN) data house. The bibliometrix R-package in CRAN is an efficient tool for quantitative research in bibliometrics and scientometrics (Aria and Cuccurullo, 2017). Readers can access the bibliometrix website (http://www.bibliometrix.org) to gain a detailed understanding of the bibliometrix package (https://cran.r-project.org/web/packages/bibliometrix/bibliometrix.pdf). The initial step while using bibliometrix is to download the relevant data files from Scopus. To do this, files were downloaded in .bib format. Such analysis and the subsequent explanations will assist in addressing the following research questions in addition to performing a "4W" analysis (When, Who, What, and Where) for the downloaded metadata.

- RQ3: To what extent is resilience incorporated in the literature on risk and uncertainty modeling for SC design?
- RQ4: What level of decision making related to risk and resilience has been incorporated in past studies exploring various modeling approaches?
- RQ5: What is the role of resilience, if any, in other SC philosophies, such as sustainability and greenness?

- RQ6: Which industrial sectors have adopted modeling approaches to deal with SCR?
- RQ7: What are the current limitations of SCR modeling approaches and the scope for future directions?

The results from the bibliometric mapping, presented in the following paragraphs, can be summarized into four major categories: (a) descriptive-level statistics, including results such as top authors, top universities, top journals, and collaboration patterns; (b) conceptual maps for keyword clustering; (c) intellectual-level descriptions, such as historiography; and (d) social-level analysis, such as co-citation or bibliographic coupling. Therefore, this mapping procedure is pivotal for the SLR. To perform such an analysis meticulously, the unit of analysis was determined as papers written in English and published in peer-reviewed journals, with no limit set on the date range. These records (research papers) are filtered based on subject matter and searched exhaustively using only the Scopus database, and the search was further restricted to article title, abstract, and keywords. Notably, each paper examined during the review process contributes to the pursuit of an integral understanding of risk, uncertainty, and resilience. Therefore, this study synthesizes the individual contributions, findings, and innovative intuition of various articles and provides the evolution and progress of the research field. However, analyzing such a vast body of knowledge is cumbersome and complicated. Thus, a filtering process employing co-citation and the PageRank algorithm was adopted. The details of this are presented in Section 3.3.

We further illustrate the research methodology adopted to implement the analysis and the steps followed during the experiment in Fig. 3. Because the process is lengthy, this brief representation of the procedure will help researchers understand the methodology with greater clarity. We reiterate the earlier explanation of the review process to provide clarity on the steps followed during the review procedure. Fig. 3 is divided into four major parts. The initial step involves collecting the relevant material, followed by the initial data statistics. Next, a deep analysis is performed by analyzing individual themes for future implications by adopting the steps prescribed in the category selection and article evaluation stages. Fig. 3 shows the respective sections for generating explanations.

3. Implementation of the research methodology using science mapping

The following section extends the research methodology presented in the previous section to the downloaded dataset. In particular, we describe the procedure for material collection in Section 3.1, the initial data analysis in Section 3.2, and data visualization using citation mapping in Section 3.2. The clustering results from Section 3.3 are then elucidated in Sections 4–7.

3.1. Data collection

An iterative procedure of (1) defining the appropriate search keywords, (2) searching the literature, and (3) completing the analysis is adopted in line with Saunders (2011) to download all relevant records. The data collection step involves the initial definition of suitable keywords and the identification of relevant research articles. This is performed by following three keyword-based assembly structures, as described by Fahimnia et al. (2015a), Rajagopal et al. (2017), which are set out below. The main context keyword is "supply chain", followed by keywords related to resilience, followed by key searches related to modeling approaches that are applied to solve the problems of SCR. Based on the conventional understanding of optimization models, that is, models or problems, fundamental techniques referenced in the operations research (OR) subject area are used as modeling keywords. These include keywords such as mathematical programming, MCDM techniques, simulation models, and other analytical methods. The modeling keywords are kept at a general level to cover a broader range of studies. Similar keywords are selected to search for modeling-related papers to those used in studies like Fahimnia et al. (2015b), Barbosa-Póvoa et al. (2018). Subsequently, we selected papers based on the top ten subject areas (Table 2). During the search, it was apparent that the numbers of records did not improve even after including specific keywords such as 'milp' or 'minlp'. General terms such as 'multi-criteria' or 'multiattribute' also did not make any difference in data collection when used instead of 'multiple criteria decision analysis' or 'multiple attribute decision analysis', a factor that many researchers have often ignored during searches in the databases (Fahimnia et al., 2015a; Mishra et al., 2017).

Keywords for search results in Scopus

Context Keyword: Supply Chain
AND Resilience-related keywords: risk OR resilience OR resilient OR resiliency OR agile OR agility OR uncertain OR uncertainty OR disruption AND Optimization-related keywords: optimization OR "mathematical model" OR "mathematical programming" OR "linear programming" OR "integer programming" OR "mixed-integer" OR "non-linear programming" OR "nonlinear programming" OR "dynamic programming" OR "multi-objective" OR multiobjective OR "decision analysis" OR "multi-criteria" OR "multi-attribute" OR "multiple criteria decision making" OR mcdm OR simulation OR stochastic OR probabilistic OR heuristic OR "meta-heuristic" OR metaheuristic

Nonetheless, such a consideration does not have an impact on the number of records obtained in the search procedure. The initial results after the first search provided 7,612 records. This large dataset was then filtered based on language (English) and article type (journal and review papers) for a timespan up to 2020. The exponential growth in the number of publications shows that the interest in the research community in SCR has increased drastically, and relevant studies are being explored across the length and breadth of the topic. Approximately 45% of the total publications were observed after 2015. This shows that an increasing number of researchers are actively working on SCR-related topics.

Table 2
Top 10 subject areas and top author profiles with respective number of publications.

Subject Area	# of papers	Authors	# of articles
Engineering	1869	Mir Saman Pishvaee	41
Business, management and accounting	1508	Reza Tavakkoli-Moghaddam	37
Decision sciences	1503	Dimitry Ivanov	33
Computer science	1374	Xueping Li	30
Mathematics	702	Manoj Kumar Tiwari	25
Environmental science	363	Kannan Govindan	24
Social science	335	Jian Li	24
Economics, econometrics and finance	307	Jian Zhang	24
Energy	275	Zigeng Liu	23
Chemical engineering	134	Alexandre Dolgui	21

Table 3
Top 10 publishing journals contributing to the area of SCR.

Year	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
International Journal of Production Research					1	1		4	4	1	4	2	8	8	11	14	10	13	18	22	8	25	22	13	48
International Journal of Production Economics				5		2	1	1	2	1	5	1	8	9	9	17	14	6	17	12	11	26	13	19	13
European Journal of Operational Research			1	3		2	2	1	2	3	6	12	10	6	12	12	4	10	16	14	12	9	14	15	9
Computers and Industrial Engineering							1				3		1	5	4		5	4	8	6	10	21	18	28	29
Journal of Cleaner Production																		2	1	1	12	13	23	22	31
Computers and Chemical Engineering					2				1			3	7	5	5	2	2	4	9	5	4	7	7	12	8
Annals of Operations Research								1		4		1			2	1	1	4		3	13	12	6	12	15
Transportation Research Part E: Logistics and Transportation Review									1			2	1	1	2		3	3	6	7	14	8	9	3	6
Sustainability (Switzerland)																			1		5	10	12	18	16
Expert Systems with Applications										1			2	5	7	5	3	1	6	7	2	3	2	6	4

3.2. Scientific development using initial descriptive analysis

As mentioned previously, we used R Studio to analyze the downloaded records. All records were downloaded in the Bibtex format and converted to data frames for further analysis. The algorithm was run on an Intel(R) Core i52400 CPU with a 3.10 GHz clock setting. This section briefly comments on the contributing authors, affiliations, sources, and holistic scientific development of SCR.

Table 2 outlines information related to the top subjects covered in the study. It also mentions highly influential authors who have contributed to the field of study. Table 3 displays the top 10 journals and their respective numbers of publications for each year from 1996 to 2020. Among these, the European Journal of Operational Research, International Journal of Production Research, and International Journal of Production Economics are among the top contributing journal sources.

Table 4 helps in analyzing the performance of various countries, journals, and universities. The table contains country specific information, such as the number of papers published and the total citations of specific countries for their top-10 performers. We identified universities producing the highest research outcomes and major journals in the field of study. The table also shows the top 10 contributing authors along with the number of publications, accompanied by the respective h-index. An h-index of value N shows that a particular author, organization, or research group has published at least N articles, and each is cited N times by other researchers (Alavifard, 2015).

The annual scientific production over the year is shown in Fig. 4(a). Fig. 4(b) shows the distribution of scientific production. It shows the rate of productivity in terms of published scientific articles over time in terms of the ratio between the number of authors publishing a given number of articles to the number of authors publishing a single article. This suggests that most researchers working on SCR have written two or three articles in the study period. Fig. 4(c) illustrates the collaboration pattern established between different countries and depicts the trend analysis for journals publishing articles in the SCR field. It shows the contribution at the scientific level from different countries, indicating the geographical distribution of research. The darker the color, the higher the contribution from a specific country. Thus, the United States, China, and India are the top countries working on SCR. In case of developing nations such as India and China, the challenges of risk and disruptions are higher compared to those in developed nations, thereby justifying the higher scientific literature output. Fig. 4(d) shows that sources such as the International Journal of Production Research, Journal of Cleaner Production, Computer and Industrial Engineering, and International Journal of Production Economics are among the top sources continually publishing articles on SCR.

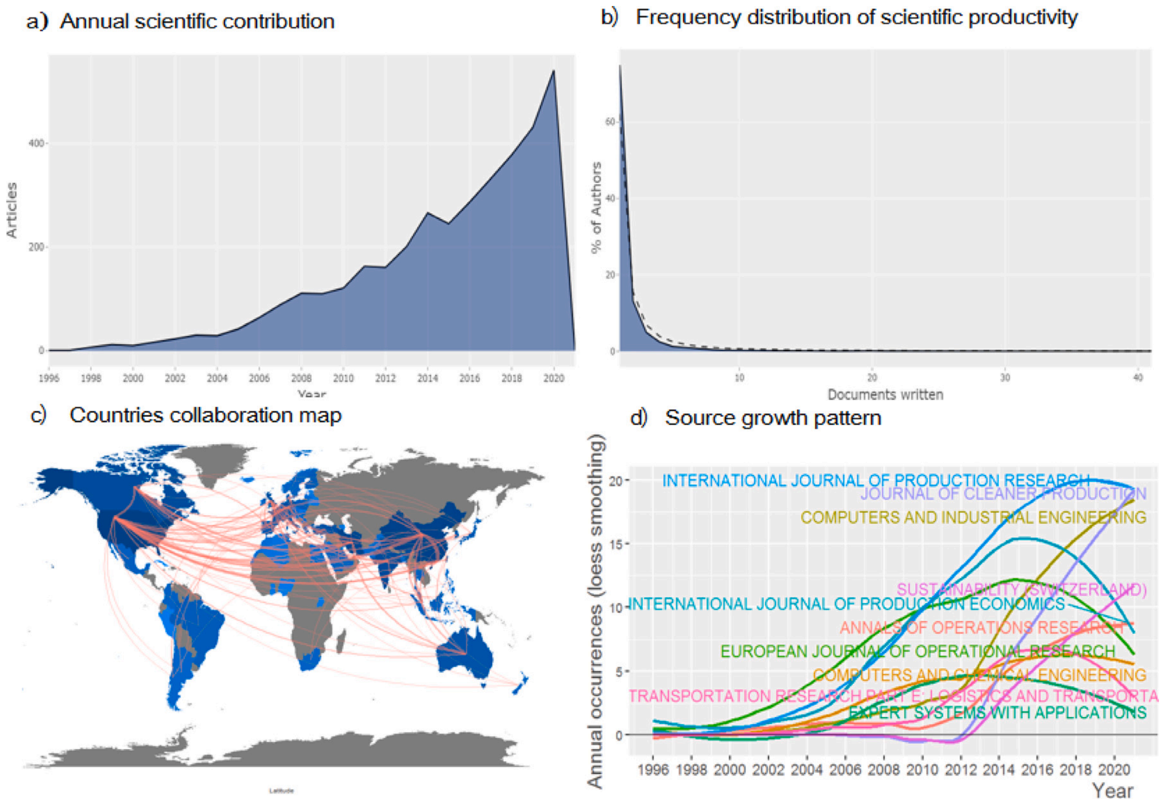

Fig. 4. Illustration of scientific development of the underlined research topic.

Fig. 5 provides an infographic visualization concerning trending topics of research in the underlined study. On a wider dimension, past studies have included research topics on management of water SC, electrical SC, and other industrial applications. The prominent methodologies considered in the past include robust programming (RP), stochastic programming (SP), fuzzy programming (FP), or other similar modeling methods that are applied to solve the problems shown in Fig. 5. The figure also helps in understanding the cross-cultural trends present in a relevant area of study. For example, sustainability, which is a separate field of study, falls within the SCR domain. Such identifications are specifically useful for understanding all possible avenues for future studies, provided that these two topics are studied together. Another important analysis that sketches the historic development and contribution toward paradigm shifts in the research topic is shown in Fig. 6.

Historiography is the creation of a genealogical profile of the evolution of scientific literature. This intellectual-level analysis explains the social and conceptual evolution of the research field for a particular period. It relates to paradigm shifts in the scientific literature by identifying significant works (papers) on a given topic and creating a complete picture of the historical background of the topic (Garfield et al., 2003). This chronological ordering is presented for the downloaded records in Fig. 6. Note that, for better visualization, the analysis is performed in two phases, as presented in Fig. 6 (a) and (b). All these articles are analyzed in further sections of this paper. Here, we highlight the key findings from some of the papers that mark the notable contribution to risk, uncertainty, and resilience. These findings are also illustrated in Fig. 7. It is produced by analyzing the listed articles in Fig. 7 and extending the risk management framework presented by Tang (2006). The analysis also shows that although many contributions are seen in terms of studies dealing with risk, uncertainty, and disruption, a vast scope is observed for research related to SCR, in particular, models promoting SCR strategies. In addition, all these past studies have applied resilience and responsiveness only loosely in their modeling approaches, thus leaving research opportunity for correctly injecting the principles of SCR during the formulation of business models.

We discuss in detail the OR modeling efforts in the subsequent sections. However, the key observations drawn from past studies on risk and resilience management are as follows:

- A risk-resilience map framework was used to evaluate SCND based on various criteria.
- Equal importance shall be given to robustness, responsiveness, and resilience when designing an SC network and logistics planning.
- Responsiveness and resilience have received less importance in past studies dealing with SC risk and uncertainty.
- Responsiveness in SCs can be built using flexibility and redundancy-level capabilities to attain a resilient SC.

Table 4
Information related to top performing affiliations, universities, and journals.

Most cited countries			Universities with the highest research outcome		Journals related information			
Country	# articles published	Total citations	University name	# articles published	Sources	Articles	h-index	Total citations
China	631	10706	University of Tehran	157	International Journal of Production Research	237	48	4818
USA	562	23776	Islamic Azad University	146	International Journal of Production Economics	192	56	7471
Iran	458	8952	Iran University of Science and Technology	130	European Journal of Operational Research	175	60	9448
India	165	3239	Amirkabir University of Technology	53	Computers and Industrial Engineering	143	33	2364
United Kingdom	118	4791	National University of Singapore	49	Computers and Chemical Engineering	83	30	3220
Canada	110	4010	Kharazmi University	42	Transportation Research Part E: Logistics and Transportation Review	66	30	2174
Germany	87	2820	Indian Institute of Technology	35	Journal of Cleaner Production	105	30	966
Turkey	76	2826	Hong Kong Polytechnic University	35	Annals of Operations Research	74	26	1005
France	73	1920	Huazhong University of Science and Technology	31	Expert Systems with Applications	54	32	2524
Hong Kong	65	3783	Southeast University	30	International Journal of Advanced Manufacturing Technology	41	21	851

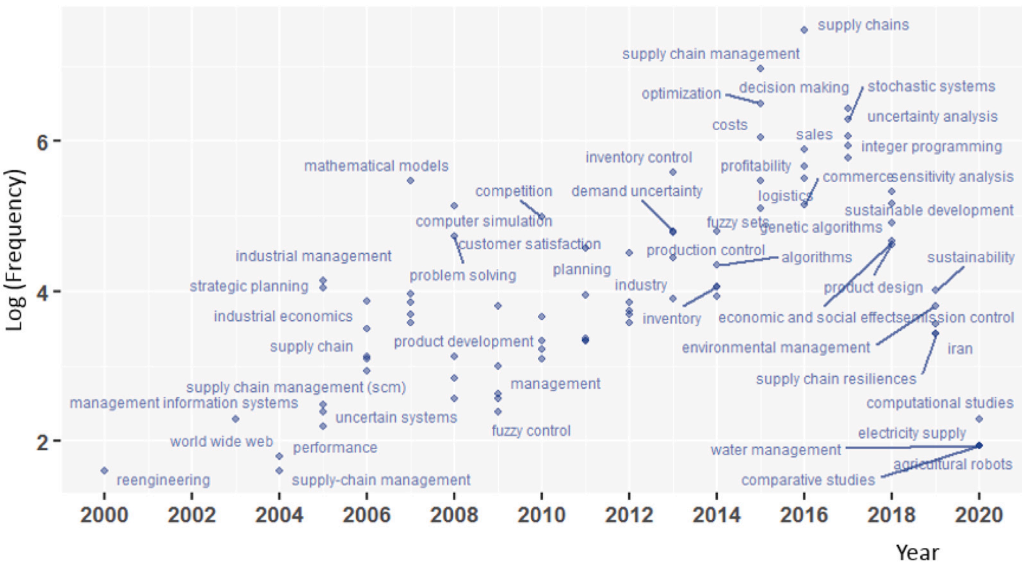

Fig. 5. Trending topics using Word cloud analysis of author's keywords.

3.3. Network mapping and theme identifications using co-citation analysis and the PageRank algorithm

The documents that are downloaded from Scopus have important information such as the author's names, titles, keywords and other information. All of this information together is called the metadata, and alternatively referred to as bibliometric attributes. The data frames that are created by considering these objects are further used to perform conceptual and social analyses. All these attributes are connected to each other through the document itself, for example, author(s) to journals, and keywords to publication

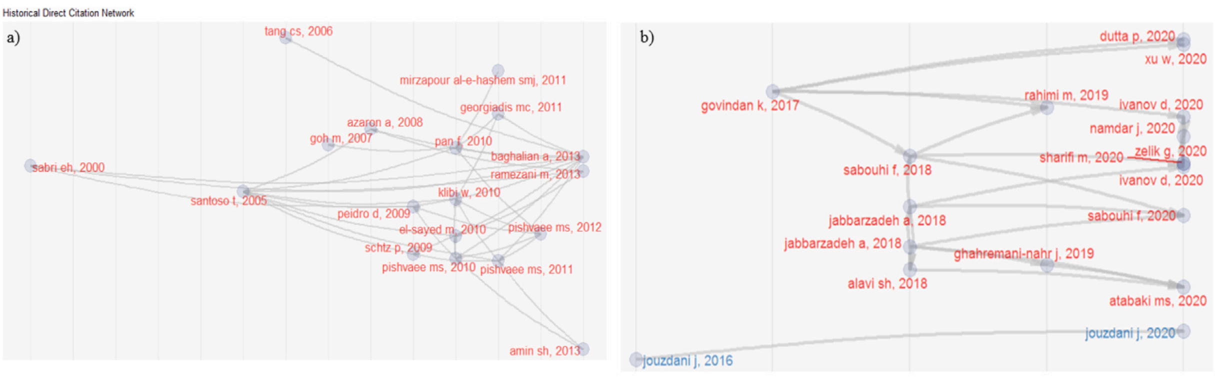

Fig. 6. Historiography of the top research articles ranging from 2000 to 2020.

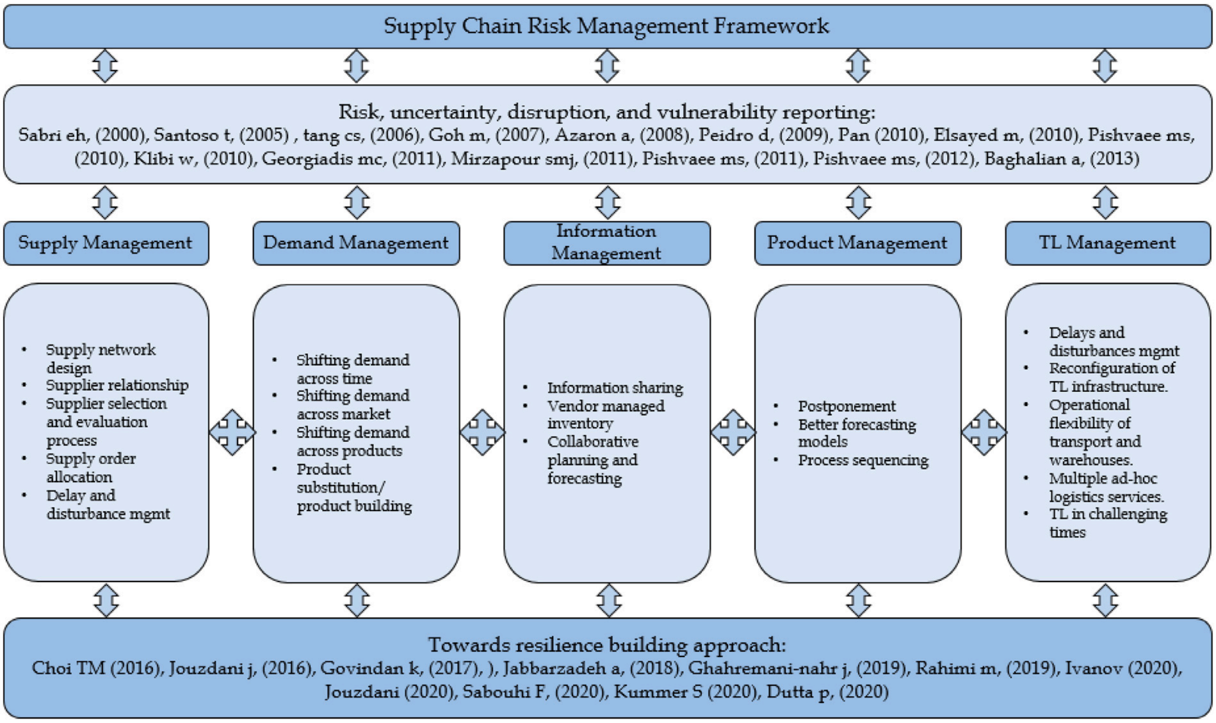

Fig. 7. Risk to resilience modeling efforts using historiography.

dates, and such connections are represented using the matrix *Document* X *Attribute*. This matrix is commonly referred to as the *cocMatrix*. Using the *cocMatrix* matrix, several further matrices are obtained, such as Document X author and *Document* X *author keywords*. These matrices are primarily used to perform further analysis, such as co-citation analysis and the PageRank algorithm. Co-citation analysis is implemented to identify seminal works in the SCR domain and to find specific studies that have impacted the underlined topic of discussion. This filtering process results in generative research themes (clusters) presented in Table 5. The idea is to identify the cohorts of papers that represent a promising research domain (research theme) obtained using co-citation analysis. This process is enhanced by implementing the PageRank algorithm to discover the trending articles (lead papers) in clusters produced using co-citation analysis (refer Table A.16). The resulting filtering process is presented in Fig. 8.

Co-citation is a method of finding the impact of a study, author, article, or publication by identifying the number of times an article is cited by other studies.[3] Table A.15 ranks the top 10 papers along with their citation counts. A local citation is a citation among the network of 3672 documents, whereas a global count is the overall citation count. For example, although the

[3] https://en.wikipedia.org/wiki/Citation_analysis.

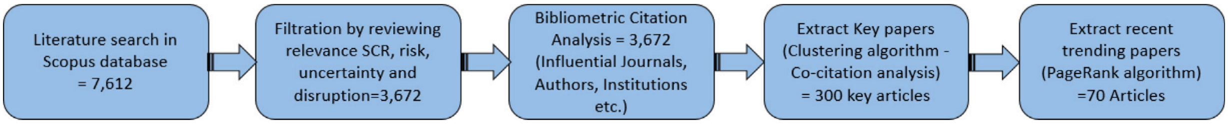

Fig. 8. Illustration of filtering processes of research methodology.

local citation for Santoso et al. (2005), Sabri and Beamon (2000) is lower, the articles are highly cited in the global environment. To better understand this concept, primarily, the bibliometric coupling is explained. Two research papers are bibliographically coupled when at least one cited source appears in the bibliographies or reference lists of both the research papers (Kessler, 1963). Similar to this, the co-citation of two articles happens when they are cited in a third article (Aria and Cuccurullo, 2017). Co-citation is the counterpart of bibliographic coupling. This can be mathematically represented as follows:

B_{cocit} = A X A'

where A is Document X Cited reference matrix as discussed in Section 2.1. B_{cocit} is a symmetric matrix, and each element b_{ij} of this matrix indicates how many co-citations exist between nodes i and j. It is generally understood that papers often cited together represent similar subject areas or related (Hjørland, 2013). A map obtained using such an analysis presents clusters, and each cluster represents specific research themes (see Fig. 9). The flexibility of applying co-citation on the number of nodes is achieved by coding the program to view future analysis. We used 300 nodes (research articles) as our basis for a prospective study. However, this selection can be very subjective and differs according to the requirements of the analysis. Thus, to keep the survey meaningful and straightforward, we have used the minimum number of nodes and found about seven clusters for further study, which in itself represents a large dataset. These clusters are often called modules, in which the connection between the nodes of the same cluster is higher than other clusters. Modularity is a popular data clustering technique, highly recognized by researchers and industry experts. Especially in bibliometric and social network analyses (Blondel et al., 2008). However, it is not recommended to follow papers having the highest citations. Therefore, factors such as "Prestige" must be considered in searching for influential papers (Ding et al., 2009). Prestige can be measured as the "number of times a paper is cited by other highly cited papers"(Fahimnia et al., 2015b, p.6). PageRank is a number used to measure the popularity and prestige of the published articles ((Brin and Page, 1998). PageRank was named after Larry Page, who invented this algorithm to determine the rank of websites in search engine results; it was initially developed to reveal the connectivity of web pages. The algorithm works by calculating the number and quality of links to a page to determine an estimate of how important a website is. The underlying assumption is that more important websites are likely to receive more links from other websites. Therefore, it can also be extended to find the citation links among papers. For example, consider paper A that other articles have cited, namely, $T_1, T_2, \ldots, T_n$, where T_i has citations C(T_i). In this case, the PageRank of A (denoted by PR(A)) calculated in a network of N papers is as follow:

$$PR(A) = \frac{1-d}{N} + d\left(\frac{PR(T_1)}{C(T_1)} + \ldots + \frac{PR(T_n)}{C(T_n)}\right)$$

where d is a damping factor between 0 and 1. Implementing the above formula gives the probability distribution over articles, so the sum of all papers' PageRank will equal one. The original Google PageRank algorithm of Brin and Page (1998) prompted the anecdotal observation that an individual surfing the web will typically follow the order of 6 hyperlinks, corresponding to a leakage probability d = 1/6 = 0.15, before becoming either bored or frustrated with this line of search and beginning a new one. However, as suggested by Chen et al. (2007), we choose a value of 0.5 for this, considering the context of journal citation to be unlike that of web pages. Table A.15 shows the values of PageRank for different papers. It is observed from the table that none of the documents appear in Table A.15, as the prestige of these papers is higher than that of the highly cited papers presented in Table A.15. Table A.15 also shows the global and local citation counts for these papers.

We used the PageRank measure to identify "lead papers" to determine the general themes rising in each cluster. These lead papers are then studied carefully to identify research implications and avenues for future research (refer to Table A.16). The process of theme recognition was enhanced by combining the latest papers and lead papers of individual clusters. Primarily, to draw generalities and combine the individual contributions of various papers in the pursuit of an integral understanding of risk, uncertainties, and resilience. In addition, a microlevel analysis is performed to combine the individual contributions of various papers and deduce generalities with respect to each cluster, keeping in mind its future scope and research directions. Ultimately, the process helps assign names to individual clusters. Sometimes, it becomes apparent that papers in one cluster are not representative of the cluster theme. In such cases, researchers assign papers to another cluster by rearrangement (Rajagopal et al., 2017). Fortunately, this problem was not identified during the theme creation procedure. Table 5 highlights the seven themes that were generated during the review process.

4. Classification and findings on various modeling approaches, risk analysis, and solution techniques

To better analyze clusters and respective papers in each cluster, we divided the analysis into two parts. In the first section, two identical tables accommodate the 60 research papers that were obtained as primary research clusters. Table 6 does not include 10 papers that present mathematical derivations for robust programming that are considered independently, and the relevant

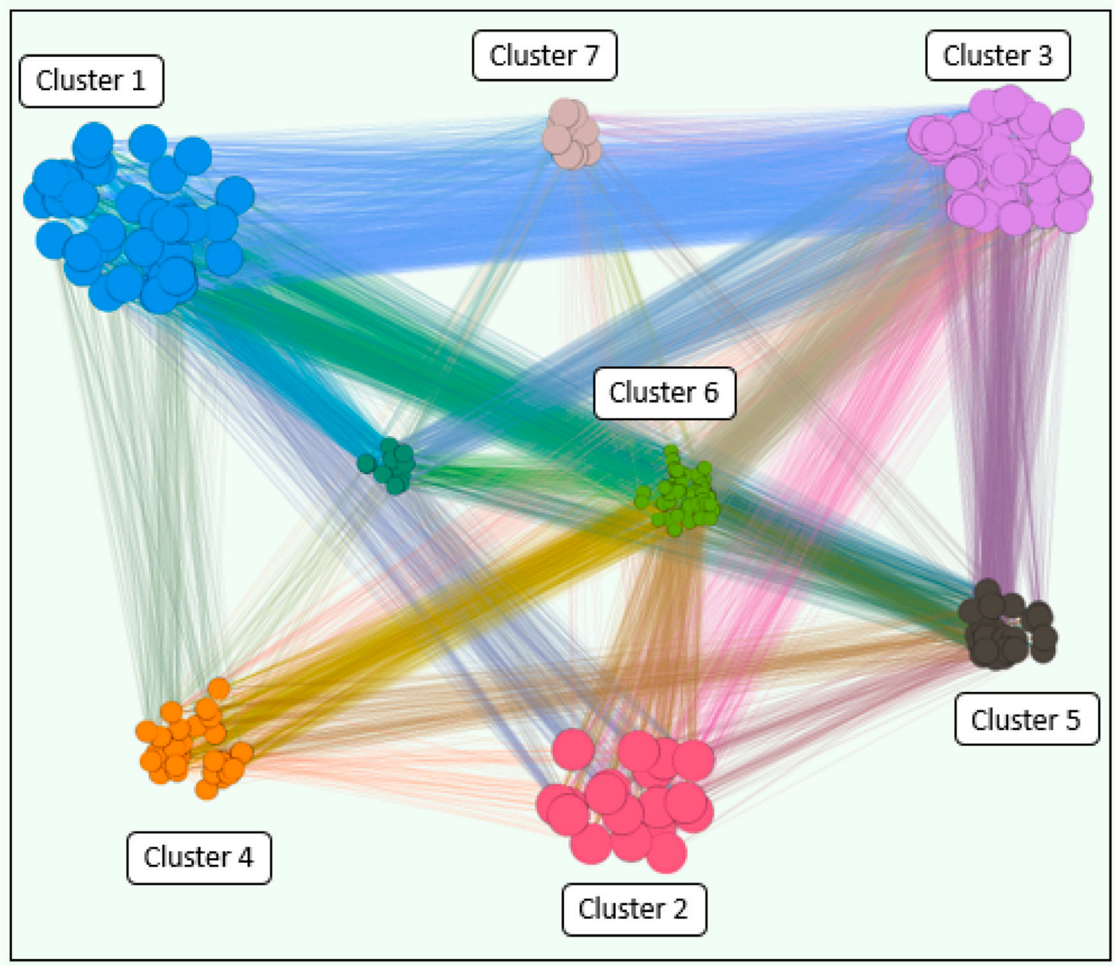

Fig. 9. Data clustering using co-citation analysis.

Table 5
Research themes identified after systematic review and network mapping procedure.

Cluster	Primary research themes
1	Selection and evaluation of SC entities (for example, Suppliers, Production processes, and Warehouses) in an SCND setting
2	Generalized stochastic programming and robust optimization approach to model uncertainty and achieve SCR
3	Modeling disruptions to design a resilient SC network
4	Uncertainty modeling in SC network design for closed-loop SC and reverse SC
5	SC network design models of perishable products
6	Planning models for SCND and facility location under uncertainty
7	OR models based on relationships or correlations between Sustainable, Resilience and Green SC

implications are derived in Section 5.2. This list of papers was obtained by adopting the co-citation and PageRank algorithm procedure described in Section 3.3. Figs. 10 and 11 show the existing decision support methods available for SCRM as well as SCR. More information on this aspect is provided in Section 7.1. As can be seen in Table 6, the initial information regarding the research papers in the primary clusters is arranged sequentially. This critical information provides an initial understanding of the data relating to the techniques, tools, decision variables, constraints, objectives, and risk types considered in the study. The richness of the initial information is sufficient to understand the quality of research being carried out in the field of SCR. This helps in identifying the types of industry sectors that adopt resilience-related approaches in their businesses. The idea here is to understand simple and basic information related to the characteristics of individual papers:

- What kinds of tools and techniques are used in the study?

Table 6
Information related to techniques, tools, decision variables, constraints, objective, and risk types considered in the study.

S.N.	Author(Year)	Technique	Tools	Decision Variables			Constraint (only the major ones)					Objective	Risk Type							
				S	T	O	C1	C2	C3	C4	C5	SO /MO	S	D	P	C	Q	I	T	F
1	Cachon and Zipkin (1999)	Game Theory		✓							Backlogged are filled									
2	Graves and Willems (2005)	Dynamic Programming		✓	✓	✓		✓			Inbound and outbound	SO		✓						
3	Kumar and Alvi (2006)	Fuzzy goal programming	LINGO			✓	✓		✓		Budget and Volume constraint	MO				✓				
4	Wadhwa et al. (2007)	ANP	Super Decisions																	
5	Chan et al. (2008)	Fuzzy AHP										SO					✓			
6	Peidro et al. (2009)	Fuzzy MILP	CPLEX		✓	✓	✓	✓			Shipment among nodes	SO	✓	✓	✓					
7	Ho et al. (2010)	MCDM	SLR																	
8	Wu and Barnes (2010)	Dempster–Shafer theory	Optimization																	
9	Shaw and Khan (2012)	Fuzzy optimization	Optimization			✓							✓	✓						
10	Chai et al. (2013)	Interval Valued Fuzzy Intuitionistic Fuzzy Set (IVIFS)	Optimization			✓												✓		
11	Carvalho et al. (2012)	Simulation	Arena			✓		✓			Zero Inventory	SO	✓						✓	
12	Schmitt and Singh (2012)	Discrete event system simulation	Arena			✓		✓					✓							
13	Klibi and Martel (2012)	Monte-Carlo system simulation	SC Studio	✓		✓														✓
14	Sawik (2013b)	MIP	AMPL+CPLEX Solver			✓	✓			✓	Order quantity and emergency inventory allocation	SO	✓							✓
15	Sawik (2013a)	Stochastic MIP	AMPL+Gurobi		✓	✓	✓			✓	Parts-customer assignment	SO	✓		✓					✓
16	Sawik (2014a)	Stochastic MIP	AMPL+CPLEX Solver		✓	✓	✓		✓		Order quantity assignment	SO	✓		✓					✓
17	Ivanov et al. (2014b)	NLR	Narration																	✓
18	Chopra and Sodhi (2014)	NLR	Narration																	
19	Fahimnia et al. (2015b)	SLR	Systematic																	
20	Heckmann et al. (2015)	SLR	Systematic																	
21	Pishvaee and Razmi (2012)	Multi-objective possibilistic mixed integer programming	Lingo	✓		✓	✓		✓		Flow conservation	MO		✓	•	✓			•	
22	Pishvaee et al. (2012)	Robust Possibilistic Programming	Lingo	✓		✓	✓				Flow conservation	MO			•				•	
23	Vahdani et al. (2013)	Fuzzy possibilistic chance-constraint mixed integer programming	GAMS	✓	✓		✓				Flow constraint and Customer assignment	MO		✓		•			•	
24	Amin and Zhang (2013b)	Fuzzy mixed integer Non-linear programming	GAMS		✓	✓	✓				Flow conservation	MO		✓						
25	Amin and Zhang (2013b)	MILP	CPLEX	✓		✓	✓		✓		Flow conservation	MO		✓	✓	✓			•	
26	Ramezani et al. (2013a)	Stochastic Programming		✓	✓		✓				Facility selection Flow conservation	MO		✓		•			•	
27	Ramezani et al. (2013b)	RO	GAMS + CPLEX Solver	✓	✓		✓				Facility selection Flow conservation	MO		✓		•			•	
28	Govindan et al. (2015)	Meta-heuristic	MATLAB	✓		✓	✓	✓			Flow conservation Less than truck load Transport-related	MO		✓						
29	Zeballos et al. (2014)	MILP	GAMS+ CPLEX solver	✓	✓				✓	✓	Flow conservation	SO	✓	✓						
30	Keyvanshokooh et al. (2016)	MILP	GAMS+CPLEX solver	✓	✓		✓				Flow conservation	SO	✓	✓					•	
31	Ekşioğlu et al. (2009)	MILP	CPLEX		✓	✓	✓			✓	Flow conservation	SO	✓							

(*continued on next page*)

- What are the major constraints followed to design the SC network?
- What are the different types of drivers of risk considered in past studies?

Table 6 (*continued*).

S.N.	Author(Year)	Technique	Tools	Decision Variables			Constraint (only the major ones)					Objective	Risk Type							
				S	T	O	C1	C2	C3	C4	C5	SO /MO	S	D	P	C	Q	I	T	F
32	Zamboni et al. (2009b)	MILP	GAMS+CPLEX Solver	✓	✓	✓	✓		✓			MO								
33	Huang et al. (2010)	MILP	AMPL+CPLEX	✓		✓			✓		Resource constraint and Technology	SO								
34	Iakovou et al. (2010)	Inventory theory				✓	✓					SO	✓			✓				
35	An et al. (2011a)	NLR	Narration																	
36	Gold and Seuring (2011)	SLR	Systematic																	
37	Dal-Mas et al. (2011)	MILP	GAMS+CPLEX Solver	✓		✓	✓			✓	Transportation link	SO		✓						
38	An et al. (2011b)	MILP	CPLEX	✓	✓	✓	✓				Transportation link Technology selection			✓	•					
39	Qiao et al. (2013)	MILP	CPLEX	✓		✓	✓			✓	Flow conversation and CO2 emission	SO								
40	Arashpour et al. (2017)	Integer Programming		✓		✓				✓		SO	✓							
41	(Birge, 1997)	Stochastic Programming				✓						SO		✓						
42	(Owen, 1998)	Sampling																		
43	Sabri and Beamon (2000)	MILP+NLP	LINGO	✓		✓	✓			✓	Production-related	MO		✓		✓			✓	
44	Tsiakis et al. (2001)	MILP	CPLEX	✓		✓	✓				Network structure Flow conservation Transport link	SO		✓						
45	Daskin et al. (2002)	NLP	Delphi	✓		✓			✓	✓		SO		✓						
46	Jayaraman and Ross (2003)	MILP	LINGO	✓		✓	✓		✓		Cross-dock assignment constraint	SO								
47	Santoso et al. (2005)	MILP	CPLEX	✓		✓	✓		✓	✓	Flow conversation	SO	✓	✓		✓			•	
48	Aghezzaf (2005)	MILP	CPLEX	✓			✓				Flow conservation	SO		✓						
49	Chopra et al. (2007)					✓						SO	✓							
50	Snyder and Daskin (2005)	MILP	CPLEX	✓		✓	✓				Flow conservation	MO	✓	✓						
51	(Beamon, 1999)		Descriptive																	
52	Srivastava (2007)	NLR	Descriptive																	
53	Linton et al. (2007)																	✓		
54	Dehghanian and Mansour (2009)	MILP	LINGO+ Matlab	✓		✓	✓				Flow conservation	MO								
55	Ahumada and Villalobos (2009)	NLR	Descriptive																	
56	Bai et al. (2010)	Rough set theory		✓								SO								
57	Kuo et al. (2010)	ANN+DEA +ANP		✓								SO								
58	Wang et al. (2011b)	MILP	CPLEX	✓		✓				✓	Flow conservation Environmental consideration	MO								
59	Wang et al. (2011a)	Regression analysis	MATLAB			✓						SO								
60	Kannan et al. (2013)	Fuzzy multi-objective programming	LINGO	✓		✓			✓	✓	Quality control	MO								

Such information provides opportunities in terms of tackling the challenges of modeling risk that have not been considered in the previous literature. Previous studies on SCR reveal that, within the inter-temporal dimension, strategic and operational issues have attracted researchers interest more than tactical issues (Pishvaee and Razmi, 2012; Amin and Zhang, 2013b; Govindan et al., 2015). Similarly, procurement, manufacturing, and distribution appear more important than sales, customers, and logistics within the functional dimension (Peidro et al., 2009; Ekşioğlu et al., 2009; Zamboni et al., 2009b), whereas facilities and clients are more important than warehouses and vendors within the spatial dimension (Kumar and Alvi, 2006; Kannan et al., 2013). Similarly, insights are drawn from Table 6.

Fig. 10 categorizes the papers based on the methodologies adopted for the pool of generated research clusters. Fig. 11 depicts a trivial but crucial analysis using a pie-chart representation. The first figure concerns the type of objectives considered in this study. As can be seen, 42% of studies consider a single objective, whereas 25% consider multiple objectives such as CO_2 emissions, social-related issues, and flexibility measures. The rest are not typical network design methods but represent different techniques such as inventory modeling and review work in the past literature. It should be noted that, in most previous studies, SCR as a

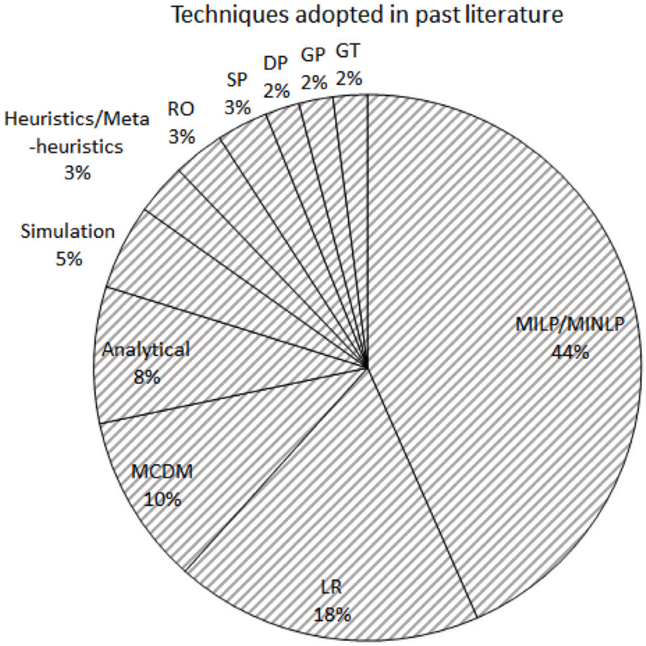

Fig. 10. Types of modeling techniques used in past studies.

measurement goal was lacking. Measurement in terms of the recovery period is inescapable, particularly when evaluating planning strategies. For example, Ivanov et al. (2016a) developed a multi-stage SC (re)planning program for evaluating recovery policies to redirect material flows in case of disruptions. The following figures illustrate the simultaneous use of a type of decision variable (DV) in past modeling studies. Any planning process in the SC must consider three basic decision types: strategic, tactical, and operational.

The figure represents information related to the class of papers that consider a single DV, two DVs, or more than two types of DV. Of the total number of studies under observation, 72% considered two or more types of simultaneous decision making. However, few studies involved all three types of decision making in their respective analyses. The purple segment of 5% in the above figure presents literature review papers from Table 6. The third figure is related to the type of uncertainty considered in the various models. By type, we refer to the disruption in quantity, as illustrated in Peidro et al. (2009), Sawik (2013b), due to various unforeseen events or uncertainties in input information (Ramezani et al., 2013b; Keyvanshokooh et al., 2016). Integrating all three levels of decision making under a single scenario is a challenging task (Graves and Willems, 2005; Zamboni et al., 2009b; An et al., 2011b). Almost all studies considered a single type of uncertainty, but not both. However, in the actual scenario, the information might be missing, incomplete, or adverse, thus leading to unsuitable and ill-informed decision making, which would damage system performance. The next section provides a microlevel analysis of an individual cohort of studies. The analysis presents a high amount of correlation within the clusters and, to some extent, inter-linkages among the clusters.

5. Theme-based research implications and future research directions

The detailed procedure for theme generation is provided in Section 3.3 and Table 5. We classified the lead papers in respective clusters based on their scope, methodology, application type, major contributions, and research gaps. Following this, the underlined section briefly discusses the developments in each theme and suggests some prospective research streams for future consideration. The findings are enhanced with the help of holocultural analysis among the identified lead papers and recently published articles on a given topic in a pool of 3672 articles.

5.1. Selection and evaluation of SC entities (for example, suppliers, production processes, and warehouses) in an SCND setting

Some crucial decisions, apart from SC nodes, arcs, and flows, are the evaluation of SC stakeholders or interconnected SC entities. The major players in the initiation of SC operations are the suppliers; therefore, making the right decision to choose the best material providers is a crucial task. Previous studies explored this area in detail. The cluster largely describes various studies that are part of this evaluation process and proposes different techniques to find reliable suppliers. The scope of the papers and a brief discussion of the methodology is presented in Table 7. We now analyze the papers with reference to their future scope and selling proposition. For example, older concepts of game theory (Cachon and Zipkin, 1999) were used as well as decades-old applications such as fuzzy sets (Chan et al., 2008); (Chai et al., 2013) to find optimal solutions for inventory policies (Shaw and Khan, 2012), sourcing

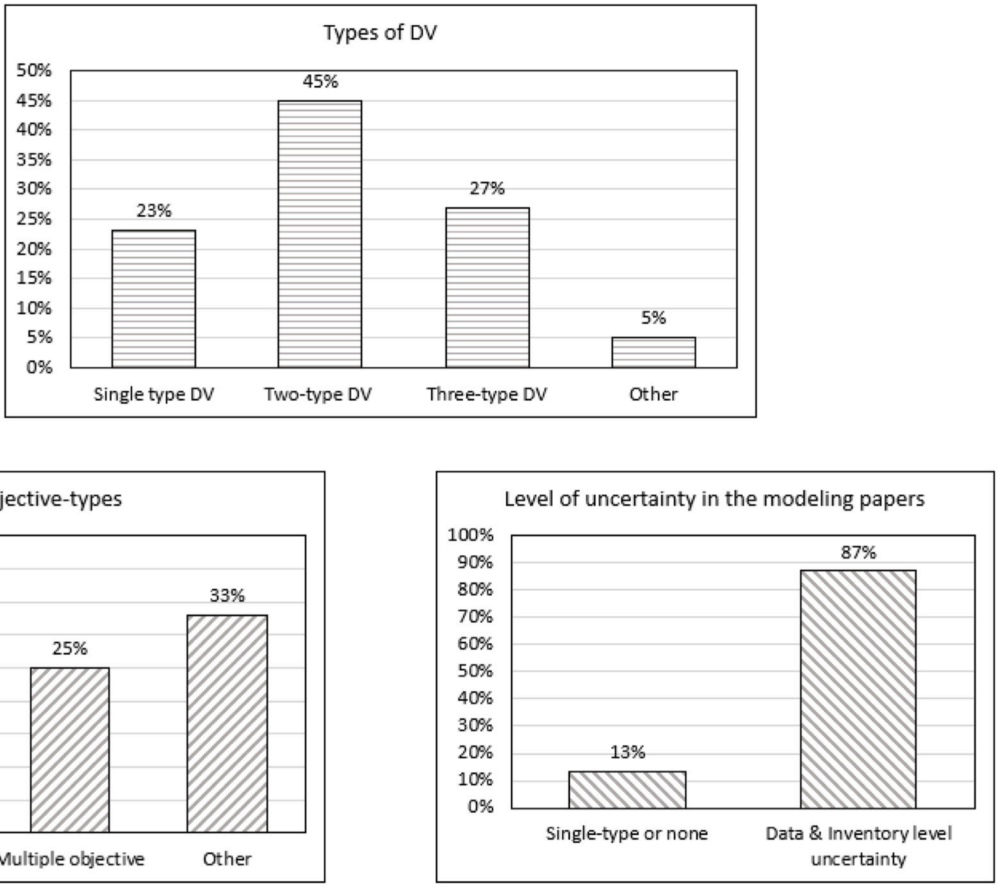

Fig. 11. Analysis related to objectives type, techniques, uncertainty, and decision variables considered in the past studies.

decisions (Graves and Willems, 2005), warehouse evaluation (Chai et al., 2013), and agile suppliers (Wadhwa et al., 2007); (Wu and Barnes, 2010) for protecting SCs against disruptions (Peidro et al., 2009). Mathematical formulations are used for vendor selection by defining the problems as multi-objective integer programming (Kumar and Alvi, 2006; Tsao and Thanh, 2019). Lin and Chen (2004) proposed incorporating SC experts' and practitioners' subjective judgments in selecting an agile player in SC operations. In contrast, Wu and Barnes (2010) proposed a Dempster-Shafer technique, which consists of a three-level classification system to identify criteria for supplier evaluation, applicable in any business setting. Briefly, the method is based on the structure proposed by Wu and Barnes (2010). An important observation from these studies is that none of the studies has implemented procedures for resilient suppliers. After inspecting, we observed that Rajesh and Ravi (2015) proposed a grey relational approach to evaluate resilient suppliers by defining a set of resilience criteria based on the literature and an evaluation strategy in case of vague information. The requirements are not exhaustive, and they need modification based on the type of industry and scenario context. Thus, the procedure adopted by Wu and Barnes (2010) can be used in cases of a resilient environment for selecting and evaluating SC entities.

We generalize the approach proposed by Lin and Chen (2004) based on the Dempster–Shafer theory in Fig. 12. Lately, supplier selection problems have been combined with optimization approaches; for example, selecting resilient suppliers and making operational decisions for creating a surplus or restoring capacity using linear-programming-based tools (Hosseini et al., 2019b). Mari et al. (2019) combined order allocation and supplier selection problems in a fuzzy environment and solved a multi-objective problem. One of the objectives includes calculating the resilience score of the suppliers. Parkouhi et al. (2019) identified SCR enablers and barriers and solved a supplier-segmentation problem using the Grey DEMATEL technique. Moreover, identifying such an indicator will always pose challenges of validity and cogency. A similar study was performed for social and environmental risk assessment considering only the drivers for SCR in a real-life application setting for an electronic company (Rajesh, 2019).

Collectively, most studies suggest the following challenges for future research:

- Concurrent effects of operational risks, delays in logistics, and disruptive risk on SC performance (Hosseini et al., 2019b).
- Combining two subjective notions of resilience and leanness to achieve "zero waste and zero time" to promote resilience in supplier segmentation (Ivanov et al., 2019a).

Table 7
Selection and evaluation of SC entities (for example, Suppliers, Production processes and Warehouses) in an SCND setting.

Sr No	Author (Year)	Methodology(Technique)	Scope	Research Gap and Contribution	Industry
1	Cachon and Zipkin (1999)	Incentive contracts in competitive and cooperative SC using game theory	Two echelon inventory optimization model	Information sharing leads better decision policies for cooperative SC than competitive SC	NA
2	Graves and Willems (2005)	Dynamic programming approach to determine SC configuration for new products	To identify which vendors to select, which manufacturing technologies, and which shipment options to choose	The paper provides a novel approach through dynamic programming for providing solutions related to SC configuration associated with the new product SC. The SC configuration evaluates multiple options during each stage and compares them to provide better network design decisions.	Computer Industry
3	Kumar and Alvi (2006)	Vendor selection under vague information using fuzzy multi-objective goal programming	Vendor selection under imperfect information	In reality, incomplete information related to capacity, delivery standards, lateness about vendors is known. The authors identified the good vendors based on the performance of quota flexibility. Three objectives were considered: net ordering cost, rejected items cost, and late delivered items due to vendors under uncertain environment.	Automobile sector
4	Wadhwa et al. (2007)	ANP to achieve agility	To evaluate enterprise agility based on responsible agile actors such as market, product, and customer	The study achieves enterprise agility in market competitiveness and serves as the benchmark for various industries. The framework captures all the significant actors such as market, product, and customers agility to attain organizational agility.	NA
5	Chan et al. (2008)	Fuzzy AHP for global supplier selection	The scope lies in finding global indicators of risk for the selection of suppliers.	To evaluate three global suppliers, the model recognized five major factors: cost of ownership, quality, service, background, and risk factors. A total of nineteen sub-criteria are selected based on past studies. A different criterion to evaluate risk factors is considered.	Manufacturing
6	Peidro et al. (2009)	Fuzzy mixed integer linear programming problem	The scope of this study is comprehensive and applies to solve practical problems wherever the information about the parameters is incomplete or vague, e.g., Demand information. The model addresses significant questions in SC planning such as inventory management, vendor selection, transport planning, distribution, etc.	The paper proposed a novel approach to solve tactical SCM issues of procurement, production, and distribution of automobile SC. The model utilized fuzzy numbers to model the uncertainty in the information.	Automobile SC
7	Ho et al. (2010)	Review on MCDM supplier evaluation and supplier selection	The study analyzed papers published from 2000 to 2008 on MCDM techniques applied to solve supplier selection, and supplier evaluation problems	The review address majorly three aspects; (1) prevailing approaches in the area specified. (2) Evaluating approach given more attention. (3) Identify inadequacy in approaches applied.	NA
8	Wu and Barnes (2010)	Agile partner selection criteria based on Dempster–Shafer theory	A general framework applied for the selection of partners for business needs, irrespective of business categories.	The Dempster–Shafer theory provides an advantage of focusing on individual suppliers' selection criteria rather than general factors. The study classified all the criteria into seven major categories: production and logistics management, Partnership management, Financial capability, Technology and knowledge management, Marketing capability, Industrial and organizational competitiveness, and Human resource management.	Chinese Electrical SC
9	Shaw and Khan (2012)	Heuristic approach to find optimal policies	The study extends the classical EOQ system considering stochastic parameters such as fuzzy demand, lead time, penalty cost, and inventory holding cost and evaluates the system performance in a series of three connected facilities	The traditional system of ordering policies assumes demand and other parameters are deterministic. This study tries to relax this constraint and consider practical challenges of fuzzy demand and penalty due to stock out at different stages of SC echelon and solve using a heuristic developed by authors.	NA
10	Chai et al. (2013)	Five aspect analysis methodology is proposed to solve problem to find among the alternatives, the best warehouse for future usage	The study is applicable in cases where decision-makers want to evaluate among the different options available for selection. Specifically, the approach is applied to select a new warehouse based on expert-designed criteria.	In cases of subjective preferences, IVIFS is better and suitable in comparison with fuzzy sets. (1) Authors incorporated techniques to determine the importance of experts' judgments apart from finding the preference order of all the alternatives. (2) This unique rule-based method originates in a dominance-based rough set approach and considers a human ranking in the account.	NA

- Approximately 60% of studies were developed based on independent methodologies such as the AHP approach, multi-objective programming, and ANP approaches. Therefore, scope exists for combining two or more approaches (integrated AHP, ANP-GP, AHP, and multi-objective) to solve a single objective problem (Ho et al., 2010).
- Some of the notable factors considered in the studies are quality, delivery, price/cost, manufacturing capability, finance, flexibility, reputation, risk, and environment. Moreover, other risk types, such as social, political, and organizational, are overlooked in the modeling literature (Wu and Olson, 2010).

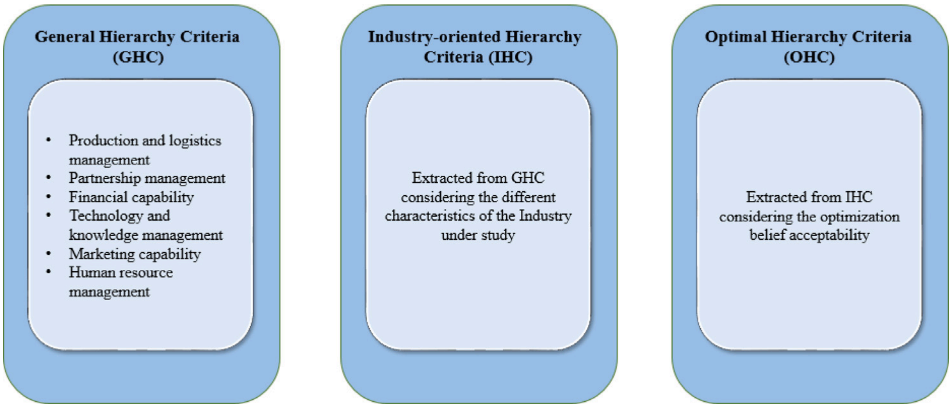

Fig. 12. General presentation for Dempster–Shafer acceptability optimization approach.

5.2. Generalized stochastic programming and robust optimization approach to model uncertainty and achieve SCR

The robust programming (RP) approach is widely deployed to solve problems related to uncertainty in input data. The solution methodology helps avoid unpredicted terminations and unexpected actions. Evolutionary work in RP was performed by Soyster (1973) for inexact linear programming problems. Later, the method was extended to solve scenario-based stochastic programming models by Mulvey et al. (1995), Ben-Tal and Nemirovski (2000), and Leung et al. (2007). Other significant contributions in RP were developed by Ben-Tal and Nemirovski (1998, 1999, 2000), and El Ghaoui et al. (1998) by considering various convex uncertainty sets. We describe the general framework of RP, as stated in the literature presented by Leung et al. (2007), Pan and Nagi (2010) in Appendix Eqs. (B.1) to (B.21). Mean Variance (MV) models are primarily applied to the inventory management domain by Katariya et al. (2014), Xue et al. (2015), Arıkan and Fichtinger (2017), Xu et al. (2018), and Xu et al. (2017), and closed form solutions were proposed, primarily, to provide optimal ordering and hedging decisions. Similarly, Bai et al. (2010), Snyder (2006), Sawik (2011b, 2013a,b), Ahmadi-Javid and Seddighi (2013), Hatefi and Jolai (2014), Sadghiani et al. (2015), Jabbarzadeh et al. (2016), Keyvanshokooh et al. (2016), and Sawik (2017) have proposed solutions for optimal distribution, inventory, and transportation plans in SC management contexts implementing MV models. Sawik (2011b, 2013a,b), and Sawik (2017) presented problems dealing with supplier selection and optimal ordering, where demand is deterministic and known a priori. CVaR is incorporated to limit the increasing amount of total cost composed of the sum of ordering, purchasing, defect, and shortage costs. The presented models mainly encourage the diversification of supply portfolios to avoid delay risk in order fulfillment in case of disruption due to labor strikes, bankruptcy, or natural disasters. Specific to network design models, MV models can be found in papers listed in Table 8.

The primary aim of the theme is to lay the foundation for the mathematical basis of applying RO and SP with risk-neutral characteristics in future applications. It also explains the past findings and the OR challenges for the implementation of these tools. Table 8 presents various articles that consider these two methodologies. It also highlights other information related to stochastic parameters, decision making scenarios, and the scope of the work. All of these studies adopted MV models to manage downside risks. Numerous applications of such models are observed in the OR domain, but hardly any papers have incorporated the generalized guidelines for the application of these models, which is proposed in the existing study. In addition, some of the questions that can be addressed in future research are as follows:

- There is scope for future studies to provide exact algorithms that can be applied to universal network design problems in a more general context. All models discussed above solve a specific type of structured problem in network design. More specifically, the CVaR-based general MILP framework with the CVaR objective can be considered as future work.
- As computing time and complexity are concerned, there are hardly any models that provide a general framework for the MV-based LP approach, especially for CVaR-based models. CVaR models can capture the severity of the losses for a specific choice of decision makers as compared to other MV models.
- To avoid solution hardness, most LPs or MILPs with constrained optimization with a complex structure of solution are solved using a scenario-based modeling approach and commercial solvers of CPLEX or MATLAB (Snyder, 2006; Ahmadi-Javid and Seddighi, 2013; Jabbarzadeh et al., 2014; Sadghiani et al., 2015; Namdar et al., 2018; Zeballos et al., 2018). However, it requires numerous scenarios, which indirectly affect the accuracy of the MV models. Therefore, future studies exploring a better theoretical proof for fixing inaccuracy in MV models are encouraged.
- Within the MV category, VAR and CVaR-based models are highly encouraged in the past literature compared to other types of formulations as they provide superior solutions by dealing with under-and-over-performance equally (refer to Proposition 2.1 by Noyan (2012)). However, the debate on the confidence level of decisions and the trade-off between solution robustness and model robustness are still relevant in the present context.

Table 8
Scope and main characteristics of MV models.

Authors	Scope	Decision-making	Stochastic approach	Risk management approach
Tomlin and Wang (2005)	SC design	General	Product demand	Flexible and dual sourcing
Leung et al. (2007)	Multi-site production planning	Robust optimization	Economic cost	NA
Yang et al. (2009)	SC coordination	Mean-CVaR	NA	Revenue sharing, buy-back, flexibility contracts
Goh and Meng (2009)	Production, inventory, and Transportation	SAA Two-stage SP	Demand, Production cost	NA
Carneiro et al. (2010)	Investment planning of SC design	Two-stage SP	Demand, investment cost	Diversification of portfolio investment
Wu et al. (2010)	SC contracts	Unconstrained optimization	Uncertain procurement quantity	NA
Pan and Nagi (2010)	SC design	RO	Uncertain demand	Agile SC
Noyan (2012)	Disaster management	Two-stage SP Benders decomposition	Uncertain demand	NA
Pishvaee et al. (2012)	SC design	Fuzzy possibilistic programming	Fuzzy demand	NA
Claro and de Sousa (2010)	Multi-stage capacity investment	Variable neighborhood and Tabu search	Demand and investment cost	Process flexibility
Soleimani and Govindan (2014)	CLSC design Location–allocation	VAR, CVaR, MAD, Two-stage SP	Demand, return, prices	NA
Namdar et al. (2018)	SC design	Scenario-based two-stage VAR, CVaR SP	Disruption intensity	Back-up, Spot purchase, visibility, and collaboration
Yu and Zhang (2018)	Facility location	Multidual decomposition algorithm	Facility disruption	NA
Zeballos et al. (2018)	CLSC design	Two-stage SP	Return	NA

- The parameter α considered in the mathematical presentation affects the objective values. The parameter $\alpha -> 0$ denotes risk-neutral decision making, whereas $\alpha -> 1$ represents the maximum risk mode. In particular, in SC design studies such as Sawik (2013b), Ahmadi-Javid and Seddighi (2013), Soleimani and Govindan (2014), Namdar et al. (2018), and Zeballos et al. (2018) the values range between 0.90 and 0.99. There is not enough evidence that selecting α in these sets of values produces more competitive results than the minimax approach. Hence, future models can be developed to provide a more practical solution with reference to the selection of the α parameter.
- Similarly, λ is another reason for concern when dealing with risk objectives in Eqs. (B.7) and (B.17). It is a weight assigned to the objective function (risk part) based on the risk preferences of the decision-maker. It raises the weight of the risk in the model and promotes a more risk-averse behavior. Therefore, an appropriate parametric analysis for determining the ideal value of λ should be performed in future studies.

5.3. Modeling disruptions to design a resilient SC network

Disruption management, specifically in the context of SC network design, has received significant attention recently (Hendricks and Singhal, 2005; Dolgui et al., 2013; Sawik, 2013b,a, 2014a; Hasani and Khosrojerdi, 2016; Ivanov et al., 2017; Ivanov and Rozhkov, 2017). As noted in Rajagopal et al. (2017), risk propagation analysis has been one of the most frequently used mitigation strategies in the face of disruption, and the ripple effect has promoted this type of research in recent times (Ivanov et al., 2017).

Table 9
Modeling disruptions to design a resilient SC network.

Sr No	Author(Year)	Methodology(Technique)	Scope	Research Gap and Contribution	Industry
1	Carvalho et al. (2012)	Evaluate SCR strategies against SC disturbances using a simulation approach	The study analyses and evaluates strategies to mitigate the negative impact of disturbances	The study evaluates the importance of redundancies and flexibility strategies to curtail the impact of SC disturbances. The simulation model developed considers two-echelon SC with one automaker with 1st and 2nd tier suppliers. It includes a real industrial problem of automobile manufacturing prone to disruptions due to delays and over-reliability on auto parts.	Automobile Industry
2	Schmitt and Singh (2012)	A discrete event system simulation approach to review mitigating strategies against SC disruptions and demand uncertainty	The scope of the study revolves around maintaining inventory throughout SC, managing backup capabilities, deal demand spikes due to customer's reactions to disruptions	The simulation model caters to the need to fight against operational and disruption risk for multi-product, multi-level SCN. The study also proposes proactive approaches to deal with different risks such as backup strategies, speeding the responsiveness to deal with demand spikes, etc.	Packaging Industry
3	Sawik (2013a)	a MIP approach to address supplier selection and customer order allocation problems under local and global level disruption challenges	A modeling approach to solve supplier selection problems under disruption at regional and international levels and consider single and multiple sourcing strategies.	The optimization model solves a customer order allocation problem under local and global events of disruption. The model includes the risk attitudes of decision-makers. It evaluates single vs. multiple sourcing strategies.	NA
4	Sawik (2013b)	A mixed-integer programming approach to select resilient suppliers and protect the supplier against the disruption risk	The study identifies resilient suppliers and protects them under the threat of disruption. It facilitates them to send the order by allocating emergency inventories.	No studies in the past have discovered such a methodology to evaluate resilient suppliers. Fortifying suppliers against disruption risk is proved with MIP modeling.	NA
5	Sawik (2014a)	Joint decision making of customer order allocation and supplier selection under single and dual sourcing strategy	The decision-making approach makes decisions of supplier selection and order quantity allocation simultaneously.	The author proposes a novel stochastic MIP problem to make supplier selection decisions coupled with customer order allocation and scheduling on selected suppliers under a single and dual sourcing strategy subjected to domestic and global disruption risk.	NA
6	Ivanov et al. (2014b)	A framework for understanding the quantitative models proposed on SC disruption management under ripple effect	The scope of this paper revolves around the rippling effect and impact on the economic performance of SC. The article describes models designed to overcome ripple effects by robustness reserves and scale and speed of recovery measures.	The study put forward a multidisciplinary framework for development in SC dynamics, control, and disruption management. The importance is given to reasons for disruption in SC, mitigating risks and uncertainty.	NA
7	Chopra and Sodhi (2014)	Reducing risk and improving the performance of SCs based on case studies and examples	Often the business world appreciates the disruption impact but is reluctant to curb or reduce them. Authors believed that reducing risk has less importance until its worth is calculated on cost efficiency. The scope of this article is to describe the significance of decision-making under disruption irrespective of its actual occurrence.	The need to balance between cost efficiency and risk reduction is discussed. Optimal choice under such circumstances is hard to make, which is why the primary aim of this article. Various contribution involves segmentation and regionalization in SC, also reducing the concentration of resources, etc.	General SC
8	Fahimnia et al. (2015b)	Co-citation analysis and PageRank algorithm to find research themes and research directions	To identify potential areas of research under SC risk and uncertainty management literature	Bibliometric analysis is a systematic approach to understanding and analyzing any area of research and coming up with potential future scope. The study mainly targets this objective by using Bibexcel and Gephi software tools to suggest prospective themes for future research.	General SC
9	Heckmann et al. (2015)	An SLR on SC risk and foundation for SC risk, mitigation strategies, and modeling approaches implemented to tackle risk situations.	The paper primarily aims at defining, quantifying, and modeling risk employing reviewing of relevant literature. Although the study considers empirical and conceptual documents, the target is to know mathematical aspects of SC risk and its mitigation strategies	Risk is an inclusive term and omnipresent in almost all business settings. Often the risk is analogous to unwanted events in day-to-day operations. However, a proper understanding of risk is missing in SCRM literature, which this paper addresses.	General SC
10	Klibi and Martel (2012)	A risk-modeling approach to deal with disruptions based on their severity of occurrences using the Monte Carlo method	The study can be executed in situations involving meta-events (multiple hazards) that affect the SC resources and markets.	The stochastic programming approach can be a suitable modeling approach in lieu of the proposed methodology.	General SC

Studies by Liberatore et al. (2012), Ivanov et al. (2014b,a, 2016b), Sokolov et al. (2016), and Ivanov (2017) have promoted such research in particular to examine the dissemination of the impact caused by disruption risk throughout the SC. Ivanov et al. (2014b) pointed out that the impact of disruptions is severe in the case of SCs characterized by complex structures, lean philosophies, geographical spread, and propensity to IT failures. Table 9 presents the relevant literature.

Mitigation strategies were promoted to fight such risk and create resilient SC networks using methodologies such as discrete event simulation (Bottani and Montanari, 2010; Ivanov, 2017, 2018; Das and Dutta, 2015; Dolgui et al., 2018); and others), two-stage or multi-stage stochastic programming (Schmitt and Singh, 2012; Klibi and Martel, 2012; Torabi et al., 2015). Past studies also suggest recovery and mitigation as two plans of action for dealing with disruption. Therefore, approaches such as graph theory, RP, SP, FP, System Dynamics (SD), and control theory can be used. A series of techniques developed by Sawik (2013b,a), and Sawik (2014a) for finding resilient strategies for dealing with SC disruption can be referred to for finding solutions relating to selecting resilient suppliers, identifying the risk attitudes of decision-makers, and adopting the best sourcing strategies (Table 9). Scenario-specific studies to visualize the probabilistic nature of risk will benefit from such types of analysis. For example, Hosseini et al. (2019b) designed a resilient network inclusive of disruption scenarios and made operational choices relating to the inventory status. Moreover, a real-life case study with a better scenario approximation would result in an impactful contribution to this field. Apart from this, the papers do not consider objectives related to SCR characteristics such as restoration time (Raj et al., 2014), recovery strategy (Mao et al., 2020), and responsiveness Ramezani et al. (2013b). We also identified a few studies considering multiple conflicting goals (Rajagopal et al., 2017). Future SCs should be based on low-certainty-need (LCN) strategies (Ivanov and Dolgui, 2019), in which the SC behaviors should be less dependent on knowledge about the environment and its changes. More resilient strategies are required to achieve such goals. In times of pandemic situations, the regionalization of SC becomes the need of the moment, and businesses should create efficient vertical integration (Chopra and Sodhi, 2014). A vast body of literature on SC management fosters lean principles of zero stock and fast delivery, thus promoting intense cost-reduction policies. However, such principles make SCs more vulnerable in times of disruption and reduce their resilience capacity. A promising scope within SCR is to achieve efficiency (leanness), in addition to strengthening robustness (resilience); this can be explored in future studies.

5.4. Uncertainty modeling in SC network design for closed-loop SC and reverse SC

This cluster mainly caters to design-level challenges in addressing disruptions and uncertainties in CLSC and reverse logistics (RL) networks (Table 10). Pishvaee and Razmi (2012), Pishvaee et al. (2012) designed a forward-reverse SC for a medical company by considering the total cost as well as the environmental impact as the objectives. A scale is derived from formulating an ecological goal from Eco-indicator 99 reference tool. The impact on all SC entities was calculated based on the methodology proposed by Goedkoop et al. (2000). Extrapolating along similar lines, Pishvaee et al. (2012) designed a similar configuration for a socially responsible SCN using the Robust Possibilistic Programming (RPP) approach. In this study, the measures adopted to formulate social objectives were based on four indicators: (1) the number of potentially hazardous products; (2) the number of lost days caused by worker disruption; (3) the number of waste items produced; and (4) the number of job opportunities created. The theoretical contribution in terms of RPP over earlier robust approaches is discussed, with weaknesses, strengths, and application suitability. A multi-echelon, multi-facility, multi-product, and multi-supplier CLSC, which efficiently makes decisions related to collection centers with failure cost as the objective, was designed by Vahdani et al. (2013). The study reveals that the total cost is more sensitive to transportation costs than the cost due to demand variability.

Amin and Zhang (2013a) designed a CLSC configuration to provide order allocation decisions. The formulation includes multiple objectives of the total cost, weights for selecting various stakeholders, the defect rate of items, and on-time delivery. The study also captures single-versus multiple-sourcing strategies and proposes quality function deployment to evaluate external suppliers, re-manufacturing subcontractors, and refurbishing sites. Further, Amin and Zhang (2013b) supplement the above study by considering the amount of clean technology such as solar power used in SCND. The model also captures the impact of demand uncertainty. According to this study, for a 10% increase in demand, the network cost increased by 6.67%. At the same time, a decrease of 10% in demand reduces the network cost by 6.49%. The study also reveals that stochastic demand's impact is higher compared with variability in product returns. Ramezani et al. (2013a), in their research, provide a Pareto-optimal solution of maximization of profit, responsiveness, and defect rate (quality) for the forward-reverse logistics network with conflicting objectives. As stated in the conclusions, the responsiveness increases for a given network, and the decrease in profit and an increase in the defect rate. A quality-level suggestion can be considered as the financial risk impacts significantly on the defect rate. The study was then modified in solution using a robust optimization technique (Ramezani et al., 2013b). The results were compared with the deterministic equivalent. Although the values for the deterministic model are better than RO, the RO approach is reliable in terms of its solution. The deterministic configuration is also infeasible under specific values of demand and return rates. The proposed model successfully provides solutions for up to four layers in both channels: forward flow (supplier, plant, distributor, and customer) and reverse flow (customer, collection center, repair center, and disposal center). A brief perusal of the cluster studies also highlights theoretical contributions by Govindan et al. (2015) in the field of advanced algorithm design. The authors developed a multi-objective hybrid approach (MOHEV) together with MOPSO and NSGA-II. The MOHEV combines AMOEMA (multi-objective electromagnetism mechanism approach) and AMOVNS (adapted multi-objective variable neighborhood search). AMOVNS provides a better solution, whereas AMOEMA helps to answer to avoid a local optimum. A solution-level contribution is proposed by Keyvanshokooh et al. (2016), improving the lower bound by introducing two valid inequalities into the main problem. These inequalities are mainly used to deal with capacity-related problems and facility availability issues. A Latin hypercube sampling technique is proposed to generate scenarios for uncertainty in transportation costs. However, the study does not consider the disruption impact on SC operations during modeling but assigns it as a scope for future research. On similar lines, Table 10 presents various studies and explains their respective scope, novelty, and tools for uncertainty modeling.

Although researchers have meticulously tackled the problems of uncertainty modeling in CLSC and RL networks, potential avenues for future work include the following:

- With regard to methodology, Bayesian networks can serve as a prospective tool for managing pre- and post-disaster situations as well as generating various risk scenarios (Hosseini and Barker, 2016). It can make knowledge-based decisions based on historical data. In our opinion, this technique is the least adopted in dealing with uncertainty issues in SC design.
- In addition to the above technique, two-stage SP and RP can be included to handle various uncertainties and simulate real-life business problems.

Table 10
Uncertainty modeling in SC network design for closed-loop SC and reverse SC.

Sr No	Author (Year)	Methodology(Technique)	Scope	Research Gap and Contribution	Industry
1	Pishvaee and Razmi (2012)	To provide an integrated solution for forward-reverse SCND under uncertainty using fuzzy programming approach	The authors solve a practical problem of SCD for a medical company by considering the environmental impact of hazardous products in their SC, considering uncertainty in input data	To the best of our knowledge, this paper is the first to design an environmental SCND problem considering uncertainty in data. A computationally tractable multi-objective possibilistic mixed-integer programming model is proposed.	Medical needle and syringe manufacturing company
2	Pishvaee et al. (2012)	Robust possibilistic programming approach to design a socially responsible SCND under uncertain conditions	Such studies primarily help identify the damages caused by specific machinery installed in manufacturing plants on worker life, wastage produced, etc., thus providing benefits of designing socially aware SCND.	This paper has made two novel theoretical and practical implementation contributions —a novel approach of robust possibilistic optimization and social aspect in designing SCN	Manufacturing Industry
3	Vahdani et al. (2013)	A CLSC problem is solved using three approaches; Fuzzy possibilistic approach, interval programming, chance-constraint programming.	The proposed model is suitable to make strategic decisions under uncertainty for CLSCND problems.	Reliability is considered as one of the objective functions while formulating a model. Strategic and tactical SC planning decisions are taken under the uncertainty of input costs. The unique methodology is proposed by combining efficient solution approaches such as the fuzzy probabilistic approach, interval programming, and chance constraint programming. A pseudo case study is presented.	Iron and Steel Industry
4	Amin and Zhang (2013a)	Facility location problem for general closed-loop SC network using weighted sums and ϵ-constraint method	The stochastic programming model considers the return of a product as uncertain compared to (Amin and Zhang, 2013b). Apart from considering uncertainty in input parameters such as transportation cost, production cost, capacities of facilities, etc. and provides a robust SC configuration.	The MILP solves a facility location problem and addresses questions of how much and where to stock the quantities in a CLSC setting. Environmental concerns of eco-friendly material usage and clean technology implementation are unique features of the model.	Electronics SC
5	Amin and Zhang (2013b)	CLSCND under demand uncertainty and uncertain input parameters	The scope of the study is to consider the selection as well as operations decisions simultaneously under uncertain environment, making it more realistic	The significant contribution of this paper is to consider the quality function deployment model to select suppliers, re-manufacturing subcontractors, and refurbish sites. Uncertainty in demand and return product is allowed using equivalent stochastic and fuzzy random variables, and their impact is quantified on SC cost.	Computer and assembly
6	Ramezani et al. (2013a)	Stochastic programming approach for the design of CLSC	A relatively straightforward CLSC network can be designed under uncertainty in input parameters	This study is an excellent contribution to the logistics network design problem with three echelons in the forward direction (suppliers, plants, and center and two echelons in reverse (collection center and disposal center).	logistics network
7	Ramezani et al. (2013b)	A robust optimization approach to design an integrated forward reverse SCN under an uncertain environment	The study has a twofold scope; one in terms of theoretical aspect and another at application based. A novel approach of RO based on scenario relaxation technique is applied to CLSCND and the robust nature of the solution.	Design of CLSC incorporating strategic decisions related to the location of facilities and tactical decisions of procurement, production, and distribution for large business groups such as logistics networks. A novel approach of scenario relaxation algorithm to solve RO problem.	Computer Electronics
8	Govindan et al. (2015)	Multi-objective electromagnetism mechanism algorithm (AMOEMA) and multi-objective variable neighborhood search (AMOVNS)	To design a sustainable SCND considering economic and environmental objective to resolve problem related to order allocation	The study contributes to research in the following ways; a multi-objective problem of SCND with the economic and environmental impact of opening facilities and suppliers selection situations. A criteria-based feature to select suppliers is incorporated. Customer demand is uncertain. Two types of shipments, DC to retailers, and DC-cross docks-retailers, are involved in network structure. As the problem is NP-hard, it is solved using a meta-heuristics approach.	Iranian Automobile
9	Zeballos et al. (2014)	Multiperiod, multi-product CLSCND under demand and supply uncertainty	The study is applicable for CLSCND considering planning periods in modeling	The CLSC structure considers the planning period and Ten-layer network (Five forward and Five backwards). A scenario reduction algorithm is proposed to evaluate uncertainty due to supply and demand. Apart from the traditional objective of cost minimization, the model minimizes the expected revenue due to the amount of product returned.	NA
10	Keyvanshokooh et al. (2016)	Hybrid robust-stochastic CLSCND	The papers consider demand uncertainty apart from uncertain scenarios of transportation cost with the use of a hybrid robust-stochastic optimization approach	Three uncertainties are considered consecutively, delay due to transportation cost, demand, and customer returns. The authors proposed a Latin hypercube sampling method for generating samples for transportation costs. A stochastic Benders' decomposition algorithm and valid inequality to improve the lower bound of the problem were implemented.	NA

- CLSC and RL are high-density networks. Logistics level issues are sparsely discussed in network design (Govindan et al., 2015; Dutta et al., 2016). In particular, disruption in transportation links or routing-level decisions can be a potential area for future research.
- There are few studies that incorporate stochastic modeling in the feedback loop. Parameters such as product return and return cost can be stochastic and have significant importance for SC performance. Such studies are applicable to e-commerce SCs.
- Compared to forward SC, a CLSC and RL network has numerous random variables that affect decision making. Generating the box uncertainty for each of these variables is not a viable solution. Therefore, constructing better uncertainty sets, such as an ellipsoidal uncertainty sets, should be promoted in this research (Ben-Tal and Nemirovski, 1999).

Table 11
Perishable products SC network design models.

Sr No	Author(Year)	Methodology(Technique)	Scope	Research Gap and Contribution	Region
1	Ekşioğlu et al. (2009)	MILP problem to design an SC for biofuel network consisting of two harvesting sites, two collection centers, two biorefineries, and two blending facilities.	The scope of this model is limited to designing a biofuel SC with decisions related to the amount of biomass collected, shipped, and processed between respective facilities	Biomass SC is uncertain, seasonal, and land-dependent. Designing SCN for such conditions requires different strategies, unlike traditional manufacturing. The paper contributes to such a type of modeling under an uncertain environment.	Mississippi (USA)
2	Zamboni et al. (2009b)	Multi-objective mixed-integer programming problem for environmentally concerned biofuel SC	The study developed a deterministic model with the objective of the impact of CO2 emission with standard SC cost components.	The model reduces the daily emission of CO2 during each stage of SC and implements the problem considering real-life cases from a corn-based ethanol production system.	Northern Italy
3	Huang et al. (2010)	Multi-stage mixed-integer linear programming problem	A unique scope of designing SCN and comparing it with a standard for a different source (lignocellulosic) for biofuel production	The model addresses the advantages of lignocellulosic biomass SC as an alternative to the corn-based production system and considers an environmental impact, energy conversion, land usage, etc.	California USA
4	Iakovou et al. (2010)	Dual sourcing strategy for capacitated/uncapacitated unreliable offshore and near-shore suppliers	The model is suitable for identifying the unreliable supplier in case of disruption situations	Disruption probabilities are considered for analyzing offshoring and near-shoring sourcing strategies. Thus the model is stochastic and evaluates a situation of unreliable foreign and domestic suppliers.	NA
5	An et al. (2011b)	Narrative literature review on OR-based approaches to manage bio-fuel and petroleum-based SCs	The paper classifies the research based on the time frame and type of SCs. The authors discussed issues related to agri-food SC, such as harvesting time and perishability.	The research is suitable to explore avenues for promoting viability and growth for the Bio-fuel Industry. Other than this, the critical finding included; no study has dealt with reverse/waste management or downstream operations. Petroleum fuel SC is better studied than biofuel SC. The paper also promotes IT-driven approaches for biofuel SCM.	NA
6	Gold and Seuring (2011)	Fundamental of logistics and SCM for a bio-energy production system using narrative literature review considering a decade of 2000–2010 time period	The scope of the study lies in addressing the following areas; (1) harvesting and collecting biomass, (2) storage throughout the bio-energy chain, (3) transportation in the bio-energy SC, (4) transport pre-treatment techniques, (5) design of the bio-energy production system.	Authors promote empirical studies based on grounded approaches such as stakeholder theory and collaborative paradigm apart from different modeling and simulation approaches.	NA
7	Dal-Mas et al. (2011)	Multi-echelon Mixed Integer Linear Programming problem to design a spatially explicit bio-mass based ethanol SC	The model is applicable in deciding whether to invest in SCN of ethanol production or not where the risk of financial disruption is involved	The MILP optimizes an ethanol production SC for a planning period of ten years, considering economic performances and financial risk. Financial criteria are embraced in the objective function in terms of expected net present value (ENPV) and CVaR.	Northern Italy
8	An et al. (2011a)	The mixed-integer linear programming model for designing lignocellulosic biofuel SC	The problem is applicable in maximizing the profit for lignocellulosic biofuel SC considering multi-commodity, multiperiod model	The formulation includes uncertainties in price, demand, resource cost, and yield. It is one of a kind study where decision-related to the selection of technologies are taken simultaneously.	Central Texas
9	Qiao et al. (2013)	The study proposes a mixed-integer linear programming approach to satisfy transportation fuel demand with the domestically available resource in the US, achieving significant environmental gains using natural gas resources and biomass as compared to petroleum	MILP modeling to design a coal, biomass, and natural gas to liquid (CBGTL) SCND to reduce economic cost as well as environmental impact	This study is a unique application of MILP for designing a SCN for CBGTL SC configuration.	USA
10	Giarola et al. (2011)	MILP modeling to design coal, biomass, and natural gas to liquid (CBGTL) SCND to reduce economic cost as well as environmental impact	To develop a strategic design and planning of corn grain- and stover-based bioethanol SC that includes environmental and financial performances simultaneously	It is the only study that consists of advanced planning of capacities in its modeling framework. Such an approach is of particular importance due to increasing global warming and scarcity of resources, and future studies shall follow the proposed unique methodology.	Italy

- The demand and return amounts are two of the most studied non-deterministic parameters in this cluster. Other parameters regarded as non-deterministic can be value-adding in such a setting; for example, customer fraud risk can reduce logistics costs in RL, especially in e-commerce industries.

5.5. SC network design models of perishable products

The perishability concern of deteriorating goods in the SC context is a much-explored area. This field of study has its roots in the design and analysis of petroleum- and biofuel-based SCs. To our knowledge, the papers that marked the initial groundwork for the development of biofuel SCND studies, followed by SC design of perishable products, were Lummus (2004), Zamboni et al. (2009b), An et al. (2011b), Huang et al. (2010), and Dal-Mas et al. (2011) (see Table 11). Nevertheless, this concept of perishability was then presented differently in the various literature by considering different SC configurations, structures, case set-ups, and varieties of products. The cluster explores various aspects that were considered in the past, such as uncertainty modeling, multi-objective analysis, financial risks, non-linear optimization, process and control optimization, and the like An et al. (2011b), Arashpour et al. (2017), Dal-Mas et al. (2011), Giarola et al. (2011), Huang et al. (2010), Iakovou et al. (2010), Qiao et al. (2013), Zamboni et al. (2009b,a). Primarily, this cluster represents the collection of papers that describe studies related to biofuel- or bio-ethanol-based SCN designs.

Ekşioğlu et al. (2009) state that the decisions in biofuel SCs are often affected by transportation distance, transport time, and biofuel availability. This study precisely considers this impact on the design of a strategic SC network for biofuel SC. Supply-level perturbation in varying inputs for raw materials such as forest residues, pulpwood, and saw timber was captured in MILP modeling by considering three different scenarios. The authors suggest that the biomass conversion rate is higher in the case of a shorter distance, thus providing a higher amount of ethanol as the fuel source. Similarly, Zamboni et al. (2009b) optimize key decision variables such as geographical locations of biomass production sites, location, scale and distribution of biofuel, and impact on global warming due to CO_2 emissions. Two scenarios were developed based on usage of DDGS (distiller's dried grains with soluble); DDGS as cattle feed and DDGS as fuel for CHP (combined heat and power). The impact of CO_2 in both instances is measured, and the SC configuration is decided accordingly. Huang et al. (2010) presented an SCN with overall minimization of system costs (feedstock procurement cost, refinery capital cost, production cost, and transportation cost). The impacts of transportation cost, refinery capacity, and feedstock availability on system costs are captured. Majorly, these studies deal with multi-stage design and SCM in the renewable energy sector. In contrast, Iakovou et al. (2010) identified the impact of disruption probabilities on order quantities. The authors explored resource flexibility for capacitated/incapacitated SCN settings with dual sourcing solutions. In the capacitated case, KKT conditions are utilized to obtain optimality. Moreover, the optimal solution moves from the supplier, which is expensive and prone to disruption, and a mix of orders is observed in both cases. The suppliers are attracted to a disruption event. DDGS is an excellent source of feedstock for animals because it is rich in protein and results in fewer methane emissions. Therefore, the efficient design of such SCs is a mandatory step addressed by Dal-Mas et al. (2011). Further, An et al. (2011a) scheduled quarter-by-quarter material flow decisions to make dependent choices, such as workforce and equipment allocation, available. Strategic decisions such as the selection and land and farms to contract to supply feedstocks, considering profitability as the main objective, were presented in the study. Qiao et al. (2013) proposed a novel approach of efficient resource management for optimizing SCN by considering hybrid coal, biomass, and natural gas to liquids (CBGTL) as optional feedstock solutions for the existing energy supply network. The model incorporates recent advances, such as carbon sequestration, into the modeling and reduces the cost per barrel for fuel transmission to the energy sectors.

Arashpour et al. (2017) tested three hypotheses: first, 0–1 programming leads to better decision making to optimize the SC; second, preference-based strategic decisions result in higher SC cost; and third, multiple supplier scenarios result in higher management costs than in the case of a single supplier. However, evaluating the SCN by considering inclusion and exclusion decisions related to supplier selection is not feasible in real life. Most of these studies do not consider the effect of stochastic demand or disruption due to demand (Ekşioğlu et al., 2009; Zamboni et al., 2009b; An et al., 2011b; Nagare and Dutta, 2012; Qiao et al., 2013; Iakovou et al., 2010; Suryawanshi and Dutta, 2021).

Moreover, the problem sizes considered are reasonably tractable and do not require advanced computational algorithms. In our opinion, the use of such advanced tools helps to provide standardized solutions to computationally challenging datasets. Apart from this, specific extensions of certain studies are possible, such as considering multiple transportation modes in the survey by An et al. [2011a] and multiple supplier cases in Iakovou et al. (2010). Generally, when this cluster is compared with others, the input cost vectors can be made uncertain, and the solutions can be revised, as in studies such as Qiao et al. (2013), Zamboni et al. (2009b), and Ekşioğlu et al. (2009).

The literature on SCs of perishable products has explored several dimensions, such as farm management, production management, scheduling, and pest/disease management for the SCs of different crops and livestock. However, SCR practices such as mitigation strategies and contingency planning are untouched, as is the integration of policy-level decision making and technology adoption for long-term planning (Ge et al., 2015; Bottani et al., 2019; Behzadi et al., 2018). We also discovered that disruption management studies, particularly the impact of the ripple effect on limited life SCs, are not included in the literature. Additionally, most previous studies incorporate general economic objectives (cost reduction and profit maximization). As perishable-product SCs are inherently vulnerable and can affect the environment significantly, societal or environmental objectives can also be examined. Furthermore, as mentioned by Behzadi et al. (2018), studies of perishable-product SCs have not considered SCR metrics for evaluation, especially in times of uncertainty modeling. Therefore, the authors suggested three measures: time to recovery, lost profit during the recovery period, and recovery level. Future research can be conducted based on such objectives. From the methodology perspective, there is a potential scope for building studies using two- or multi-stage stochastic programs and simulation-based approaches considering the advantages of dealing with numerous scenarios.

5.6. Planning models for SCND and facility location under uncertainty

Planning plays a crucial role in SC management, particularly when risk is involved. Major decisions in the SC involve facility location, customer allocation, and supplier selection (Aghezzaf, 2005; Daskin et al., 2002; Sawik, 2013b). Table 12 illustrates the importance of planning in managing the inter-temporal dimensions of decision-making. Several studies have adopted a stochastic programming approach to capture the uncertainty in the input parameters (Birge, 1997). Since scenario generation is a critical task related to these problems, better scenario approximation techniques have evolved. For example, Owen (1998) proposed a Latin super-cube sampling (LSS) method with the help of quasi-Monte Carlo (QMC) simulation. The variables are taken in a subset, and QMC is applied to identify near-random representations. The study also extends LHS and LSS to infinite-dimensional sampling. Papers in this cluster mainly target SC planning-level decisions by considering the risk of disruption, stochasticity, and random uncertainty in exogenous variables such as demand, price, cost, and the like. Tsiakis et al. (2001) developed a MILP model to solve both deterministic and demand-uncertain conditions. SCND solutions were provided for the situations, and the results were compared. Daskin et al. (2002), Snyder and Daskin (2005), and Aghezzaf (2005), exploited the structure of SC using Lagrangian relaxation. Aghezzaf (2005) designed a search procedure for the assignment of retailers to open distribution centers (DC) to acquire a better upper bound to the solution. Two datasets, comprising 88 retailers and 150 retailers, were solved and compared with the

Table 12
Planning models for SCND and facility location under uncertainty.

Sr No	Author (Year)	Methodology(Technique)	Scope	Research Gap and Contribution	Industry
1	Birge (1997)	Stochastic program to solve a simple newsvendor model	Order demand mismatch problem	Often the demand, in reality, is unknown; thus, the issues of overstocking or under-stocking occur. Practically, the research is applicable in diverse areas such as lot-sizing, order allocation, demand planning, inventory optimization, and the like.	NA
2	Owen (1998)	An approach to generate near-random samples of input parameters	Sampling technique	NA	NA
3	Sabri and Beamon (2000)	MILP for the initial solution of SC configuration and non-linear program for further analyzing at operational level decisions and optimizing service level, batch sizes, etc.	The authors proposed simultaneous decision making under production, delivery, and demand uncertainty considering cost, service level, and flexibility(volume or delivery) as objective	Flexibility as a performance measure is never considered in past studies. Volume and Delivery flexibility are incorporated in the model.	GSCM
4	Tsiakis et al. (2001)	MIP for designing a production-distribution system under demand uncertainty	Specifically to solve any SCND problem under demand uncertainty apart from using flexibility in production and transportation modes.	Production distribution problem under demand uncertainty is solved—scenario generation approach to demand creation.	Production-distribution SC
5	Daskin et al. (2002)	P-median approach for selection of facilities and risk pooling strategy for minimizing the distribution of goods among the facilities	To decide inventory and allocation level decisions for e-commerce based SC	The problem contributes by providing a novel approach in solution methodology by incorporating an LR approach and a local searching technique. The applicability of the model is justified in the e-commerce and blood Bank SC system.	E-commerce
6	Jayaraman and Ross (2003)	Simulated annealing approach to solve SCND problem considering PLOT (Production, Logistics, Outbound, Transportation) design	Cross-docking is a rarely used concept in SCND, e.g., Wal-Mart. The article investigates the integration and advantages of cross-docking, considering a real-life example	The model utilizes the SA technique to exploit the advantages of the cross-docking system in SCND. Time and flexibility in SC planning are explored using the SA technique.	Retail distribution planning
7	Santoso et al. (2005)	Sample average approximation and Accelerated Benders' decomposition for SCD	Designing SCN under stochasticity for multiple input parameters	SAA combined with Accelerated Benders' technique is implemented to achieve better lower bounds. The model is implemented for two cases, one for the domestic network and the other for global configuration, considering after-tax profit as the ultimate objective.	Cardboard package Industry
8	Chopra and Sodhi (2014)	Building resilient SC	Fighting the odds of disruptions	The paper investigates different strategies such as segmentation, regionalization, centralization, insurances, and the like to fight disturbances in SC.	GSCM
9	Snyder et al. (2016)	A multi-objective optimization approach to manage facility failures during disruptions.	The paper addresses the incapacitated facilities locations problem and P-median problem using a reliability approach	The study uses the P-median approach with the reliability feature to address the uncertainty problem for classical facility location problems.	NA
10	Arashpour et al. (2017)	0-1 binary programming	The model is applicable in an environment where prefabrication and assembly steps are involved.	The study proposes an SCM framework for a prefabricated construction environment. Major supplier selection decisions under multiple production environments are taken apart from uncertainty in purchasing strategies.	Construction SC

standard set-partitioning problem. However, facilities under the study were incapacitated, which will not be the case in real-life situations. Similar to this, a simulated annealing procedure was adopted by Jayaraman and Ross (2003) for a PLOT (Production, Logistics, Outbound, and Transport) design system.

Santoso et al. (2005) designed an accelerated Benders' decomposition technique for a demand that is lognormal in a case study for the cardboard packaging industry. It is apparent from Section 5.2 that robust programming is useful when the formulation is efficient in both model and solution-level complexities. Decomposition techniques such as Benders' approximation (Santoso et al., 2005) and Lagrangian relaxation (LR) Aghezzaf (2005) contributed valuable results. Aghezzaf (2005) solved a sub-problem using LR and provided decisions related to the expansion and location of warehouses. A facility-level constraint was relaxed using the LR approach, and the resultant model was solved to optimality (Snyder and Daskin, 2005). The algorithm terminates (reaching an optimal solution for about 93% of the instances) within a limit of 600 s. Snyder et al. (2016) proposed simultaneous strategic and operational planning problems under a multi-objective framework considering volume flexibility as one of the objectives. As planning plays a crucial role in investment and operations, future research relevant to this cluster is highly encouraged. Advanced OR approaches, including heuristic-level solutions such as genetic algorithm, simulated annealing, or Tabu search, can be good tools for solving such problem types. Studies that incorporate such techniques are Zhang et al. (2015), Meena and Sarmah (2013); the latter solved a long-term supplier-segmentation and order-allocation problem with the risk of disruption at its sources. Moreover, decomposition techniques serve as the best tools when strategic planning or large-scale networks are designed. Therefore, algorithms such as Lagrangian relaxation and Benders' decomposition can be effectively used to divide a problem into parts to reduce the computational challenges. Apart from this, addressing the uncertainty in input data in studies by Tsiakis et al. (2001), Snyder and Daskin (2005), and Aghezzaf (2005) by using real industry data will serve as the best guide for future SC solutions. As per the analysis, we observed that complex SC structures are highly vulnerable to disruptions, resulting in structural changes. Therefore, recovery process control-based studies are highly recommended (Ivanov et al., 2018); (Ivanov and Sokolov, 2019). The authors state that degradation due to disruption is always out of control and, therefore, recovery process control could also be considered (Banker, 2016).

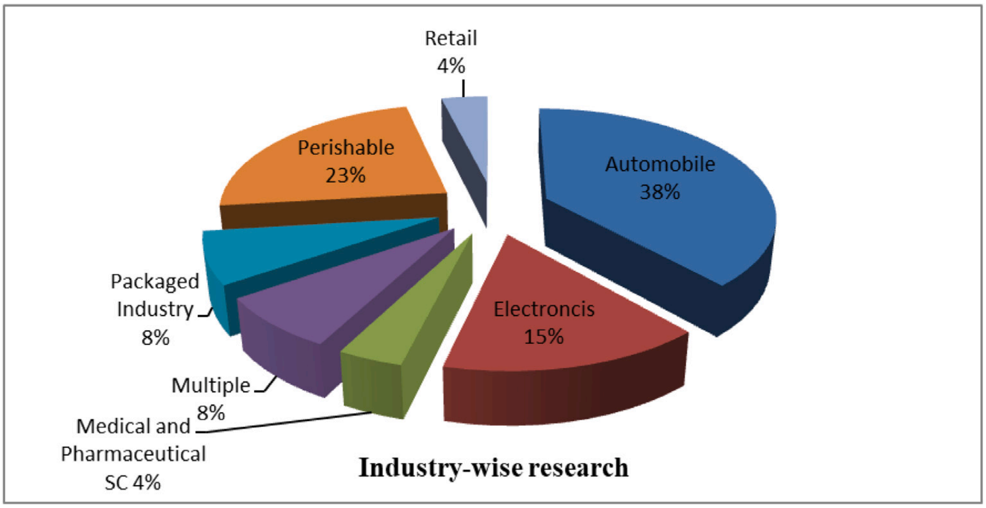

Fig. 13. Industry-wide application of SCR.

5.7. OR models based on relationships or correlations between sustainable, resilience and Green SC

Performance measurement is the key idea behind evaluating any process, organization, or method to understand the output, impact, and growth of entities. The same is the case with the fill rate, on-time delivery, customer response time, flexibility, and the like, which are some of the key indicators that were developed in the past to evaluate the SC performance (Charnes and Cooper, 1959); (Beamon, 1999). Modern-day regulations pose greater challenges for SCs, resulting in revised SC indicators that take into account social and environmental impacts (Brundtland et al., 1987). Therefore, different SCs, such as the green SC, the social SC, and the sustainable SC, came into existence with their inherent risks. Traces of this cluster theme were evident and cited in Fahimnia et al. (2015b) and Table 13. The further amalgamation of studies related to sustainability and resilience was realized in the early works of Linton et al. (2007), Ahumada and Villalobos (2009), Iakovou et al. (2010), Derissen et al. (2011), Fiksel (2015), Fahimnia et al. (2018), Jabbarzadeh et al. (2018), Fahimnia et al. (2019), and Dutta et al. (2020). Dehghanian and Mansour (2009) applied a multi-objective genetic algorithm (MOGA) to minimize the social and environmental impacts due to scrapped tires. To our knowledge, this study is the only one of its kind in which the social objective was derived using the analytical hierarchy approach. In addition, a lifecycle analysis was performed to quantify the environmental impacts of products, services, and technologies. A recent review of SCR also highlights that existing topics such as collaborations and relationships, purchasing and supply management, strategy, SC integration, and customer service strategy have attracted less attention as far as the consideration of resilience in SC implementation is concerned (Swanson et al., 2018). Fahimnia et al. (2019) investigated the cross-disciplinary perspective and proposed two major research issues that have not been dealt with in detail.

- the interaction effect of sustainability and resilience on the overall SC, and
- the effect of resilience practices on the sustainable performance of SCs.

The authors also highlight classic examples of the integration of these two concepts by proposing: (1) minimizing stock points and storage spaces can reduce waste and maximize efficiency; (2) sustainable supply sourcing often faces challenges due to a handful of reliable suppliers, which qualifies the problem to be considered for some of the remedies from a resilience culture.

6. Industry focused research

This section highlights the industrial application-related research articles. Recent trends have shown that the inclusion of a case study or real-life case examples for solving research problems generates more meaningful and valuable insights that benefit the research community and industry practitioners. This industry-wide classification is shown in Table 14. The pie chart in Fig. 13 represents the share of different industries following crude risk management and resilience practices in their operational implementation. The information for the mentioned analysis is extracted from the last column of Tables 7–13 presented in Section 5. Approximately 54% of the research articles of all the papers considered have shown the direct application of a solution methodology to various industries. Additionally, a few papers have created pseudo-case examples to validate and explain the modeling approach by considering various non-deterministic parameters imitating real-life, uncertain variables.

A significant cohort of studies that set the benchmark for the evolution of research on sustainability are papers catering to biofuel and related topics. We observed noteworthy contributions by exploring methodologies as well as simulation-based research in this cluster.

In summary, the key insights derived from the analysis that are beneficial for industry practitioners and academicians are as follows:

Table 13
OR models based on relationships or correlations between Sustainable, Resilience and Green SC.

Sr No	Author(Year)	Methodology(Technique)	Scope and sustainable dimension	Research Gap and Contribution	Industry
1	Beamon (1999)	Measurement of SC	This paper majorly look into measurement of performance factors for complex SC systems	A systematic approach for measurement of performance factors for SCs.	GSCM
2	Srivastava (2007)	The paper presents an SLR on green SC practices. Specifically related to green SC design and green operations and classify the past literature on proposed dimensions.	The study helps understand the various issues and tools adapted to solve problems in green SC management.	The paper presents a blend of studies, including mathematical modeling and empirical studies on green SC management. In detail, various aspects such as environmentally-conscious design (ECD) and life-cycle assessment/analysis (LCA) of product life cycles are studied. Elements of green manufacturing, green SC network design, and green practices such as source reduction and pollution prevention are promoted in the study.	NA
3	Linton et al. (2007)	The paper introduces the early study on the convergence between SC and sustainability.	The usefulness of this article is to draw attention to the larger picture of sustainability in SC operations right from production, consumption, customer service, and post-disposal disposition.	The study provides the importance of sustainability considerations in the early life of product design, manufacturing by-products, by-products produced during product use, product life extension, and product end-of-life.	NA
4	Dehghanian and Mansour (2009)	Multi-objective mixed-integer linear programming problem was solved using Genetic algorithm technique	A sustainable SCN can be developed considering economic, environmental, and social aspects of designing an SC structure	Use of eco-indicator to quantify the environmental impact of processes involved in SC. Multi-objective SC design involving sustainable perspective. Use of GA to provide Pareto-optimal solutions. Application to the real-life tire industry.	Tire Industry
5	Ahumada and Villalobos (2009)	Paper presents the planning models in the agri-food SC. The aspect of production and distribution is addressed throughout the study.	The study includes planning models at strategic, tactical, and operational levels for non-perishable products and fresh produce agricultural SCs.	The paper identifies the importance of economies of scale, strategic positioning, risk management, and market control for Agri-SCs. These challenges are even unattended in present days, thus, leaving the scope for future work. The authors also promote the importance of industry-based requirements such as traceability, quality certifications, food safety, and quick response in the study.	NA
6	Bai et al. (2010)	Rough set methodology for selection of green and sustainable suppliers	Evaluation and selection of green and sustainable suppliers. Method to evaluate decisions related to green supplier selection.	The procedure is applicable whenever weights are assigned to alternatives. Decision-making under imprecise information can be handled using such an approach.	NA
7	Kuo et al. (2010)	The two multi-attribute decision analysis (MADA) methods are used to solve a supplier selection problem	The paper identifies green supplier selection criteria apart from modifying the traditional approach of ANN and DEA to be applied for the selection methodology	Authors defined supplier selection criteria based on CSR, Service, Delivery, Cost, Quality, and Environment. A case study of a digital camera producing firm is presented.	Digital Cameras
8	Wang et al. (2011a)	Multi-objective MIP to design an SC concerned with environmental issues.	The model can be applied as a strategic planning tool for green SCND	The model provides solutions using improved sensitivity analysis; remarkably, it suggests that increasing more facilities decreases the cost and environmental impact. A separate variable for linking ecological concerns in the planning phase is introduced. The variable represents the investment in better technologies or missionaries to reduce CO2 emissions —a normalized constraint method to provide evenly distributed Pareto-optimal solutions.	NA
9	Wang et al. (2011b)	Sales forecasting accuracy using adaptive network-based fuzzy inference system (ANFIS)	Improved accuracy for sales forecasts	Sales forecast method for automobile firm tested empirically. ANFIS model in conjunction with step-wise regression results in an effective forecasting tool. The model provides a great understanding of the dynamic nature of the single market and the whole market.	Automobile Industry
10	Kannan et al. (2013)	Fuzzy AHP+Fuzzy TOPSIS+ Fuzzy MILP	Sustainable supplier selection and order allocation	Application for Fuzzy multi-attribute utility theory for criteria identification and weight assignment is new to the supplier selection problem. A pseudo-automobile case example is presented with economic and environmental criteria in the multi-objective setting.	Automobile Industry

- As the study has revealed, the automobile sector has made the highest contribution in terms of research (Kumar and Alvi, 2006; Peidro et al., 2009; Pishvaee et al., 2012; Kannan et al., 2013; Govindan, 2015) followed by IT and electronics (Graves and Willems, 2005; Wu and Barnes, 2010; Amin and Zhang, 2013a,b; Ramezani et al., 2013b) and other important areas of application such as medical SC (Pishvaee and Razmi, 2012), bio-gas SC (Qiao et al., 2013), construction SC (Arashpour et al., 2017), logistics network design (Ramezani et al., 2013a), and others. However, a wide scope remains for the consideration of non-traditional SC industries such as food SCs, packaging industries, and e-commerce.
- It is also evident from past research that most applied research came from the USA and Europe. A broader geographic dispersion of applied research will serve the purpose of various industries belonging to other countries or emerging markets.
- Techniques such as two-stage stochastic programming and RO are the most suitable for solving uncertainty and disruption-related issues in SCs. RO is beneficial in cases requiring optimal solutions despite infeasible conditions, whereas two-stage SP is suitable for making one-off decisions. Unlike traditional modeling tools, these methods are instrumental in solving real-world business problems.
- This study provides an alternate platform to industry experts, in addition to traditional approaches such as business continuity management and risk management. These traditional practices share ideas based on mere avoidance and preparation, and do

Table 14
Research article categorization based on the application to real life problem solving domains.

Sr No.	Industry type	Articles
1	Manufacturing	Chan et al. (2008), Pishvaee et al. (2012), Vahdani et al. (2013), Dehghanian and Mansour (2009)
2	Automobiles	Kumar and Alvi (2006), Peidro et al. (2009), Carvalho et al. (2012), Govindan (2015), Wang et al. (2011b), Kannan et al. (2013)
3	Electronics	Graves and Willems (2005), Wu and Barnes (2010), Wu et al. (2010), Amin and Zhang (2013a), Amin and Zhang (2013b), Ramezani et al. (2013b), Kuo et al. (2010)
4	Bio fuel SC	Ekşioğlu et al. (2009), Zamboni et al. (2009a), Huang et al. (2010), Iakovou et al. (2010), An et al. (2011a), Gold and Seuring (2011), Dal-Mas et al. (2011),An et al. (2011b), Qiao et al. (2013),Arashpour et al. (2017)
5	Packaging	Schmitt and Singh (2012), Santoso et al. (2005)
6	Medical and syringe manufacturing	Pishvaee and Razmi (2012)
7	Logistics and distribution	Ramezani et al. (2013a), Tsiakis et al. (2001)
8	Retail	Daskin et al. (2002), Jayaraman and Ross (2003)
9	General SC	Beamon (1999), Sabri and Beamon (2000), Klibi and Martel (2012), Chopra and Sodhi (2014), Fahimnia et al. (2015a), Heckmann et al. (2015), Arashpour et al. (2017)

not provide solutions based on the severity of unexpected events. SCR, in contrast, can fight disruptions as well as unexpected recurrent events in business operations. We believe that empirical research and case studies are required to improve decision making in times of difficulty by bridging the gap between theory and practice.

7. Discussion and conclusion

SCR has emerged as a subfield in SCRM literature and has achieved greater importance in the past decade. Early studies on this topic focused on defining and understanding SC operations' perspectives (Ponomarov and Holcomb, 2009). However, the importance of risk management principles has been over-emphasized in the SCR literature. Past studies have adopted traditional risk management tools for risk identification, avoidance, and analysis, rather than adopting SCR strategies such as quick responsiveness, better cooperation, robust decision making, and so on. Therefore, this study attempted to justify the role of SCR in past, present, and future scenarios. To do so, we limited the search to articles based on optimization approaches. Themes were generated based on co-citation analysis and the PageRank algorithm. The co-citation algorithm performs a multiple correspondence analysis that helps generate a conceptual structure of the field and uses K-means clustering to identify clusters of documents that express similar concepts. Based on this, seven influential clusters are proposed in Section 5. The overarching understanding of this extensive information is presented in the conceptual model in Fig. 14. The framework delineates the scope of the study, with findings suitable for the future course of action. It is based on the microlevel analysis performed in Section 5 and the areas targeted in this review process.

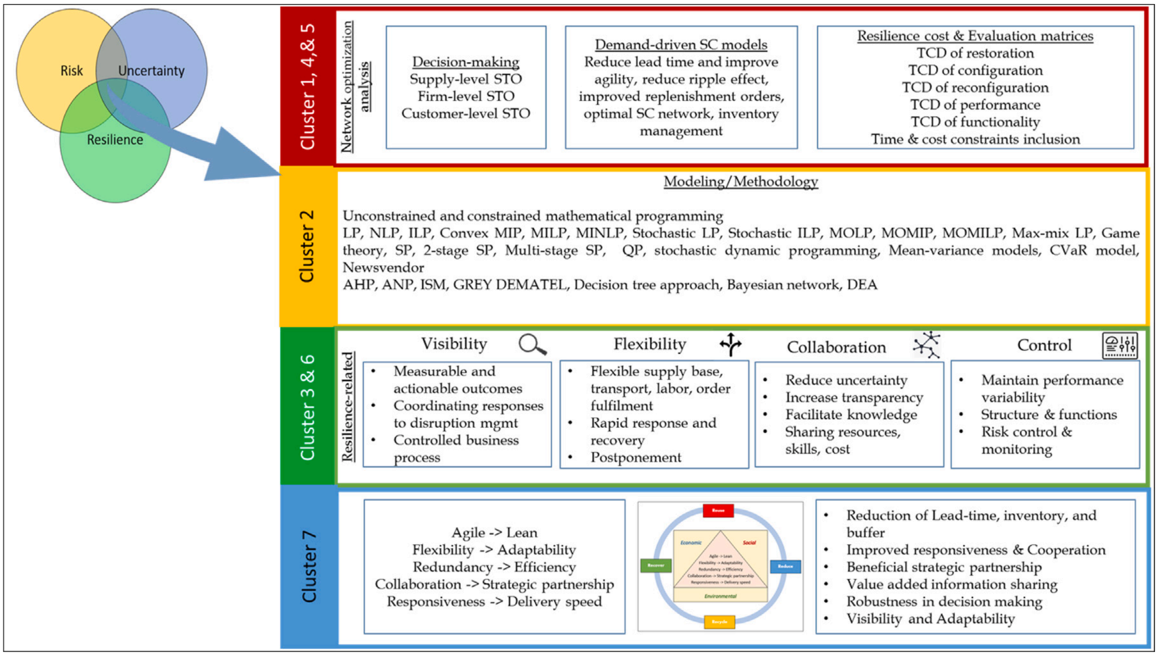

Fig. 14. A conceptual model illustrating the cardinal contributions to the research topic and future directions in SCR.

The seven independent themes are integrated under a common conceptual framework, in which every theme provides a different perspective with novel findings and innovative intuition. It conglomerates the contributions of various themes and provides the evolution and progress of SCR, risk, and uncertainty. The seven themes are (1) selection and evaluation of SC entities (for example, suppliers, production processes, and warehouses) in an SCND setting. (2) A robust optimization approach to model uncertainty to achieve SCR. (3) Modeling disruptions to design a resilient SC network. (4) Uncertainty modeling in the SC network design for closed-loop SC and reverse SC. (5) Perishable-product SC network design model. (6) Planning models for SCND and facility locations under uncertainty. (7) OR models based on relationships or correlations between sustainable, resilient, and green SC. Clusters 1, 4, and 5, which present the models related to network optimization, are clubbed together, and suggestions related to future mathematical developments are provided. For example, considering the time and cost dimension (TCD) of restoration, recovery, and reconfiguration, etc., can be considered a primary/secondary objective while formulating a disruption-based mathematical problem. Clusters 3 and 6, which promoted resilient planning in facility location and SC design problems, can effectively include basic features of resilience optimization such as visibility, flexibility, collaboration, and risk control. The basic features and primary characteristics of such a designed problem are mentioned in Clusters 3 and 6. Cluster 2 lists the critical modeling tools that have been implemented in the past and are useful for future solutions. Finally, resilience with other measures of business philosophies, such as sustainability and a green economy, is presented. Overall, the framework covers an overarching idea underlying building a resilient model in the business ecosystem, where the primary goal is not only to elevate the profit function but also to develop an efficient network design, distinct solution approaches, effective disruption management, and uncertainty analysis and inculcate sustainable growth in existing resilient cultures. Furthermore, we discuss some of the critical findings from the different studies presented in these individual clusters as follows.

Studies dealing with network optimization have focused more on risk identification, analysis, and mitigation procedures. The metric for evaluating an SC network based on resilience dimensions was lacking in previous studies. For example, objectives such as restoration, configuration, functionality, or cost due to restoration, configuration, functionality, and resilience are not considered in formal modeling structures and require attention from the research community. A similar finding holds for the constraints representing the dimensions of time and cost related to resilience or restoration measures.

Despite the increase in SCR publications, few studies have focused on assessing or measuring SCR to practical network problems. For example, Soni et al. (2014) proposed an SCR index to advocate resilience aspects in network design and building competitiveness. However, the ranking differs based on risk profiles and sample size. Similarly, Munoz and Dunbar (2015) developed a metric to evaluate the operational performance of SCs and to limit the findings to supply–demand mismatch problems. Recently, Dixit et al. (2020) computed the resilience rank of supply networks based on the compounded effects of density, connectivity, centrality, and network when subject to disruptions. A higher rank shows better performance in terms of robustness against disruption impacts. Nevertheless, the study lacked a unified approach to quantitatively measure resilience. SCR is a multi-valued function that cannot be measured using a single dimension. Previous studies, such as Munoz and Dunbar (2015), Fiksel (2006), and Melnyk et al. (2014) have developed operational resilience metrics using transient responses after disruptive events. However, the metric should incorporate overall design-level resilience covering operational performance, which was lacking in the past. A similar finding was

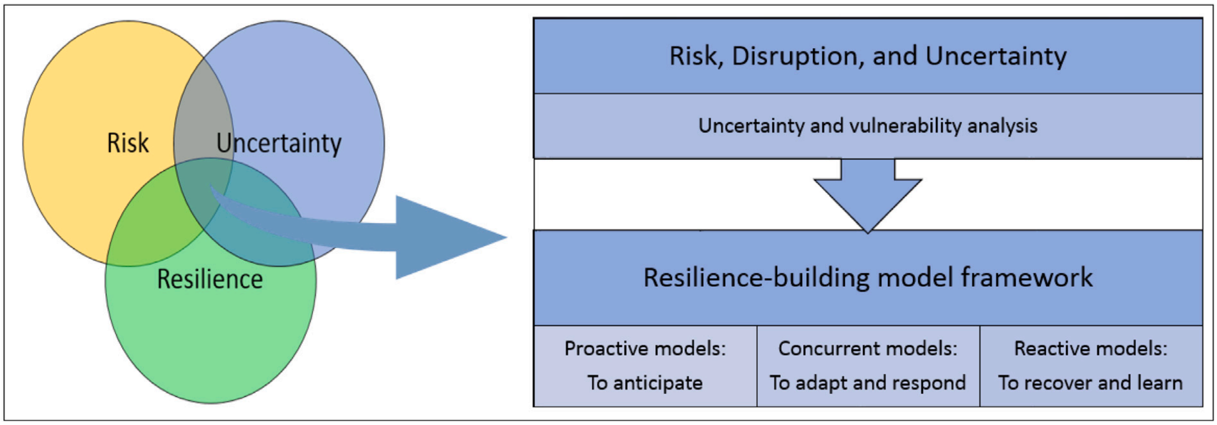

Fig. 15. Model building based on vulnerability reporting.

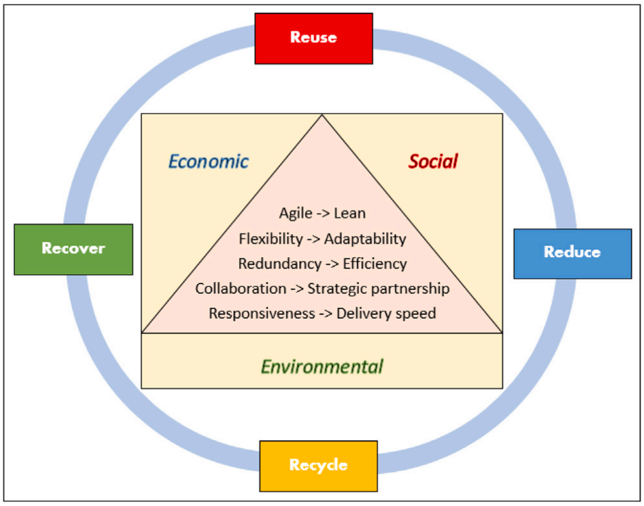

Fig. 16. Dimensions of SURE SC.

observed by Namdar et al. (2021), who extended the framework presented by Zobel and Khansa (2014) to measure resilience rank. Additionally, while evaluating resilience, rank dimensions should consider recovery and robustness. The rank also includes rapidity, redundancy, and resourcefulness in future developments. The process of ranking can be enhanced using a risk-resilience exposure matrix and vulnerability analysis. Based on these findings, a suitable solution comprising proactive, concurrent, or reactive models can be suggested. The resilience-building framework is illustrated in Fig. 15. which can be universally applied while formulating models to tackle disruption, uncertainty, or risk.

Today's markets change instantaneously and require responsive operations to satisfy customer, environmental, and social needs. Therefore, the urge to consider government regulations of sustainable standards and the economic aims of business processes are highly regarded in day-to-day decision making. Effective waste minimization and culture of four Rs (reuse, reduce, recycle, recover) is essential for sustainable growth and resilient decision making. The overlapping dimensions of responsiveness and delivery speed, flexibility and adaptability, collaboration and strategic partnership, redundancy and efficiency, and agility-lean are still scope for future research when exploring (sustainable resilient (SURE) SC (Fig. 16). Similar results have been reported in many recent studies by Derissen et al. (2011), Fiksel (2015), Fahimnia et al. (2018), Jabbarzadeh et al. (2018), Fahimnia et al. (2019), Rajesh (2018), Dutta and Shrivastava (2020), and Suryawanshi et al. (2021). For example, Suryawanshi et al. (2021) proposed an MINLP problem to effectively manage food losses owing to the perishability of products as one of the objectives while simultaneously promoting visibility and additional buffer allocation to build a resilient design of SC for perishable products. Further, we realized the dimension of why and when SURE SC has been greatly explored in the past. Therefore, it leaves the scope of further studies to unlock the who, where, and how to carry the experimental analysis to improve sustainable growth and resilient decision making.

While dealing with real-life complexities, combining different methodologies such as MIP with multiple criteria evaluation techniques can be effective in the future. This will eventually help in stress testing and assessment of the operational performance of the supply network (Chan et al., 2008; Ho et al., 2010; Haldar et al., 2012; Torabi et al., 2015; Parkouhi et al., 2019; Rajesh, 2019). For example, a Bayesian network for designing an SC under the risk of disruptions or imprecise information is another effective methodology for building an SCR. The detailed scope of this approach is presented in Section 5.4 and is succinctly highlighted in the latter part of the discussion. Traditional OR tools of linear programming are widely used to design SC networks (Govindan et al., 2017), and the same is true for models developed to address disruption management (Bode and Wagner, 2015; Nooraie and Parast, 2016; Snyder et al., 2016; Ivanov and Dolgui, 2019) and uncertainty modeling (Snyder, 2006; Dutta, 2010; Simangunsong et al., 2012; Govindan et al., 2017). However, resilience is over-utilized and restricted to problems in disruption management, and the least attention is given to tackle problems due to uncertainty issues. SCR has broader applications beyond merely solving disruption issues. An effective resilience strategy can even consider uncertainty modeling and improve decision making. For example, demand-driven models are suitable for managing ripple impact upstream of the SC, minimizing lead times and improving order delivery. Extensive research on demand disruption is available in past research (Ivanov, 2017; Ivanov et al., 2017; Ivanov and Dolgui, 2019; Tiedemann, 2020), but the resilience perspective is lacking. In addition, some key takeaways from the review analysis are

- Based on the methodologies adopted in the past, Bayesian network approaches have not been implemented regularly, and the primary focus is aligned to either an exact approach of problem solving or the adaptation of some advanced optimization algorithms, such as meta-heuristic techniques.
- The study provides mathematical derivations for incorporating CVaR, VaR, mean–variance, and mean-downside risk optimization models in the simplest forms.
- As noted earlier, individual approaches such as DEA, case-based reasoning, and fuzzy sets are preferred over combined strategies of problem solving, such as integrated AHP with supplier evaluation or ANP-goal programming.
- Most RL/CLSC studies have considered the economic aspect of product return and the social impact of product life in the chain channeling is disregarded.
- The SC of perishable products is more challenging to handle owing to perishability, supply spikes, and long lead times. Many issues are still unaddressed in this work owing to the paucity of literature available on this topic. However, many of the supply side issues have not been quantified in past studies, apart from addressing the disruption-level challenges at destination nodes. Resilience in the SC of perishable products is not quantified in terms of the mean time to recovery, responsiveness, or an equivalent measure as the primary objective.
- Cluster 5 has a unique application as it advocates the design and implementation of biofuel and bioethanol SCs. As the world has insufficient resources, an alternative such as biofuel can minimize dependence on fossil fuels. Such studies are of particular importance in emerging economies such as India, where abundant resources and manpower are available to reap benefits of parallel resources.
- The toggling between robustness and resilience has not been clearly identified in past studies.
- Industry-specific research should be promoted in the studies because it provides the reader with the scope to replicate and reproduce the research with better findings, which provides opportunities for diverse applications.
- Resilience is not a solo concept to be studied in isolation. Combining resilience with sustainability or green engineering could be promising for future research. This would cause researchers who work with different ideas and in various research areas to work together.
- Incorporation of a time aspect in modeling is needed for the hour, particularly for the SCs of perishable products. The scope of building design models for managing periodic decisions is promoted.
- Segmentation provides flexibility in an SC to avoid risk, while also increasing cost-efficiency. A product that has a low margin can be sourced from multiple low-cost suppliers (this reduces cost as well as the disruption impact). Regionalizing SC can increase the cost efficiency but de-risk disruption risk.
- Component commonality helps in cost reduction, but over-reliance can propagate huge risks due to low quality or reliance on a single supplier. Therefore, decisions need to be made to reduce recurrent risk by minimizing the pooling of resources and keeping the fragility of an SC low. This vulnerability can be reduced by avoiding resource pooling from distant nodes in the SC, thereby reducing the disruption impact.
- Digitalization is currently the key for both cyber SC and physical SC. SC data related to sourcing, manufacturing, logistics, and sales are distributed across numerous systems via ERP, RFID, sensors, and blockchain technology. The data from various channels are fueling AI algorithms in the cyber SC and help decision makers in the physical SC. Therefore, current generations are witnessing new standards for optimization and simulation models. These real-time models will be useful for combating disruption situations, if their use is effective and timely. Therefore, digitalization can serve as a fruitful tool in the future.
- The COVID-19 pandemic has triggered a wave of severe economic disruption around the world, causing widespread chaos, profound changes in the business landscape, and overwhelming operational challenges. Although the solution for such situations is not simple, the right technological tool can improve decision making. From the literature, mathematical optimization has shown promising results. If utilized in the right fashion, mathematical optimization can serve as a powerful deductive technology. It can capture the key features of real-world problems by including decision variables, business constraints, and objectives. For example, techniques such as RO and SP are effective in achieving better results in times of uncertainty and disruption. Widely used, these tools can help governments and businesses address real-world problems from SC network design to resource allocation, production and distribution planning, strategic investment, routing decisions, customer satisfaction, and many more. This paper provides a context in which these tools can be applied, that is, SCR. SCR is more effective in combating disruptions than traditional risk management approaches that motivated this study. However, such tools provide

greater benefits if applied in combination with machine learning (ML) principles, which are relevant to the prediction of future events.

The section also highlights major developments in resilient SCND by categorizing models based on commonly used resilience strategies (Section 7.1) and OR implementation challenges in the resilient logistics domain (Section 7.2).

7.1. Quantitative resilience models based on risk-types

The increasing SC uncertainties and unprecedented disruptions have raised awareness for SC risk and resilience studies in recent years. Therefore, the literature on SC risk and resilience is likely to extend over the next few years. Keeping in view this supposition, we conducted an extensive literature analysis on SCR in general and conceptual as well as mathematical approaches of SCR in particular. Especially, we advocate research on building SCR to fight against uncertainties and SC risks. For example, Tang (2006), Goh et al. (2007), and Kleindorfer and Saad (2005) referred to operational risk in situations of inherent uncertainties such as demand disparity, supply variations, and cost uncertainties. These Low-Impact-High-Frequency risks are managed by improved coordination and collaboration. Specifically, vendor-managed inventory (VMI); collaborative planning, forecasting, and replenishment (CPFR); and electronic data interchange have improved over the years to avoid such risks (Chopra and Sodhi, 2014; Govindan, 2015; Xu et al., 2015). We witnessed some of the studies endorsing solutions to fight the risk of operational failures and ultimately achieve SCR:

- Models dealing with problems related to customer demand: Shen and Daskin (2005), Ko and Evans (2007), Romeijn et al. (2007), You and Grossmann (2008), Pan and Nagi (2010), Cardoso et al. (2015), Park et al. (2010), Hsu and Li (2011), Cardoso et al. (2015), Han et al. (2015), Yin et al. (2015), Dutta and Shrivastava (2020).
- Models dealing with problems related to supply capacities: Santoso et al. (2005), Yu et al. (2009), Bode and Wagner (2015), Giri and Bardhan (2015), Jabbarzadeh et al. (2018), Ghahremani-Nahr et al. (2019), Widodo and Januardi (2021), Jouzdani and Govindan (2021).

Unlike these recurrent risks, disruption risks are less frequent, more severe, and longer-duration events. These risks result from natural disasters (e.g., floods, earthquakes, and hurricanes) or man-made threats (e.g., terrorist attacks and employee strikes). Chopra and Sodhi (2014), Knemeyer et al. (2009), Torabi et al. (2014), Kamalahmadi and Parast (2016), and Ivanov et al. (2017) suggest that recovery policies in SCs are crucial to coping with disruptive events. Therefore, the concept of SCR plays a vital role in handling disruptions. The modeling contributions listed provide a classification based on SCR strategies used to build resilient SCs:

- Multiple sourcing and assignment: Iakovou et al. (2010), Peng et al. (2011), Sawik (2011b,a), Costantino et al. (2012), Sawik (2013a), Meena and Sarmah (2013), Sawik (2014a,b), Sadghiani et al. (2015), Zhang et al. (2015), Fahimnia et al. (2015a), Torabi et al. (2015), Kamalahmadi and Parast (2016), Hasani and Khosrojerdi (2016), Sawik (2016a,b), Ivanov et al. (2016a), Fahimnia and Jabbarzadeh (2016), Nooraie and Parast (2016), Torabi et al. (2016), Sawik (2017), Rezapour et al. (2017), Behzadi et al. (2017), Jabbarzadeh et al. (2018), Zhalechian et al. (2018), Namdar et al. (2018).
- Contracting with backup facilities: Snyder and Daskin (2005), Aryanezhad et al. (2010), Hou et al. (2010), Jabbarzadeh et al. (2012), Azad et al. (2013), Fang et al. (2013), Li and Savachkin (2013), Shishebori et al. (2014), Torabi et al. (2015), Ivanov et al. (2016b), Snyder et al. (2016), Behzadi et al. (2017), Namdar et al. (2018), Jabbarzadeh et al. (2018).
- Fortification of suppliers: Lim et al. (2010), Azad et al. (2013), Sawik (2013a,b), Li and Savachkin (2013), Li et al. (2013), Torabi et al. (2015), Hasani and Khosrojerdi (2016), Jabbarzadeh et al. (2016), Behzadi et al. (2017), Fattahi et al. (2017), Zhalechian et al. (2018).
- Holding additional inventory: Sawik (2013b,a), Garcia-Herreros et al. (2014).
- Pre-positioning emergency inventory: Qi and Shen (2007), Mak and Shen (2012), Qin et al. (2013), Benyoucef et al. (2013), Sawik (2013b,a), Garcia-Herreros et al. (2014), Torabi et al. (2015), Hasani and Khosrojerdi (2016), Ivanov et al. (2016b), Khalili et al. (2017), Rezapour et al. (2017).
- Adding extra supply/production capacities: Ivanov and Morozova (2016), Khalili et al. (2017), Ivanov et al. (2016b), Jabbarzadeh et al. (2018), Rezapour et al. (2017).
- Component commonality: Kamalahmadi and Parast (2016).
- Developing business continuity and disaster recovery plans: Torabi et al. (2014), Heckmann et al. (2015), Torabi et al. (2015), Ivanov et al. (2017).
- Reducing flow complexity: Cardoso et al. (2015), Zahiri et al. (2017).
- Managing node complexity: Cardoso et al. (2015), Zahiri et al. (2017).
- Big data analytics, Industry 4.0, digitalization: Chowdhury and Quaddus (2015), Dutta et al. (2019), Schlüter et al. (2019), Ivanov et al. (2019a).

Furthermore, Levalle and Nof (2015a,b) have addressed SC design problems using collaborative planning and reconfiguration techniques. These authors also realized that both approaches are practical for building resilience capacity as well as long-term sustainability. In addition to this, plans of action such as backup suppliers, buffer and surplus storage, multiple sourcing, minimal inventory, and reduced redundancy are essential in the sustainability literature (Ivanov, 2018; Linton et al., 2007). Although these strategies improve overall resilience capability, very few papers realized the importance of communication as one of the effective measures to curb disruption and manage SCs.

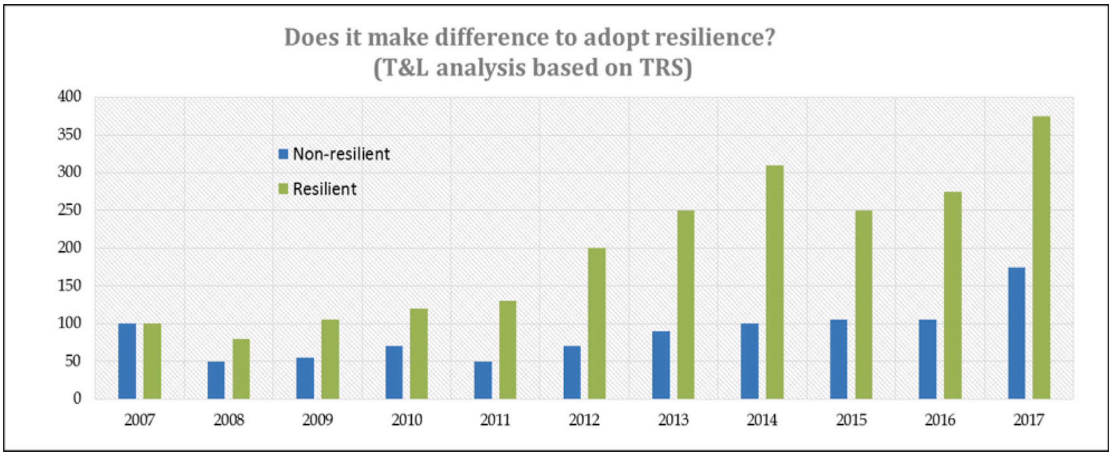

Fig. 17. Return performances of resilient VS. non-resilient TL firms.
Source: Arora (2021), McKinsy report, 2021.

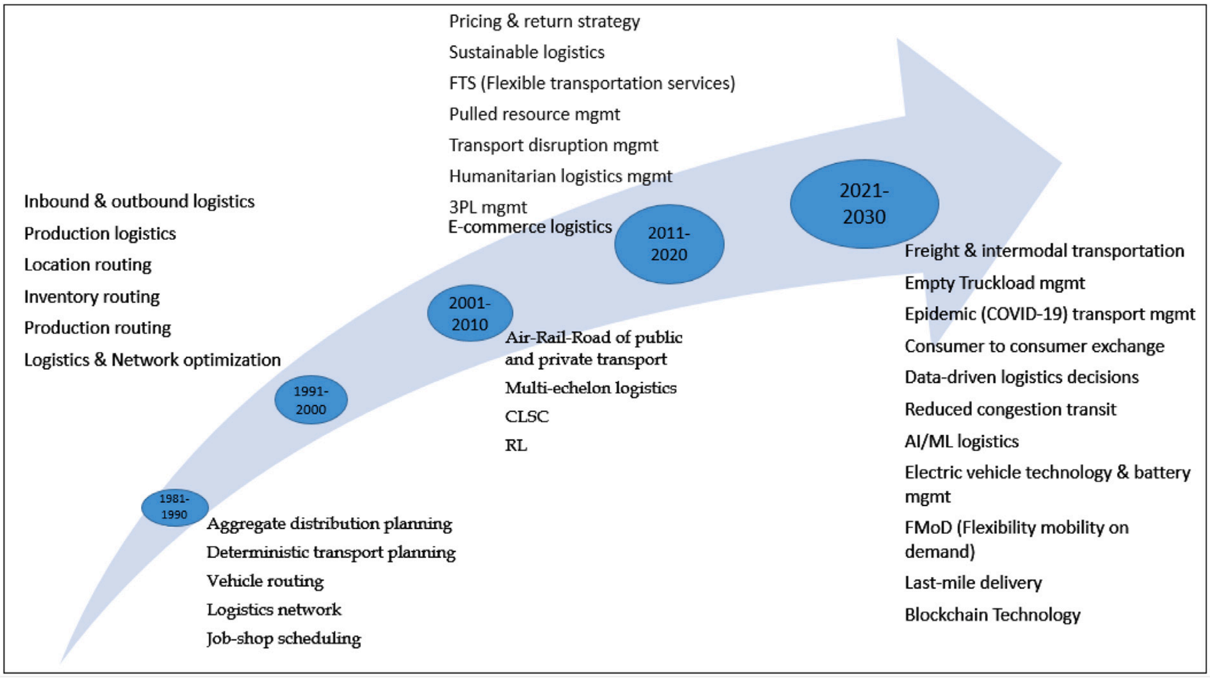

Fig. 18. Past and future scope of OR in different dimensions of logistics and resilience management.

7.2. OR challenges in resilient logistics

The importance of resilience is equally essential for logistics-related activities as logistics represents a critical blueprint for SC management. A recent study by Mandal et al. (2016) found a direct association between a firm's integrated logistics capabilities and SCR features of SC collaboration, visibility, flexibility, and velocity. The hypothetical model was validated using a structural equation modeling approach. A recent analysis by McKinsy stated that transport logistics (TL) firms with resilience capabilities could bring 150% total return to shareholders compared to non-resilient counterparts. These benefits of resilience implementation are seen longitudinally in Fig. 17.

The report mentioned that following data-driven and advanced analytics methods is key to success in achieving SCR. After analyzing the past articles on resilient logistics, we recognized that the following domains have received significant contributions (see Fig. 18). The illustration also includes some of the potential scope of further research on emerging topics.

Data-driven models help identify bottlenecks, evaluate different alternate configurations, and stress-test the design for numerous scenarios. However, quantifying the effects of disruption management, operational risk, disaster, and emergencies and the influence of transportation and shipping partners on SC performance are difficult to model in OR models (Choi et al., 2016). We found sufficient literature on the creation of a logistics infrastructure in the past. For example, Dutta and Chakraborty (2010), Moghaddam (2015), Ayvaz et al. (2015), Rahimi and Ghezavati (2018), Senthil et al. (2018), and Zhang and Ding (2017) presented OR-based models to design reverse logistics design problems. The typical objectives considered in these studies are related to optimizing profit, defective parts, late deliveries, supplier reliability, recycling management, and social and environmental impacts. Furthermore, Mavi et al. (2017), Shakourloo et al. (2016), Zhang and Zhao (2014), Habibi et al. (2019), Chen et al. (2018), Dutta et al. (2016), Ivanov et al. (2015), and Gao et al. (2019) presented work on the management of warehousing, transportation services, and integrated operation of third-party logistics providers. Kummer et al. (2020) promoted resilience in logistics management by leveraging the upsides and downsides of capacity options. Additionally, optimizing the logistics infrastructure, personnel capacity planning, and enforcing digitalization and data management are the key to building a resiliently enabled logistics system. Moreover, close observations of these articles highlight some of the taxing problems that require the attention of OR/MS scholars:

- To efficiently manage delays and disturbances.
- To produce a flexible reconfiguration of logistics infrastructure.
- To enhance the operational flexibility of transport and warehouses.
- To provide a multiple ad-hoc logistics services.
- To improve cross-border transport capacity, especially during challenging times.

Conclusively, we state that the insights derived above are purely based on the studies presented in the literature, which have been included in the network mapping process. This study presents a holistic comparison among various areas of research to provide a deep analysis of the generated research themes. This results in a description of the data clusters based on their scope, methodology, contribution, and application in terms of the type of industry. We hope that the research community and peer network find this review insightful and are inspired to perform innovative research in the field of SCR.

CRediT authorship contribution statement

Pravin Suryawanshi: Conceptualization, Writing – original draft, Methodology, Software, Diagram and flowchart preparation, Investigation, Editing and reviewing. **Pankaj Dutta:** Conceptualization, Writing – original draft, Methodology Editing, Validation, Reviewing, Supervision.

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Appendix A. Definitions and significance of various terminologies used during the review process

A more simplified way to define the scope of the study is presented in Fig. A.19 As noted in the Introduction, we limit our analysis to considering studies that cater to SC design challenges incorporating risk and uncertainty and the reflection of resilience in past studies for building capacity. In particular, we look for modeling efforts developed in the past that relate to the tripoint presenting the three concepts. The key terminologies used during the review process are explained below.

Risk: Risk can be broadly defined as a chance of danger, damage, loss, injury, or any other undesired consequence. In the SC context, the risk is a variation in the distribution of possible SC outcomes (Zsidisin, 2003). Ivanov et al. (2019b) state that risk emerges from uncertainty and can be identified, analyzed, controlled, and regulated.

Disruption: Disruptions are characterized by the likelihood of occurrence, intensity, and a consequential situation that affects ordinary business operations. Such breakdowns occur at certain parts of the SC or across the entire SC due to factors including, but not limited to, labor disputes, war, terrorism, natural disasters, fires, and pandemics.

Uncertainty: According to Ivanov et al. (2019b), uncertainty represents a substantial space of unexpected events compared with risk as it is an antecedent of risk and can also result in positive consequences (Simangunsong et al., 2012). Fig. A.20 can help visualize the interrelation between uncertainty, risk, and disruption.

Vulnerability: Refers to the degree to which a system is susceptible to the effects of SC disruptions or disturbances. Vulnerability is also considered as change or transformation when confronted with disruptions. A capacity to preserve the structure or operations of SC comes under vulnerability, whereas the capacity to recover is a characteristic of resilience. Resilience is considered a subset of a system's capacity to respond and is related to an ability to adjust to disturbances and get through with the consequences of any system transformations (Gallopín, 2006) (see Fig. A.21).

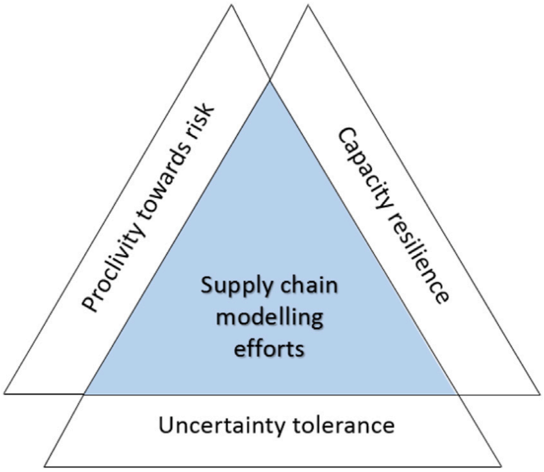

Fig. A.19. Venn diagram representing the scope of the study.

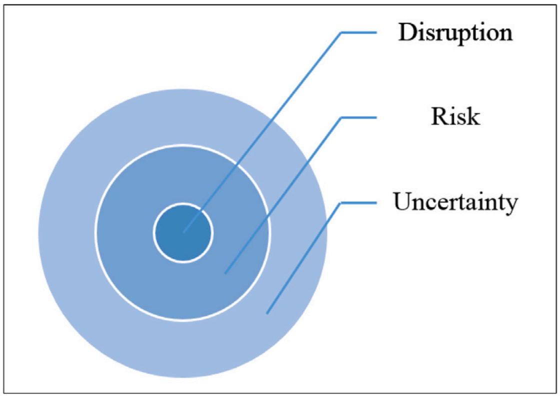

Fig. A.20. Relation between disruption, risk and uncertainty.
Source: Ivanov et al. (2019b)

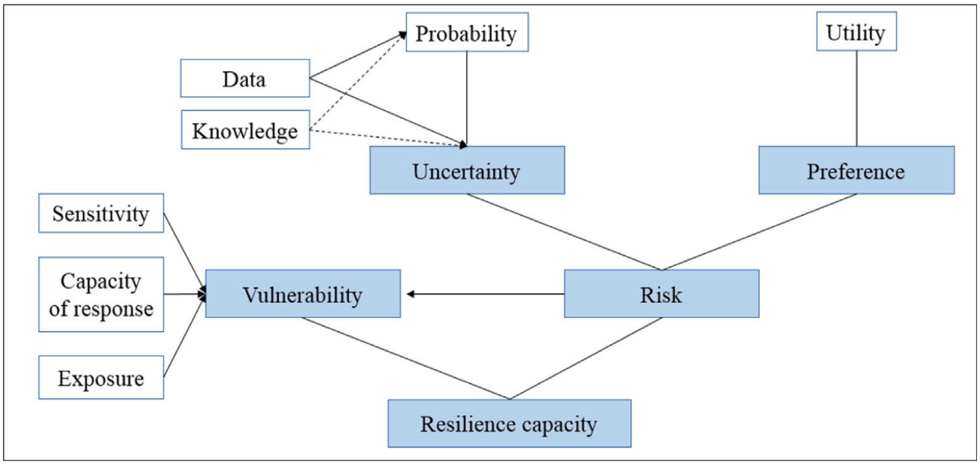

Fig. A.21. Interrelationship between risk, uncertainty, vulnerability, and resilience.

Table A.15
Top 10 papers using co-citation and PageRank algorithm and their information.

Author		Local Citation		Global Citation		Author information based on PageRank	
Co-citation	PageRank	Co-citation	PageRank	Co-citation	PageRank	Respective cluster	PageRank
Chan and Kumar (2007)	Fahimnia and Jabbarzadeh (2016)	159	15		88	5	0.034167
Santoso et al. (2005)	Snyder et al. (2016)	137	135		369	5	0.026434
Tsay (1999)	Fahimnia et al. (2015b)	124	35		191	2	0.01755
Buyukozkan and Cifci (2012)	Heckmann et al. (2015)	94	105		402	2	0.016705
Klibi et al. (2010)	Hasani and Khosrojerdi (2016)	142	29		83	5	0.01183
Mohanty et al. (2005)	Eskandarpour et al. (2015)	91	50		297	6	0.011289
Chan et al. (2008)	Keyvanshokooh et al. (2016)	83	39		112	3	0.011201
Sabri and Beamon (2000)	Rezaee et al. (2017)	68	30		85	6	0.010332
Yue et al. (2014)	Brandenburg et al. (2014)	65	284		693	6	0.009376
Pishvaee et al. (2011)	Sawik (2013b)	61	138		624	3	0.011321

Table A.16
Lead papers contributing to theme generation using co-citation and PageRank algorithm.

Cluster1	Cluster2	Cluster3	Cluster4
Cachon and Zipkin (1999)	Soyster (1973)	Carvalho et al. (2012)	Pishvaee and Razmi (2012)
Graves and Willems (2005)	Mulvey et al. (1995)	Schmitt and Singh (2012)	Pishvaee et al. (2012)
Kumar and Alvi (2006)	Ben-Tal and Nemirovski (1998)	Sawik (2013a)	Vahdani et al. (2013)
Wadhwa et al. (2007)	El Ghaoui et al. (1998)	Sawik (2013b)	Amin and Zhang (2013a)
Chan et al. (2008)	Bertsimas and Sim (2003)	Sawik (2014a)	Amin and Zhang (2013b)
Peidro et al. (2009)	Ben-Tal and Nemirovski (2000)	Ivanov et al. (2014b)	Ramezani et al. (2013a)
Ho et al. (2010)	Sahinidis (2004)	Chopra and Sodhi (2014)	Ramezani et al. (2013b)
Wu and Barnes (2010)	Bertsimas and Thiele (2006)	Fahimnia et al. (2015b)	Govindan et al. (2015)
Shaw and Khan (2012)	Leung et al. (2007)	Heckmann et al. (2015)	Zeballos et al. (2014)
Chai et al. (2013)	Pishvaee et al. (2012)	Klibi and Martel (2012)	Keyvanshokooh et al. (2016)

Cluster5	Cluster6	Cluster7
Ekşioğlu et al. (2009)	Birge (1997)	Beamon (1999)
Zamboni et al. (2009b)	Owen (1998)	Srivastava (2007)
Huang et al. (2010)	Sabri and Beamon (2000)	Linton et al. (2007)
Iakovou et al. (2010)	Tsiakis et al. (2001)	Dehghanian and Mansour (2009)
An et al. (2011b)	Daskin et al. (2002)	Ahumada and Villalobos (2009)
Gold and Seuring (2011)	Jayaraman and Ross (2003)	Bai et al. (2010)
Dal-Mas et al. (2011)	Santoso et al. (2005)	Kuo et al. (2010)
An et al. (2011a)	Chopra and Sodhi (2014)	(Wang et al., 2011a)
Qiao et al. (2013)	Snyder et al. (2016)	Wang et al. (2011b)
Giarola et al. (2011)	Arashpour et al. (2017)	Kannan et al. (2013)

Appendix B. Mathematical significance of RO and SP to model uncertainty and achieve SCR

$$Min\ \ c^{\tau}x + d^{\tau}y \tag{B.1}$$

Subject to

$$Ax = b \tag{B.2}$$

$$Bx + Cy = e \tag{B.3}$$

$$x, y \geq 0 \tag{B.4}$$

The x is a vector of decision variables, and y is a vector of control variables. Structural constraints, such as Eq. (B.2), are free of uncertainty and control constraints, whereas Eq. (B.3) is subject to noise or uncertainty. The equivalent RO representation of the above linear program is presented as follows.

$$Min\ \ \sigma(x, y_1, y_2, \dots, y_s) + \omega\ \rho(\delta_1, \delta_2, \dots, \delta_s) \tag{B.5}$$

Subject to

$$Ax = b \tag{B.6}$$

$$B_s x + C_s y + \delta_s = e \quad \forall s\epsilon\varphi \tag{B.7}$$

$$x_s, y_s \geq 0 \quad \forall s\epsilon\varphi \tag{B.8}$$

For every scenario $s\epsilon\varphi$, the coefficient of control constraints d_s, B_s, C_s, and e_s with an associated probability P_s, such that $\sum_{s\epsilon\varphi} P_s = 1$, a robust feasible/optimal solution can be obtained. A non-optimal solution can be robust under a given setting provided it remains feasible for all conditions, also termed model robustness. Solution robustness is when an optimal solution remains close to optimality for any realization of scenarios. The scenario-based representation of the above formulation is presented in Eqs. (B.5) to (B.8). Where Eq. (B.7) is the in-feasibility penalty function and represent weight for adjustment. The solution for this set of problem is represented as per Mulvey et al. (1995) in Eq. (B.9), and the quadratic term making the whole equation complicated to solve is approximated in Eq. (B.10) using Yu and Li (2000). Equivalently, the robust optimization problem is then reformulated, where θ_s is used as deviational variable in Eqs. (B.13) subject to Eqs. (B.6) to (B.8), (B.12), and (B.13).

As stated above, the model can be infeasible under some scenarios; the second term represents the in-feasibility penalty function and represent weight for adjustment. The solution for the above set of problem is represented as per (Mulvey et al., 1995).

$$\sigma(x, y_1, y_2, \dots, y_s) = \sum_{s\epsilon\varphi} p_s \varphi_s + \lambda \sum_{s'\epsilon\varphi} p_s \left(\varphi_s - \sum_{s'\epsilon\varphi} p_s \epsilon\varphi \right)^2 \tag{B.9}$$

λ is a constant and part to its right represents the variance. This quadratic term was further approximated into absolute deviation by Yu and Li (2000) as:

$$\sigma(x, y_1, y_2, \dots, y_s) = \sum_{s\epsilon\varphi} p_s \varphi_s + \lambda \sum_{s'\epsilon\varphi} p_s \left| \varphi_s - \sum_{s'\epsilon\varphi} p_s \epsilon\varphi \right| \tag{B.10}$$

Equivalently, the robust optimization problem is then reformulated as follows, where θ_s is used as deviational variable:

$$Min = \sum_{s\epsilon\varphi} p_s \varphi_s + \lambda \sum_{s'\epsilon\varphi} p_s \left[\left(\varphi_s - \sum_{s'\epsilon\varphi} p_s \epsilon\varphi \right) + 2\theta_2 \right] \tag{B.11}$$

subject to

$$\varphi_s - \sum_{s'\epsilon\varphi} p_s \varphi_s + \theta_s \geq 0 \tag{B.12}$$

$Equation$ (B.6)–(B.8)

$$\theta_s \geq 0 \tag{B.13}$$

The risk-neutral two-stage stochastic program of above formulation can be presented as below:

$$\min_{x\epsilon R^n} \mathbb{E}(f(\mathbf{x},\ \omega)) = \min_{x\epsilon R^n} c^T \mathbf{x} + \mathbb{E}(Q(x,\ \xi(\omega))) \tag{B.14}$$

In the equation above, $f(\mathbf{x},\ \omega) = c^T \mathbf{x} + Q(x,\ \xi(\omega))$ is the total cost function, including objectives of both stages of the two-stage stochastic program. The variable $\mathbf{x}$ is a vector of first-stage decision variables (main decision variables). Eq. (B.6) presents the second-stage problem with recourse function and some constraints; here, the variable $\mathbf{y}$ represents the vectors of second-stage decision variables.

$$Q(x,\ \xi(\omega)) = \min_{y_s} \{(q_s)^T y_s \ :\ T_s x + W_s y_s = h_s,\ y_s \geq 0\} \tag{B.15}$$

The recourse cost function $Q(x,\ \xi(\omega))$ of the second-stage problem is a random variable and, therefore, the main objective function $f(\mathbf{x},\ \omega)$ is a random variable. Decision theories in the past have realized the challenges of comparing random variables under uncertainties (Miller and Ruszczyński, 2011; Noyan, 2012). Hence, computing the optimal decision vector $\mathbf{x}$ leads to the problem of comparing random cost variables $\{f(\mathbf{x},\ \omega)\}\_x\epsilon X\}$. These efforts can be minimized by considering the effect of variability and preference relations among the random variables (Noyan, 2012). Therefore, the risk-averse two-stage framework will be:

$$\min_{x\epsilon R^n} \mathbb{E}(f(\mathbf{x},\ \omega)) + \lambda\ \rho(f(\mathbf{x},\ \omega)) \tag{B.16}$$

λ is a non-negative weighted coefficient of risk part, specified by the decision-makers according to the risk preferences. The resultant MILP formulation of the two-stage stochastic program with $CVaR_{\alpha}$ is presented with basic understandings of random variables Z, α level of significance, VAR, and CVaR.

$$VaR_{\alpha}(Z) = inf\{\eta \in R : F_z(\eta) \geq \alpha\} \ and \ CVaR_{\alpha}(Z) = E(Z|Z \geq VaR_{\alpha}(Z))$$

where F, represents cumulative distribution function of a set of random variables 'Z'.

$$CVaR_{\alpha}(Z) = \min_{x \epsilon R^n} f(\alpha, \eta, x)$$

$$f(\alpha, \eta, x) = \eta + \frac{1}{1-\alpha} E\{max\{Z(x, \omega)\} - \eta, 0\}$$

Following the above equations, the mean-VAR and mean-CVaR objectives can be incorporated in the two-stage stochastic framework as follows:

$$\min_{x \epsilon R^n} \mathbb{E}f(\mathbf{x},\ \omega) + \lambda VaR_{\alpha}(f(\mathbf{x},\ \omega))$$

$$\min_{x \epsilon R^n} \mathbb{E}(f(\mathbf{x},\ \omega)) + \lambda CVaR_{\alpha}(f(\mathbf{x},\ \omega)) \tag{B.17}$$

Therefore, the resultant MILP formulation of two-stage stochastic program with $CVaR_{\alpha}$ is presented as follows:

$$min\ (1+\lambda)\ \mathbf{c}^T\mathbf{x} + \sum_{s=1}^{N} p_s(\mathbf{q}_s)^T y_s + \lambda \left(\eta + \frac{a}{1-\alpha} \sum_{s=1}^{N} p_s\ v_s\right) \tag{B.18}$$

subject to

$$W_s\mathbf{y}_s = \mathbf{h}_s - T_s\mathbf{x}, \quad s = 1, \ldots, N. \tag{B.19}$$

$$v_s \geq (\mathbf{q}_s)^T \mathbf{y}_s - \eta, \quad s = 1, \ldots, N, \tag{B.20}$$

$$\mathbf{x} \in X,\ \mathbf{y}_s \geq 0,\ \eta \in \mathbb{R},\ v_s \geq 0, and\ s = 1, \ldots, N. \tag{B.21}$$

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