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ORIGINAL - SURVEY OR EXPOSITION

Designing resilient supply chain networks: a systematic literature review of mitigation strategies

Abdolreza Roshani[1] · Philip Walker-Davies[3] · Glenn Parry[2]

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Abstract
With increased globalisation supply chain (SC) disruption significantly affects people, organisations and society. Supply chain network design (SCND) reduces the effects of disruption, employing mitigation strategies such as extra capacity and flexibility to make SCs resilient. Currently, no systematic literature review classifies mitigation strategies for SCND. This paper systematically reviews the literature on SCND, analysing proposed mitigation strategies and the methods used for their integration into quantitative models. First to understand the key failure drivers SCND literature is categorised using geography, with local, regional or global disruptions linked to vulnerable sections of a SC. Second, the strategies used in mathematical models to increase SC resilience are categorized as proactive, reactive, or SC design quality capabilities. Third, the relative performance of mitigation strategies is analysed to provide a comparison, identifying the most effective strategies in given contexts. Forth, mathematical modelling techniques used in resilient SCND are reviewed, identifying how strategies are integrated into quantitative models. Finally, gaps in knowledge, key research questions and future directions for researchers are described.

Keywords Supply chain · Network design · Resilience · Resilience strategies · Mitigation Strategies · Systematic literature review

1 Introduction

The 9/11 terror attacks, the 2011 Japanese tsunami, and the 2020 COVID-19 pandemic are events that significantly impacted supply chains [SCs] (Aldrighetti et al., 2021; Snyder et al., 2016; Suryawanshi & Dutta, 2022). Although the risk likelihood of these events is low, they significantly impact SC performance (Tang, 2006) and encourage design of resilient SCs that can adjust to disruption (Wieland & Durach, 2021). Supply Chain Network Design [SCND]

✉ Abdolreza Roshani
a.roshani@surrey.ac.uk

1 Department of Business Analytics and Operations, Surrey Business School, University of Surrey, Guildford, UK

2 Centre of Digital Economy, Surrey Business School, Guildford, UK

3 University of Bristol Business School, University of Bristol, Bristol, UK

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is of interest to academics and practitioners as it decreases (increases) the cost (profit) of SCs (Simchi-Levi & Kaminsky, 2004) and effects performance and resilience (Shen, 2007). Resilience can be achieved through creating redundancy (Sheffi, 2005), including holding safety/emergency stocks, having multiple suppliers and low capacity utilization rates to hedge against disruptions. In the literature, different redundancies are modelled to create mitigation strategies (Hosseini et al., 2019a, 2019b), hedging against disruption risk (Ivanov et al., 2017). Mitigation strategies have two subcategories, proactive and reactive, depending if their applied pre- or post-disruption (Elluru et al., 2019).

Supply chain disruption and resilience have been analysed using both qualitative and quantitative models. Empirical and conceptual qualitative models are commonly used to identify, assess, and manage risks of disruption (Hervani et al., 2022; Hosseini et al., 2019a, 2019b). Quantitative models are applied to assess the impacts of disruptions on supply chains and to evaluate relevant mitigation strategies (Azad & Hassini, 2019; Snyder et al., 2016; Taleizadeh et al., 2022). Quantitative work integrates mitigation strategies into mathematical models to design resilient SCs [RSCs] (Abbasian et al., 2023; Aldrighetti et al., 2021; Kabadurmus & Erdogan, 2020). However, before integration several critical challenges must be addressed. First disruptive events may affect different parts of SCs. Thus, the failure parameters in the models must be adjusted to show the actual condition of SCs' vulnerability. Second, the efficiency of resilience strategies differs with context. When modelling resilient SCND [RSCND] problems, identifying an optimum strategy needs information of the relative performance of mitigation strategies in specific context. Third, RSC design requires that modelling approaches integrate the appropriate mitigation strategies and define their characteristics.

To address these challenges, a systematic literature review (SLR) of quantitative models of SCND was undertaken, focusing on mitigation strategies, their relative performance and their integration into mathematical models. The SLR is a well-established method used in analysing literature, including supply chain resilience (Aldrighetti et al., 2021; Maharjan & Kato, 2022; Naghshineh & Carvalho, 2022). However, few literature reviews examine quantitative models of RSC design that consider strategic facility location and supplier selection decisions. Table 1 details the content of extant literature reviews articles; $\surd$, o and x imply the area is covered, partially covered, and not covered respectively.

Whilst this review has some overlap with references from previous work (Table 1), significant differences exist. To our knowledge, no published review classified mitigation strategies applied in designing SCs based on vulnerabilities, none categorises them into proactive, reactive and SC design quality groups, none identify the relative performance of mitigation strategies that improve SC resilience, and none identify methods to integrate mitigation strategies into quantitative models. This paper aims to advance research in these areas by answering the following research questions:

- RQ1: What is the classification of disruptions based on their geographic scope and the part of SCs they affect?
- RQ2: Focussing on vulnerable SC sections, what strategies have been introduced to improve resilience?
- RQ3: Drawing on performance criteria from literature, how have these strategies improved the resilience of supply chains?
- RQ4: How are resilience strategies integrated into mathematical models?

The remainder of this paper is organized as follows: Sect. 2 presents the research method. Section 3 addresses RQ1, Sect. 4 addresses RQ2 & 3, whilst Sect. 5 addresses Q4. Concluding remarks, managerial insights, and future research directions will follow in Sects. 6.

Table 1 Existing relevant review articles

References	Mitigation strategies	Relative performance analysis of strategies		Math. Modelling elements	Solution approaches	Timespan	# Shared references with this study
		Int	*Ext*				
Snyder et al. (2016)	√	x	x	o	o	Up to 2015	12 (11.65%)
Ivanov et al. (2017)	o	x	x	o	√	Up to 2017	15 (14.56%)
Rajagopal et al. (2017)	o	x	x	√	√	2005–2016	17 (16.5%)
Hosseini et al., (2019a, 2019b)	o	x	x	o	o	2002–2018	12 (11.65%)
Aldrighetti et al. (2021)	√	x	x	o	√	Up to 2019	31 (30.1%)
Suryawanshi and Dutta (2022)	x	x	x	o	√	Up to 2020	28 (27.18%)
Maharjan and Kato (2022)	√	x	x	o	√	2008–2020	12 (11.65%)
Proposed study	√	√	√	√	x	2001–2024	

Int: Internal; *Ext*: External; √: covered; o: partially covered; x: not covered

2 SLR methodology

The SLR was undertaken in three stages, Fig. 1 (Tranfield et al., 2003). Stage one is process planning, in stage two the review process is undertaken and in stage 3 findings from analysis of the literature are reported, and each are now detailed.

2.1 Data source, inclusion, and exclusion criteria

Scopus and Web of Science (WoS) databases were selected as the most relevant sources, in accordance with previous reviews papers (Aldrighetti et al., 2021; Katsaliaki et al., 2021). The earliest articles on SC disruption and resilience were published the early 2000s, following the 9/11 Terrorist attacks (Katsaliaki et al., 2021), so the sample selection timeframe is restricted to 2001–2024. To ensure the inclusion of only top-tier research and industrial development, our analysis specifically targets articles published in prominent English-language journals. In this regard, we exclusively consider articles published in journals listed in the latest Chartered Association of Business Schools (CABS) 2021 ranking. This ranking incorporates multiple journal quality assessments, providing a reliable measure of research rigor

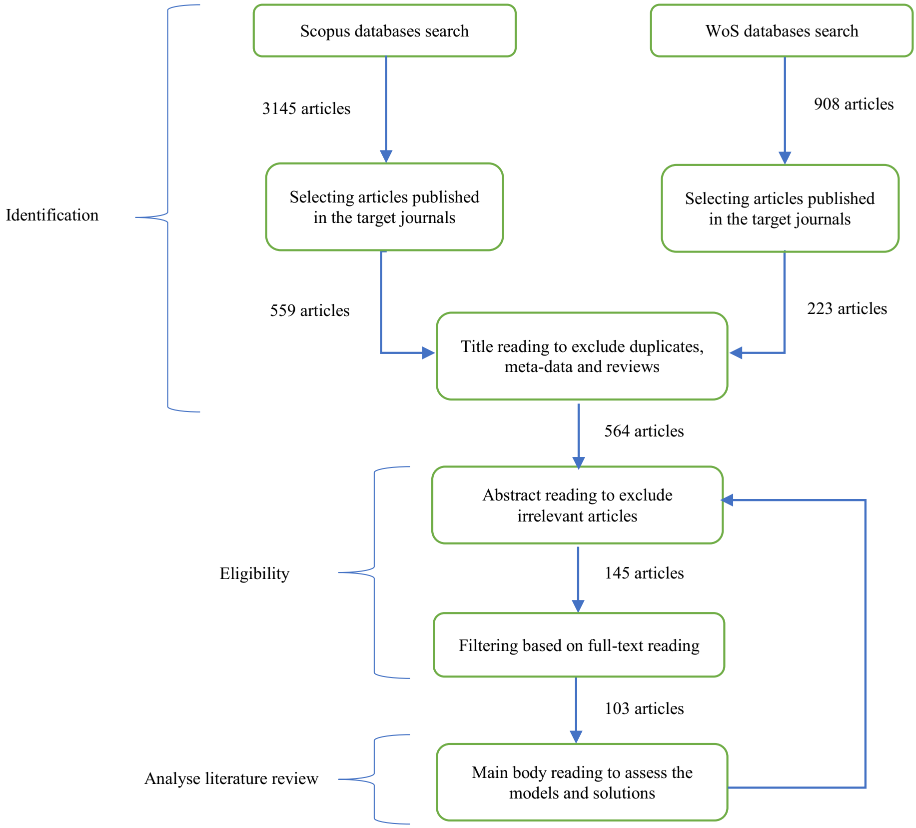

Fig. 1 Literature review methodology. A flow diagram represents the process of searching selected keywords in Scopus and WoS databases, to find reference articles by excluding duplicates, reviews and irrelevant articles

and excellence. While journal rankings are inevitably subject to debate, the CABS ranking is widely recognized for its consistent and high standards of research quality (Kamal & Irani, 2014; Miemczyk & Johnsen, 2012; Rajagopal et al., 2017). Thus, in accordance with (Kamal & Irani, 2014; Rajagopal et al., 2017) only journals rated CABS 3, 4, and 4* are selected, and lower ranked and grey literature excluded (selected journals are listed in table i in supplementary materials).

Content criteria filters are employed in selecting articles to review. First, selected articles should be categorized as SC design problems. Second, only resilient decision-making [DM] problems with strategic and tactical time scales are considered. Third, papers must contain mathematical models, with binary variables used for selecting suppliers or opening facilities. Following Aldrighetti et al. (2021), we focus on SCND applied in industrial commercial sectors, excluding design of water, telecommunication and healthcare SCs. R-interdiction and fortification problems are also omitted since their goal is to select existing facilities to fortify, rather than relocating them (Liberatore et al., 2012; Starita & Paola Scaparra, 2021).

2.2 Retrieval strategy and review process

Following Saunders et al. (2009) the article retrieval strategy employed an iterative procedure of defining appropriate keywords, searching, analysing the literature and finalising results. Examination of research reviews on similar topics gave rise to two groups of keywords. The first relates to SCND and the second to resilience. The keyword combinations used to search given databases are provided in the supplementary material (table i).

The SLR starts (Fig. 1) with a keyword search on Scopus (3145 articles identified) and WoS (908 articles) databases, and was performed at the end of April 2024. Article titles were used to exclude duplicates. The abstract and main body of the paper were examined to exclude irrelevant papers and those not published in target journals, leaving 145 papers. Finally, the full-text was read and to avoid missing relevant papers, forward and backward snow balling methods performed. 103 articles were selected for final analysis (Supplementary Material Figure i shows number of articles published by year).

3 Definitions

To establish a clear and consistent understanding of terms related to supply chain disruption and resilience several researchers' definitions for these terms have been analysed. Through analysis and consideration of contexts of these definitions, we have sought to unify a comprehensive understanding. Five key terms were selected, which include "supply chain disruption," "supply chain resilience," "resilience or mitigation strategies," "proactive strategies," and "reactive or contingency strategies." The definitions and explanations of these terms have been thoroughly examined, and the resulting insights presented in Table 2.

4 Finding from the content analysis

In this section we present the findings from the content analysis, which explore various aspects of supply chain disruptions and mitigation strategies. We investigate the types of disruptions and vulnerable sections in 4.1, followed by a detailed review of proposed mitigation strategies in designing supply chains in 4.2. Furthermore, we investigate the integration of resilience

Table 2 Definitions of supply chain resilience related terms

Term	Definition	References
Supply chain disruption	Random events that cause a supplier or other element of the supply chain to stop functioning, either completely or partially, for a (typically uncertain) time period	(Aldrighetti et al., 2021; Chapman et al., 2002; Chopra & Sodhi, 2004; Craighead et al., 2007b; Garvey et al., 2015; Kinra et al., 2020; Snyder et al., 2016; Tang, 2006)
Supply chain resilience	The capability of a supply chain to return to its original state or even a more desirable condition after being disrupted	(Spiegler et al., 2012; Hosseini et al., 2019a, 2019b; Zhao et al., 2019; Sheffi & Rice Jr., 2005; Wieland & Durach, 2021; Ponomarov & Holcomb, 2009; Shekarian & Mellat Parast 2021; Christopher & Peck, 2004; Rajabzadeh & Babazadeh, 2022)
Resilience or mitigation strategies	Strategies used to reduce vulnerability of SCs to potential disruptions	(Dolgui et al., 2018; Elluru et al., 2019; Snyder et al., 2016; Spiegler et al., 2012; Tomlin, 2006)
Proactive strategies	Proactive strategies refer to measures taken to anticipate and prevent potential problems before they occur	(Tukamuhabwa et al., 2015)
Reactive or contingency strategies	Strategies focusing on designing SC processes and structures, which can be adjusted when disruption occurs	(Aldrighetti et al., 2021; Dolgui et al., 2018; Ivanov et al., 2017; Tomlin, 2006)

strategies into mathematical models in subSect. 4.3, focusing on disruption-related parameters in 4.3.1 and the methodology for incorporating these strategies into the mathematical models in 4.3.2.

4.1 Type of disruption and supply chain vulnerable sections

To answer to RQ1, “what is the classification of disruptions based on their geographic scope and the part of SCs they affect?”, disruption events reported in the SCND literature were categorized based on their geographic affect: local, regional, or global (Sawik, 2013b, 2019, 2014). Local disruptions are characterized by their confined impact, typically affecting specific facilities or locations within a supply chain. For instance, an illustrative example of a local disruption is the Philips microchip plant fire that occurred in New Mexico in 2000, which had repercussions limited to that particular facility. Researchers and scholars, such as (Norrman & Jansson, 2004), have explored and documented local disruptions extensively.

Moving beyond localized disruptions, regional disruptions encompass a broader scale, impacting multiple nodes and arcs within a particular geographic region. These disruptions can be caused by various events, including but not limited to regional labour strikes, logistical errors, and natural disasters like floods or earthquakes. The devastating Tohoku earthquake of 2011 (Park et al., 2013) and the unexpected 2018 UK KFC chicken shortage (Young & Bhattacharyya, 2020) are compelling instances of regional disruptions that affected different parts of the supply chain within their respective areas.

On a grander scale, global disruptions have the potential to disrupt entire supply chains, transcending regional and local boundaries. These disruptions are often caused by significant global events such as economic crises, labor strikes in the transportation sector, or catastrophic events like the Covid-19 pandemic in 2019 (Remko, 2020). The Covid-19 pandemic, in particular, had far-reaching consequences, profoundly impacting supply chains worldwide (Paul et al., 2021).

To organize the body of literature, Table 3 provides a comprehensive categorization based on the type of disruption and the corresponding decision-making (DM) problems studied. The DM problems are grouped into four main classes: resilient supplier selection (RSS), reliable facility location (RFL), resilient logistic network design (RLND), and integrated reliable facility location (IRFL). The table includes a summary column presenting the percentages of studies that address each DM problem based on the categories of disruptions, namely, global, regional, and local.

From the table, it becomes evident that the majority of the studies have focused on local disruptions, accounting for approximately 96.12% of the research. Regional disruptions constituted about 14.56% of the studies, while global disruptions represented 4.85% of the analysed articles (total exceeds 100% due to overlaps in the data). When dealing with global and regional disruptions, researchers have primarily concentrated on RSS and RLND, likely due to the broader and more severe impact these disruptions can have on the supply chain. In contrast, studies addressing local disruptions have often explored RLND and RFL, given the more contained scope of these disruptions.

Supply chain networks usually encompass multiple tiers, including suppliers, manufacturers (plants), distribution centres (warehouses or depots), retailers, and customers (demand zones). To represent this interconnected system, a general graph, $G = (V, A)$, is employed, where V denotes the set of nodes representing the different facilities and customer zones dispersed across R disjoint geographic regions. The set of arcs, denoted by A, captures the various routes that connect these nodes, symbolizing the intricate flow of goods and information within the supply chain network. Table 3 summarizes the percentage of studies that have addressed specific vulnerable areas of the supply chain concerning the type of disruption. From the table, it is evident that researchers have primarily focused on studying the vulnerabilities of suppliers, which represents approximately 55.34% of the examined articles. Following closely, distribution centres have garnered significant attention, constituting 30.1% of the studies, while general facilities have been the subject of 29.13% of the analysed research.

4.2 Mitigation strategies

In this subsection, we provide a comprehensive exploration of different aspects related to the design and evaluation of supply chain mitigation strategies. Included is a thorough review of proposed mitigation strategies in designing supply chains (Sect. 4.2.1), an analysis of mitigation strategy combinations (Sect. 4.2.2), and an assessment of the relative performances of various mitigation strategies (Sect. 4.2.3).

Table 3 Studies that address different vulnerable areas of SC by DM problem and disruption type

Types of disruption	DM problem	Vulnerable sections of SC							Share of articles by disruption type (%)
		Suppliers	Facilities				Trans. Modes, 3P logistics or Routes	Customers' demand	
			General	Plants or manufacturers	DCs, TCs, warehouses, or depots	Retailers			
Global									**4.85**
	RSS	[6, 13, 14, 35]							3.88
	RLND	[100]			[100]	[100]	[100]	[100]	0.97
Regional or semi global									**14.56**
	RSS	[23, 35, 36, 48, 69, 77, 91]							6.80
	RFLP		[15, 63]						1.94
	RLND	[46, 67, 92, 100]		[46, 67, 84, 92, 100]	[46, 84, 92, 100]	[84]	[100]	[100]	4.85
	IRFLP			[78]	[78]			[78]	0.97
Local									**96.12**
	RSS	[3, 6, 13, 14, 23, 27, 35, 36, 41, 48, 49, 55, 56, 60, 64, 69, 75, 77, 79, 86, 91, 98, 103]		[60]					22.33

Table 3 (continued)

Types of disruption	DM problem	Vulnerable sections of SC							Share of articles by disruption type (%)
		Suppliers	Facilities				Trans. Modes, 3P logistics or Routes	Customers' demand	
			General	Plants or manufacturers	DCs, TCs, warehouses, or depots	Retailers			
	RFL		[1, 2, 4, 8, 10, 11, 15, 16, 18, 19, 20, 25, 26, 28, 29, 30, 32, 33, 37, 38, 50, 51, 58, 63, 66, 70, 80, 95]		[39, 94]			[25, 85]	30.1
	RLND	[5, 9, 21, 34, 42, 43, 44, 52, 53, 54, 57, 68, 71, 74, 76, 81, 88, 89 90, 93, 96, 99, 100, 101]		[22, 42, 44, 45, 54, 61, 68, 71, 87, 89, 90, 93, 96, 99, 101]	[9, 12, 17, 22, 42, 45, 47, 57, 59, 61, 65, 68, 72, 81, 82, 87, 88, 96, 97, 100, 101, 102]	[5, 76, 81, 100, 101]	[17, 22, 34, 44, 52, 59, 65, 68, 81, 87, 90, 93, 100, 102]	[42, 47, 59, 61, 81, 100]	36.89
	IRFL		[7, 62]	[24, 73]	[31, 40, 83]	[83]	[24, 31, 62]		6.80
Share of Articles by SC vulnerability (%)		55.34	29.13	23.3	30.1	5.82	16.5	8.74	*

*Note that the summation of *% share of articles* (by disruption type or by SC vulnerability) exceeds 100% due to overlaps in the data. For instance, certain references account for both regional and local disruptions

4.2.1 Review of proposed mitigation strategies in designing supply chains

RQ2 asked "focussing on vulnerable SC sections, what strategies have been introduced to improve resilience?". We identify SCs resilience strategies used for different vulnerable sections and examine their use in the design of SCs. Chowdhury and Quaddus (2017) define three groups of capabilities that determine the resilience of a SC against disruptions: (a) proactive capabilities, (b) reactive capabilities, and (c) SC design quality capabilities. Proactive capabilities, such as SC readiness and flexibility, help systems to recognise, anticipate and defend against the risk of disruption, reducing impact before it occurs. Reactive capabilities of SCs form from SC response and recovery. *SC response* is the capability of the system to mitigate the disruption in the shortest possible time and with smallest impact, while *recovery capability* is defined as the ability to rapidly return to a normal operational state (Pettit et al., 2013). SC design quality capability is determined by node density, complexity and critically (Chowdhury & Quaddus, 2017; Craighead et al., 2007a, 2007b). The full list of 133 mitigation strategies from literature is in Table 8, categorising resilient strategies based on specified vulnerable section i.e. suppliers, general facilities etc., and the three SC capabilities from Chowdhury and Quaddus (2017).

Proactive strategies are mainly applied to suppliers (PrasannaVenkatesan & Goh, 2016; Sawik, 2020), DCs (Gholami-Zanjani et al., 2021a; Hasani & Khosrojerdi, 2016) and plant and manufacturers (Gholami-Zanjani et al., 2021b; Hasani & Khosrojerdi, 2016). SC design quality strategies are used extensively for suppliers (Nooraie & Parast, 2016; Sawik, 2011), general facilities (Snyder & Daskin, 2005; Saha et al., 2023), DCs (Hasani & Khosrojerdi, 2016) and transportation (Ghavamifar et al., 2018, Wang and Yao 2023). Reactive strategies are commonly applied to suppliers (Cheng et al., 2018, Ghomi-Avili et al., 2021; Fattahi et al., 2020), DCs (Alikhani et al., 2021; Zhang et al., 2024), demand points (Hosseini et al., 2019a, 2019b; Alikhani et al., 2023a, 2023b), plant and manufacturers (Feng et al., 2023; Sabouhi et al., 2020) and general facilities (Egri et al., 2023; Xie et al., 2019).

Reviewing information summarised in Table 8 reveals a set of mitigation strategies commonly used to make SCs more robust and resilient. Table 4 lists those strategies applied to at least two different vulnerable sections of SCs. We have also assigned a code referring to each mitigation strategy in column one of Table 4. The last column reports the percentage of reference articles that apply the respective strategy in their quantitative model. Table 4 contains eight proactive mitigation strategies (labelled P1–P8). *P5* (11.65%), and *P7* (9.71%) utilising *reserve capacity*, and *P1* (11.65%) from *SC readiness* are the most commonly studied approaches in the sample. Though commonly used, these strategies may perform differently in different SCND contexts. For example, in designing a global supply chain (GSC) for an electro-medical device manufacturer, with the objective of maximising total net present value of the GSC after-tax profit, Hasani and Khosrojerdi (2016) applied P1 to protect suppliers, manufacturers, and warehouses against disruptions. They applied P7 in warehouses to deal with the finished product shortage resulting from capacity disruption of facilities in the upper tiers. They found that P1 significantly mitigated the risk of disruptions, while the efficiency of strategy P7 was not significant. In contrast, Rezapour et al. (2017) analysed the design of a resilient automotive parts manufacturer SC under competition to maximise total expected profit. They applied P5 to enable suppliers to increase their production capacities and P7 to allow retailers to hold emergency stock as a mitigation strategy. They showed that P7 is more efficient than P5 in both reducing profit variation and improving the SC worse case profit. Recently, Alikhani et al., (2023a, 2023b) applied various combinations of mitigation strategies, including P1 and P7, to design resilient retail supply chains. They demonstrated

Table 4 Proactive, reactive, and SC design quality resilience strategies applied for at least two different vulnerable sections

Code	Strategies	Strategy code*	RFL	IRFL	RSS	RLND	% Share of Articles by strategy
Proactive							
SC readiness							
P1	Protection or fortification	SP1, FP1, PP1, DP1, RP1, TP2	[10, 16, 37]		[13, 27]	[46, 47, 81, 82, 99, 100, 102]	**11.65**
P2	Cybersecurity	SP4, DP3, RP2				[100]	**0.97**
Flexibility and reliability							
P3	Flexibility	SP5, SP6, FP2, PP4 ,DP4, TP3		[73]	[35, 60, 75, 91]	[87]	**5.82**
P4	Reliability	SP7, PP5, DP5, TP4			[60, 75, 86]	[44, 52, 74, 87, 101]	**7.77**
Reserve capacity							
P5	Additional or backup production capacity	SP8, FP3, PP8	[10]	[62]	[60, 86]	[52, 53, 54, 68, 81, 84 96, 99]	**11.65**
P6	Additional inventory capacity	SP9, DP6, RP3		[78]	[64]	[61, 72, 81, 92]	**5.82**

Table 4 (continued)

Code	Strategies	Strategy code*	RFL	IRFL	RSS	RLND	% Share of Articles by strategy
P7	Pre-positioned Inventory & holding safety and emergency stocks	SP10, PP9, DP7, RP4			[13, 27, 69, 77]	[46, 52, 53, 81, 96, 100]	**9.71**
P8	Collaboration	SP11, PP10, DP9			[56]	[96]	**1.94**
Reactive							
Response							
R1	Customers' demand reallocation or modification of the amount of shipment from primary or backup facilities	SR4, FR4, PR3, DR3, RR2	[66, 94]	[78]	[27, 55, 64, 91, 98]	[9, 12, 42, 43, 45, 46, 54, 57, 67, 71, 81, 82, 84, 88, 89, 93, 96, 97, 99, 100, 102]	**28.15**
R2	Reassignment of customers to survived facilities	FR1, PR9, DR2	[8, 19, 25, 26, 28, 32, 63, 80, 85, 95]	[24, 31]		[72, 88]	**13.59**
R3	Applying the lateral transhipment	SR8, FR3, PR10, DR1	[66]		[49, 69, 77]	[17, 67, 68, 81, 88]	**8.74**

Table 4 (continued)

Code	Strategies	Strategy code*	RFL	IRFL	RSS	RLND	% Share of Articles by strategy
R4	Recalculating the amount of products transferred through different routes	PR4, DR4				[22, 43, 59, 61, 65, 68]	**5.82**
R5	Recalculating the inventory position of products	PR8, DR6		[78, 83]	[60]	[12, 46, 47, 59, 72, 81, 93]	**9.71**
Recovery							
R7	Recalculating the amount of order from backup or recovery suppliers (recovery supply portfolio)	SR15, PR13			[48, 69, 77, 91]	[67]	**4.85**
R8	Recalculating the capacity recovery time	SR17, PR12				[89]	**0.97**
R9	Recalculating the recovery or restoring level of capacities	PR14, DR10, TR6				[99, 102]	**1.94**

Table 4 (continued)

Code	Strategies	Strategy code*	RFL	IRFL	RSS	RLND	% Share of Articles by strategy
SC design quality							
Density							
D1	Supplier dispersion	SD2, PD1, DD1				[46, 92, 100]	**2.91**
Complexity							
D2	Using multiple sourcing	SD3			[3, 6, 13, 14, 23, 35, 36, 41, 42, 48, 49, 55, 56, 60, 69, 75, 77, 79, 86, 91, 99]	[43, 46, 53, 57, 65, 68, 71, 74, 82, 88, 89, 93, 97]	**33.0**
D3	Contracting with (reliable or unreliable) recovery or backup suppliers	SD4, FD2, PD2	[4, 16, 37]		[27, 48, 56, 64, 86, 91, 98]	[52, 54, 67, 68, 88, 89, 90]	**16.50**
D4	Multiple transportation routes or channels	TD3				[59, 61, 68]	**2.91**
D5	r-level assignment of suppliers to customers	SD6, FD1, DD3, RD1	[1, 2, 11, 15, 18, 20, 29, 30, 32, 38, 39, 50, 51, 58, 63]	[7, 40, 73]	[103]	[76]	**19.42**
D6	Backup supply route	SD7, PD3, TD2				[90]	**0.97**
Operational vulnerability							
D7	Inventory control	SD9, PD4, DD5, RD3		[78, 83]	[13, 49, 60, 79, 86]	[5, 12, 21, 72]	**10.68**

*See Table 8 for full descriptors and references for strategy codes that combining P1 with SD8 (see Table 8) yields superior results by generating synergistic effects among resilience strategies under budget limitations for supply chain resilience.

Table 4 lists nine reactive supply chain resilience strategies (R1 to R9) commonly used to hedge vulnerable sections of SCs against disruptions. The most frequently employed reactive strategies are *R1* (28.15% of 103 reference articles), *R2* (13.59% of 103 reference articles) and *R3* (8.74% of 103 reference articles). The RSCND literature reveals that, similar to proactive strategies, the efficiency of this group of strategies is dependent on the nature of the SC. For example, Fattahi et al. (2017) addressed the design of a glass company SC for which the objective function is the minimisation of the total cost of SC network over a planning horizon. Based on several computational experiments, they concluded that R1 the most effective strategy in designing a resilient SC. In contrast Gholami-Zanjani et al. (2021a) addressed a location-inventory problem in a food supply chain where the objective function is the expected total profit minus total strategic costs, andthey found R1 to be dominated by P1 and DR8 strategies.

Table 4 also contains seven mitigation strategies from the SC design quality category (D1 to D7). The most common SC design quality strategies in the academic papers are *D2* (33%), *D5* (19.42%), and *D3* (16.50%) all from complexity group. A less complex SC has fewer nodes and/or fewer interconnections, so increased complexity is expected to create more vulnerabilities. However, additional nodes that create a buffer in the SC reduce vulnerability (Chowdhury & Quaddus, 2017). Adding additional nodes, D2 strategy, is found to be effective in comparison to a single sourcing strategy (Berger & Zeng, 2006). The efficiency of a D2 strategy has been compared to other mitigation strategies (see Hasani & Khosrojerdi, 2016; Sabouhi et al., 2020; Aldrighetti et al., 2023). The details of the performance comparison of this strategy is given in the next subsection. Strategy D5 is used to increase the reliability of the system in the event of a failure at a facility, and has mainly been applied in RFL models. Each customer is assigned to *r* closest facilities such that if their primary facility is disrupted their order is met by the next facility and so on. We found no evidence of any comparative performance analysis of D5 against other resilience strategies in the literature. Strategy D3 has been used in the design of many different RSCs (Jabbarzadeh et al., 2018, Wang & Yao, 2023). Literature indicates that D3's performance depends on SC context. For example, Sabouhi et al. (2020) applied several mitigation strategies including D3 to the design of an industrial paint manufacturer SC where suppliers, factories, DCs and routes are at risk of disruption. They found D3 was the most efficient mitigation strategy to minimise total cost.

4.2.2 Mitigation strategy combinations

In the previous subsection, to answer RQ2, the proposed mitigation strategies in the reference articles were categorized into three subcategories and the most common strategies were analysed. In this subsection, building upon the analysis already conducted, our objective is to specify the strategies introduced in each article and explain how they are combined in the proposed mathematical models in reference articles.

Table 9 lists the resilience strategies used in the mathematical models proposed in each reference article in designing RSCs. Reviewing the information summarized in Table 9 reveals that resilience strategies have been used both singularly and in combination to construct the proposed mathematical models. Table 5 displays the number of reference articles that have utilized a subset of strategies in each group in designing their mathematical models. The models have been categorized into two groups: those that applied single resilience strategies and those that combined resilience strategies.

Table 5 The number of single or multiple strategies in the proposed models in reference articles

Implemented strategies	Number of articles
Single	
Single proactive	0
Single reactive	8
Single SC design quality	21
Combined	
Multiple proactive	3
Multiple reactive	8
Multiple SC design quality	3
Multiple Proactive–Reactive	5
Multiple Proactive-SC design quality	9
Multiple Reactive-SC design quality	23
Multiple Proactive–Reactive-SC design quality	23

In Table 5, the models that have employed only one strategy are categorized into three groups based on the capabilities of the supply chain. However, none of these models presented the use of purely proactive strategies. Among the models discussed, eight utilized single reactive strategies, six of which applied FR1 (reassignment of customers to surviving facilities). The remaining models in this category employed one of FR2 (customers rerouting until receiving a service), or FR5 (reassignment of demand nodes to *r* closer facilities (level-r)) from reactive strategies. In addition, single strategies from SC design quality were employed in 21 articles. Specifically, FD1 (assignment of demand nodes to the closest facilities) was applied in 13 articles, while SD3, DD3, FD2, and RD3, and SD6 were applied in three, two, one, one, and one time respectively.

Table 5 lists possible combinations of different sets of resilience strategies and the number of reference articles that applied such combinations. Among these articles, some only combine strategies selected from the same category, with researchers predominantly focusing on combining more reactive strategies compared to other types.

Furthermore, several researchers have attempted to apply combined strategies selected from different categories. Among these studies, a larger number of authors applied (1) a combination of strategies selected from all categories, and (2) a combination of strategies selected from both reactive and SC design quality categories, with 23 articles referencing each approach.

Strategies such as SD3 (Using dual or multiple sourcing) and SD4 (contracting with (reliable or unreliable) recovery or backup suppliers) from the SC design quality category, as well as SR4 (customers' demand reallocation or recalculation of purchase or shipment from primary or backup suppliers), and DR6 (recalculating inventory position), DR3 (recalculating the amount of products transferred from DCs) and MR1 (recalculating the amount of lost sales or unmet demand to apply penalties) from the reactive strategies category, were frequently combined in the design of RSCNs. Additionally, strategies such as SP1 and FP1 (protection or fortification), SP10 and DP7 (pre-positioned inventory & holding safety and emergency stocks), and SP8 and PP8 (additional extra production capacity) and DP6 (Adding extra inventory capacity) were among the strategies that were combined more often than others.

Researchers have explored the potential to enhance supply chain resilience by combining strategies and applying them simultaneously. For instance, Alikhani et al., (2023a, 2023b) uses a multi-method approach that integrates analytical modeling and qualitative theory development to propose a framework for selecting the optimal set of resilience strategies for SCND problems. Their approach includes a two-stage stochastic programming model to design a resilient network for a three-echelon RSC comprising multiple suppliers, DCs, and retail stores. The model aims to select the best resilience strategies to maximize their synergistic effects while minimizing the fixed and operational costs of SCND. Considering different vulnerable sections within a supply chain is another reason for employing a combination of resilience strategies in its design. For example, in their study Jabbarzadeh et al. (2018), introduce a model to design a three echolnes RSC that accounts for random disruptions at both suppliers and factories by employing resilience strategies, such as 'contracting with backup suppliers and facilities,' 'multiple sourcing,' and 'adding extra supply/production capacities'. In another study, Sabouhi et al. (2020) addressed the problem of designing a four-echelon RSC (Resilient Supply Chain) in which suppliers, factories, DCs (Distribution Centers), and transportation routes were identified as vulnerable sections of the supply chain. In this study, the authors aimed to combine different resilience strategies to hedge the supply chain against disruptions. Some of the mitigation strategies are interrelated, and implementing one strategy from a particular group may necessitate the application of another strategy from a different group. For instance, SP10 and DP7 from the proactive strategies category, along with SR3 from the reactive strategies category can be synergistically applied together. Strategies like SD3 and SD4 have been integrated with various strategies from diverse groups (see Table 9). Various reference articles have examined the efficiency of several resilience strategies in enhancing the resilience of a supply chain (see Sect. 4.2.3) without providing justification for the combination of these strategies (see for example: Fattahi et al., 2017; Azad & Hassini, 2019).

4.2.3 Mitigation strategies relative performances

One of the challenges faced in SCND is deciding on the most effective mitigation strategy. RQ3 asks "how have these strategies improved the resilience of supply chains?", and draws on relative performance of mitigation strategies literature. In the previous section, several mitigation strategies were identified place into three categories: proactive, reactive and SC design quality. However, few studies analyse and compare mitigation strategy application. In our literature review we identify 21 strategies where comparative analysis is reported.

The results in Table 6 show: (1) The most common strategies, D2 and P1, often outperform other strategies regardless of industrial application (Fattahi et al. (2017) provide an exception). (2) The relative performance of mitigation strategies is related to the objective function (see D3, P3 in Kamalahmadi et al. (2022), D2 and single sourcing in Sawik (2013b)). (3) Combined strategies often outperform single applications (see D2, D3, P5, and D5 in Jabbarzadeh et al. (2018) and SD8, P1, SR10, P7 in Alikhani et al., (2023a, 2023b)). (4) The most commonly employed strategies, identified in Table 4, do not necessarily provide the best performance in a given context (see SP9, SP10, D2, P5 in Yoon et al. (2018) and D2, D3, P1, and R9 in Aldrighetti et al. (2023)).

Table 6 A review of relative performance of mitigation strategies reported in the reference articles

References	DM and industrial application	Performance measures	Comparison results	Strategies* compared and their rankings
[12]	RLND & numerical examples	Strategic design cost of SC	DD2 is more cost effective than single sourcing. Single sourcing is not effective, especially when risk aversion is high	(1) DD2 (2) Single sourcing
[17]	RLND & numerical examples	Total expected cost	The expected cost of the model based on the soft-hardening strategy is lower than that of hardening strategy. The percentages of improvements increase by increasing the number of customers	(1) DP2 (2) P1
[46]	RLND & electro-medical device	Net after tax profit Inventory cost	All strategies have positive impacts however, only P1, D1 and D2 have significant impacts on mitigating risk of SC disruption Applying all given strategies results in designing more RSC than those applying single strategies	(1) P1 (2) D1 (3) D2 (same ranking for both measures) [ranking for P7, PP8, PR2 not been reported]
[47]	RLND & glass industry	Total cost of SC network	R1 is more efficient than P1 in decreasing the total cost	(1) R1 (2) P1
[53]	RLND & automotive parts	Average profit of SC	The share of P5 and P7 in average profit improvement is 50% for both strategies;	Same priorities for D2, P5, P7
		Profit variation	The share of P7 and P6 in reducing the profit variation is 72% and 28%	(1) P7 (2) P5

Table 6 (continued)

References	DM and industrial application	Performance measures	Comparison results	Strategies* compared and their rankings
		SC worst case profit	The share of P7 and P5 in improving the SC worst case profit is 100% and 0%	(1) P7 (2) P5 (is not effective)
[74]	RLND & numerical examples	Total cost	Unimodal transportation strategy is more costly than TD4	(1) TD4 (2) Unimodal strategy
		Total emission	The unimodal scenarios use significantly more emissions than the TD4 ones	(1) TD4 (2) Unimodal strategy
[90]	RLND & medical equipment	Total cost of SC	When the disruption level is on lower value, the cost advantage of P1, D3, and TD3 is clear. However, with the increase in the disruption level, the cost advantage of D6 is observed gradually	For the lowest disruption level: (1) P1, (2) D3, (3) TD4, (4) D6 For the highest disruption level: (1) D6, (2) P1, (3) D3, (4) TD3
		Viability	The advantage of the structure characterised by D6 is more significant	For both lowest and highest disruption levels: (1) D6, (2) TD4, (3) D3, (4) P1
[78]	IRFL, numerical examples	Expected profit	R1 is strongly dominated by P1 and DR8. Applying all given strategies results in more RSC than those applying single strategies	High fixed cost: (1) P1, (2) DR8, (3) R1 Low fixed cost: (1) P1, DR8, (2) R1
[68]	RLND & industrial paint	Cost saving	By comparing the results according to the best performance, D2 and D3 had the best performances, respectively	(1) D2, (2) D3, (3) PR1, (4) D4, (5) P5, (6) R3

Table 6 (continued)

References	DM and industrial application	Performance measures	Comparison results	Strategies* compared and their rankings
[87]	RLND & footwear	Flexibility, Reliability	The results show that using D2 strategy instead of the single sourcing strategy and slightly increasing the costs, both reliability and volume flexibility of plants can be improved	(1) D2 (2) single sourcing
[49]	RSS& numerical examples	Total cost	The comparison results indicate the superiority of D2 over single sourcing. Besides, the model that applies both D2 and R3 strategies simultaneously has a better performance than the model that only applies D2 strategy	(1) D2 + R3 (2) D2 (3) Single sourcing
[14]	RSS & numerical examples	Number of suppliers Total costs	A general comparison of the corresponding results for single sourcing and D2 indicates that for both risk-neutral and risk-averse solutions, for D2 greater number of suppliers is selected and lower costs are achieved	(1) Single sourcing (2) D2 (1) D2 (2) single sourcing

Table 6 (continued)

References	DM and industrial application	Performance measures	Comparison results	Strategies* compared and their rankings
[60]	RSS & numerical examples	Total reliability	If the focal company's manufacturing capacity and selected suppliers' capacity are high enough (compared to demand), the majority of proposed strategies do not significantly improve the focal company's performance. SP10 is the only strategy that can significantly improve the focal company's performance, which implies that inventories can more effectively manage risks than D2, SP10 and/or SP9	(1) SP10 (2) SP9 + D2 (3) P5
[54]	RSS & plastic pipes	Total expected cost	All resilience strategies are effective in reducing the expected total SC cost. The simultaneous adoption of the three resilience strategies gains approximately 80% cost reduction benefits compared to the situation when only 'multiple sourcing' strategy is used	(1) D2 + D3 + P5 (2) D2 + D5 (3) D2 + D3 (4) D2
[91]	RSS & numerical examples	Expected total cost	Both strategies have the same effectiveness in reducing costs. Inclusion of both strategies has a higher efficiency compared to single use	(1) D3 + P3 (2) D3 = P3

Table 6 (continued)

References	DM and industrial application	Performance measures	Comparison results	Strategies* compared and their rankings
		Service level	D3 is more effective than P4. Inclusion of both strategies has a higher efficiency compared to single use	(1) D3 + P3 (2) D3 (3) P4
		Expected lost sales	Employing each of the strategies will reduce the lost sales. D3 is more effective than P3. Inclusion of both strategies has a higher efficiency compared to single use	(1) D3 + P3 (2) D3 (3) P3
[94]	RLND &	Profit	The use of mobile facilities generates an economical profit by saving extra opening and closing costs using facilities displacements	(1) DR8 + DR9 (2) Not using the mobile facilities strategy
		CO2 emissions	The use of mobile facilities generates an increase in CO2 emissions due to moving facilities	
[97]	RLND, retail industry	Total costs	Under the same capacity uncertainty budget, for instance, when the number of disrupted DCs is 0, the non-collaborative approach incurs a total cost that is approximately 47.8% higher than the collaborative approach, and the optimal network configurations differ significantly. However, when the number of disrupted DCs reaches 10, both approaches result in the same network configuration and total cost	(1) TR5 (2) Not using TR5

Table 6 (continued)

References	DM and industrial application	Performance measures	Comparison results	Strategies* compared and their rankings
[99]	RLND, numerical examples and plastic components industry	Total costs	Considering the suppliers' disruption, the D2 strategy significantly reduces total costs, even in cases of small to medium-scale disruptions. Additionally, the D3 strategy effectively reduces costs when disruptions severely impact suppliers' operability. D2 dominated D3 in most of the cases	(1) D2 (2) D3
		Total costs	Considering the facilities' disruption, recovery actions (R9) reduces total costs and increasing main effects for small- and medium-scale disruption, after which it slightly reduced its effectiveness for high-scale disruption. For disruption with high impact on facility operations, the P1 strategy is the most effective. The D2 strategy maintained a moderately positive effect in reducing the total costs even for facilities' disruption. In addition, the biggest effect was assumed via a multi-sourcing strategy in high-scale disruption at suppliers, followed by protection systems in high-scale disruption at facilities	High-magnitude disruption events: (1) P1 (2) R9 (3) D2 (4) D3 Small & Medium-magnitude disruption events: (1) R9 (2) D2 (3) P1 (4) D3

Table 6 (continued)

References	DM and industrial application	Performance measures	Comparison results	Strategies* compared and their rankings
[100]	RLND, retail chains	The synergistic effect	Multiple set covering (SD8) has the most interacting effect with other strategies, especially with fortification (P1 + RP1). However, among the paired strategies, the combination of SD8 and direct shipping (SR10) shows the best performance	(1) SD8 + P1 + SR10 + P7 (2) SD8 + P1 + P7 (3) SD8 + SR10 + P7 (4) SD8 + P1 + SR10 (5) SD8 + SR10 (6) SD8 + P1 (7) SD8 + P7 (8) P1 + SR10 + P7 (9) SR10 + P7 (10) P1 + P7 (11) P1 + SR10
[102]	RLND	Total cost	Total network cost is lowest when both the fortification (P1) and recovery strategies (R9) are considered. (R9) outperforms (P1)	(1) P1 + R9 (2) R9 (3) P1

*See Table 8 for full descriptors and references for strategy codes

4.3 Integration of resilience strategies into mathematical models

This section aims to show how resilience strategies are integrated into mathematical models by analysing: (1) decision making environments and proposed modelling approaches; and (2) the main characteristics of the mathematical models used for common strategies.

4.3.1 Disruption related parameters

In developing mathematical models for RSCND, decision making environment play an essential role, specifying how failure probabilities, and disruption scenarios are defined. In this article, decision making environments are categorised into three groups in accordance with Rosenhead et al. (1972): certainty, risk, and uncertainty situations (see table iv in the supplementary material). Certainty situation (DET) involves models in which all parameters are deterministic and known. DET models do not include any disruption related parameters and are used to investigate the impact of disruptions events on SCs for each pre-defined disruption scenario separately (Kungwalsong et al., 2022). Models designed for supply chains known to be at risk of disruption (RSK) containing parameters where exact risk values aren't known, but have known probability distributions (Snyder et al., 2006). In this paper, we categorise RSK models into five sub categories (the first three categories are from Snyder et al. (2016)): implicit functions (IF), reliable backup (RB), scenario-based (SB), stochastic programming (SP), and reliability and risk based (R&R) models. In IF modelling methods, three different categories of failure parameters are used. Facilities are often given identical local disruption probabilities to make modelling easier (Albareda-Sambola et al., 2017; Alcaraz et al., 2015; Snyder & Daskin, 2005; Yun et al., 2015; Zhang et al., 2016). However, this approach is not representative of practice (Aboolian et al., 2013; Cui et al., 2010). To better simulate reality, researchers define site- or facility-dependent failure probabilities for local independent failure modes (Albareda-Sambola et al., 2015; Berman et al., 2007; Yu & Zhang, 2018; Yun et al., 2020). Another approach is to remove the facility failure independence hypothesis and define failures as correlated disruption probabilities (Li et al., 2013a, 2013b, 2013c; Xie et al., 2019). In RB models, as with some IF models, facility failure probability is considered as facility-dependent (Benyoucef et al., 2013; Lim et al., 2010). In IF and RB modelling facility failure probabilities are implicitly imposed and the decision process is not divided into pre- and post-disruption phases (Lu et al., 2015). For this reason, IF and RB have not been applied for modelling reactive strategies, however, used to apply several proactive and SC design quality strategies (Azad et al., 2019; Lim et al., 2010). SB models presented in reference articles fall into the class of two-stage programming models. In these models, the first-stage decisions are made prior to realizing any stochastic event (e.g. facilities disruptions) while the second-stage decisions are made after the uncertainty is revealed as a set of disruption scenarios. The probability for each scenario is calculated independently, taking into account the probability of facility disruption, which may be global, regional, or local (Sawik, 2011, 2013a, 2017). SB aims to optimise the first-stage objective function and the expected value of the random second-stage objective across all possible disruption scenarios. SB is one of the most widely applied modelling approaches in designing RSCs (see Table iv in supplementary materials) and have been successfully applied to model proactive, reactive, and SC design quality strategies (Alikhani, Torabi, and Altay 2021). However, one of the main limitations of SB models is that when the number of scenarios increases, the problem size increases exponentially making solving the problem difficult and in some cases impossible (Sabouhi et al., 2020). In SP models, some model's parameters (such as demand and lead-time) follow specified statistical distributions (Saputro et al., 2021). Facility failure parameters in SP models are defined as the disruption frequency rate and disruption downtime rate (Firouz et al., 2017). SC design quality such as multiple sourcing and inventory control (Yoon et al., 2018) and proactive strategies (Saputro et al., 2021) are among the mitigations strategies that have been integrated into SP models. R&R models are used to either minimise risk in the entire SC, or maximise reliability. In Ravindran et al. (2010), each facility is associated with two risk types; value-at-risk (VaR) and miss-the-target (MtT). The risk of selecting a supplier or opening a facility is defined as a value between 0 and 1 (Kaur and Prakash Singh 2021; Yoon et al., 2018). Some researchers (Yildiz et al., 2016) aim to maximise network reliability by assigning each node and arc a given reliability index. The SCND objective function is first to minimise the total cost and second to maximise total reliability.

In models defined under uncertainty situations (UCT), parameters are uncertain or vague and no information about the probabilities is known. In this paper, we categorise UCT models into two subcategories: robust (RO) and Fuzzy (FUZZ) models. In RO models, parameters are uncertain and no information about probabilities are known. Similar to SB methods, RO models have been successfully applied to model proactive, reactive, and SC design quality strategies (An et al., 2014; Cheng et al., 2021; Hernandez et al., 2014; Lu et al., 2015). The main advantage of RO models is that they do not rely on probability distributions or the generation of scenarios (Cheng et al., 2021). A solution to an RO model is defined either as solution robust or model robust. A solution robust remains 'close' to optimal for all scenarios of the input data, and a model robust solution remains 'almost' feasible for all data scenarios (Jabbarzadeh et al., 2014). The RO model aims to measure trade-offs between solution and model robustness (Lu & Cheng, 2021). FUZ models are used when some critical parameters (such as demand and capacity levels) are imprecise in nature due to incompleteness and/or unavailability of data (Torabi & Hassani, 2008). Torabi et al. (2015) proposed a fuzzy enhanced possibilistic programming approach to deal with epistemic uncertainty in input data such as costs, demands, and number of returned products. The scenario-based method including scenario dependent failure probabilities is applied to define the possible disruption of facilities. They integrated proactive, reactive and SC design quality strategies in their model.

4.3.2 Integrating resilience strategies into the mathematical models

In this subsection, we show how mitigation strategies have been integrated into the mathematical models by analysing the characteristics of the mathematical models employing most efficient and frequently applied strategies in the models in the references articles; these include P1 from proactive resilience strategies, R1 from reactive strategies and D2 and D5 from SC design complexity strategies. Tables 7 summarize the information related to proactive, reactive and SC design strategies, respectively. A review of the characteristic of the models listed in Table 7 shows that RB (Jabbarzadeh et al., 2016; Li et al., 2013a, 2013b, 2013c), SB (Aldrighetti et al., 2023; Alikhani et al., 2021; Gholami-Zanjani, et al., 2021a; Sawik, 2013a; Torabi et al., 2015; Zhang et al., 2024) and RO (Aksen & Aras, 2012; Hasani & Khosrojerdi, 2016) models have been applied to model P1 strategy. For example, Aldrighetti et al. (2023) propose that facilities can be reinforced through investments in protection systems. This resilience investment is quantified as a percentage of the standard facility establishment costs and is categorized into various protection levels. Each level corresponds to a reduction in disruption magnitude. In these models, non-scenario dependent binary variables are used as the dominant variables in modelling. As an exception, Gholami-Zanjani et al. (2021a) employ the fortification of facilities as a continuous function based on investment costs,

Table 7 The main characteristics of the models applying proactive, reactive, and SC design quality resilience strategies

Strategies	Model characteristics				
	Parameters	Related variables	Related objective functions	Related constraints	Design approaches
Proactive					
P1	Protection cost of a facility (fixed or at specified levels): [10, 13, 16, 27, 82]	Binary variable for protecting a facility (at single or multiple levels): [10, 13, 16, 27, 82]	Minimisation of total fortification or protection costs: [10, 13, 27, 78, 82, 99, 100, 102]	Total available budget: [16, 37, 46, 100]	RB: [16, 37] SB: [13, 27, 78, 82, 99, 100, 102] RO: [10, 46]
	Fix cost of opening a (unreliable) facility with a specified fortification level: [37, 100]	Binary variable of selecting or opening a facility with a specified protection level: [27, 37, 99, 100]	Minimisation of total expected fortification or protection costs: [46]	Facilities can be protected at only one level of protection [37, 82, 99, 100, 102]	
	Protection cost of each facility in two consecutive periods: [46]	Binary variable indicating the protection status of a facility during a specific time period: [46, 102]	Minimisation of the expected total transportation cost associated with satisfying the demands of all customers: [16, 37]	Applying the protection investment to the right capacity level for already established and new facilities [78, 99]	
	Protection cost of each facility in a time period: [102]	Binary variable of selecting or opening a facility with a specified capacity and protection level: [99]			
	Portion of capacity that is protected through a protection system at a specified protection level: [99]	Continuous variable of protected capacity, dependent on disruption effects through the protection system at each facility under each scenario: [78]			

Table 7 (continued)

Strategies	Model characteristics				
	Parameters	Related variables	Related objective functions	Related constraints	Design approaches
	Percentage reduction of disrupted capacity after investing in protection systems at a specified level: [78, 99]	Continuous variable of protected capacity, dependent on disruption effects through the protection system at each facility: [99]			
Reactive					
R1	Transportation cost per unit of product (and per unit of distance): [9, 42, 57, 66, 78, 82, 88, 91, 94, 97, 98, 100]	Quantity delivered or shipped to each facility or customer under each scenario: [27, 43, 66, 89, 98]	Minimisation of expected transportation cost: [9, 42, 64, 66, 78, 81, 82, 88, 91, 96, 99, 100]	Limiting the shipment to demand in each scenario: [82]	SB: [9, 27, 42, 43, 64, 66, 67, 71, 81, 82, 91, 93, 96, 99, 100]
	Distance between facilities and customers or between suppliers and facilities: [64, 99]	Product flow on an arc under each scenario: [9, 57, 81, 82, 91, 96, 100]	Minimisation of expected purchase cost: [43, 71, 81]	Limiting the shipment to the capacity of a facility: [9, 27, 43, 57, 64, 71, 78, 88, 96, 97, 98, 100]	RO: [46, 57, 78, 88, 97, 98]
	Selling price of each product in each time period: [46]	Proportion of customer's demand that is served by each supplier in each time period under a scenario: [64]	Maximisation of total expected profit: [46]	Limiting the shipment to the maximum amount of transportation capacity: [66]	FUZ: [89]

Table 7 (continued)

Strategies	Model characteristics				
	Parameters	Related variables	Related objective functions	Related constraints	Design approaches
	Selling price of each product: [43]	Quantity of items that a facility or customer received from a primary or backup supplier under a scenario: [27, 43, 71]	Minimisation of transportation cost in worst case scenario: [57, 97]	Balance between the inbound and outbound flows in each facility: [46, 57, 96, 97, 99, 100]	DET: [94]
	Unit purchasing cost of materials: [71, 81, 89]	Amount of product transferred from facilities to other facilities or customers in each time period under a scenario: [42, 46, 78, 88, 93, 99]	Maximisation of expected selling revenue: [42]	Limiting the shipment to capacity of a facility with or without a fortification level under each scenario: [42, 81]	
	The unit transportation costs of a product on an arc under a scenario: [96]	Amount of product transferred from facilities to other facilities or customers in each time period: [94]	Minimisation of transportation cost: [94, 98]	Customers are exclusively served by opened facilities: [94]	
	Unit price of an item purchased and shipped: [27]	Number of products shipped from a node to another node by a carrier: [97]	Minimisation of the total environmental impact by considering CO2 emissions generated by products transportation: [94]	Limiting the shipment to demand in each scenario: [82]	

Table 7 (continued)

Strategies	Model characteristics				
	Parameters	Related variables	Related objective functions	Related constraints	Design approaches
	Unit cost to transport a product from one location to another location under scenario s in each period: [42]		Minimisation of worst-case Mean-CVaR value of the second-stage cost including production and transportation costs: [98]	Limiting the shipment to the capacity of a facility in each time period under a disruption scenario: [99]	
	Unit sales revenue for each product sold to a customer under each scenario in each period: [42]		Minimisation of the expected costs of purchasing and shipping items: [27]		
	Expected defect rate of products supply by each supplier: [64]		Minimization of the expected cost of supplying low quality products: [64]		
SC design quality					
D2	Fix cost of ordering parts from each supplier: [6, 23, 69, 98]	Binary variable of selecting a supplier: [6, 23, 35, 55, 98]	Minimisation of ordering costs: [6, 23, 35]	Capacity of each supplier: [6, 35, 55, 69]	IF: [35] SB: [6, 23, 55, 69]
	Expected defect rate of each supplier: [6]	Binary variable of selecting a supplier from a tier: [69]	Minimisation of expected purchasing costs: [6, 23, 35]	Per period capacity of each supplier: [23]	RO: [98]
	Purchasing price of each part from each supplier: [6, 35, 23, 69, 98]	Fraction of total demand (or order quantity) assigned to each supplier: [6,23, 35, 69, 98]	Minimisation of expected defects costs: [6]	Supply quantity available at each supplier for each carrier: [98]	

Table 7 (continued)

Strategies	Model characteristics				
	Parameters	Related variables	Related objective functions	Related constraints	Design approaches
	Preference value of a supplier: [35]	Compensation received from an undisrupted supplier: [35]	Minimization of the expected worst-case costs (calculating VaR and minimizing CVaR simultaneously): [6]	Demand satisfaction: [6, 23, 35, 55, 98]	
	Fixed cost of managing a supplier: [35, 55]	Quantity purchased from a supplier for a customer in each scenario: [55, 98]	Maximisation of utilising suppliers based on preference values: [35]	Limiting the number of selected suppliers: [98]	
	Supply flexibility index for each supplier: [35]	The fraction of parts required for each customer order ordered from each supplier: [6]	Maximization of expected profits: [55]	Least segregation distance constraint (between every pair or among all suppliers): [98]	
	Cost of a unit of a product delivered by a supplier to a customer or other facilities: [55, 98]	Surplus quantity that the a customer will receive from the non-disrupted supplier under scenario s: [98]	Minimisation of purchasing and/or transportation costs: [69, 98]		
			Maximization of the minimum total transportation cost (worst-case Mean-CVaR scenario): [98]		
			Minimisation of the expected ordering cost: [69]		

Table 7 (continued)

Strategies	Model characteristics				
	Parameters	Related variables	Related objective functions	Related constraints	Design approaches
D5	The cost per unit of demand to ship from facilities to customers: [1, 7, 11, 20, 29, 39, 50, 51, 63, 76, 103]	Binary variable of assigning customers to a facility at level r: [1, 2, 7, 11, 20, 29, 39, 50, 51, 76, 103]	Minimisation of expected transportation or acquiring costs: [1, 2, 7, 11, 20, 29, 39, 51, 63, 76]	For each customer i and each level r, either i is assigned to a facility at level r or it is assigned to a non-failable facility at a certain level: [1, 2, 7, 11, 20, 29, 50, 51, 76]	IF: [1, 2, 7, 11, 20, 29, 39, 50, 51, 63, 76, 103]
	Shortest distance between facilities and customers: [2]	Probability that a facility is assigned a customer at level r: [39, 51, 76]	Minimisation of expected annual inventory cost: [7]	Assigning the customers to facilities that have been opened: [1, 2, 7, 11, 20, 29, 39, 50, 51, 76, 103]	
	Unit cost of acquiring products: [76]	Binary variable of assigning customers to a station-facility pair at level r: [63]	Minimisation of expected cost of acquiring products: [76]	A customer is only assigned to one facility at each assignment level: [1, 2, 7, 11, 20, 29, 39, 50, 51, 76]	
	Rank of each supplier in the preference list of each demand site: [103]	Quasi probability for a customer to be assigned a station-facility pair at level r: [63]	Minimization of the sum of the maximum expected cost incurred for each product among all demand sites: [103]	Customers are assigned to open facilities level by level in increasing order of distance: [39]	
		Probability that a demand site will need to use its rth backup supplier: [103]	Minimization of CVaR value across all possible facility failure scenarios: [51]	Calculation of Probability that a facility is assigned a customer at level$r$: [51, 76]	

Table 7 (continued)

Strategies	Model characteristics				
	Parameters	Related variables	Related objective functions	Related constraints	Design approaches
			Minimization of total risks based on coherent risk measure (ASD) across all possible facility failure scenarios: [51]	A supplier is in backup level r of a demand site only if there is a more preferred supplier in level $r - 1$: [103]	
				Asserting that if a supplier j is selected and demand site i prefers supplier j to m, then supplier m is in backup level r only if j is in an earlier backup level $s < r$: [103]	
				Capacity of each facility: [50]	
				Compute the probability that each demand site will need to use its backup suppliers in each level: [103]	

which can be adjusted at any time period under each disruption scenario. The facilities which are protected in case of disruption either do not fail (Aksen & Aras, 2012; Li et al., 2013a, 2013b, 2013c; Sawik, 2013a), or lose capacity according to their fortification level or the amount of investment (Gholami-Zanjani, et al., 2021a). In the implementation of this strategy, the protection cost is minimized as the objective function and the amount of investment may be limited to available budget (Hasani & Khosrojerdi, 2016; Jabbarzadeh et al., 2016; Zhang et al., 2024).

Table 7 also presents the main characteristics of the mathematical models that applied R1 strategy as a post disruption scenario. As reported in Table 7, SB (e.g. Hosseini et al., 2019a, 2019b; Fahimnia & Jabbarzadeh, 2016; Ghanei et al., 2023), RO (e.g. Alikhani et al., 2023a, 2023b; Hasani & Khosrojerdi, 2016), DET (Maliki et al., 2022), and FUZ (Namdar et al., 2021) models have been applied to model R1. A review of the decision variables used in modelling R1 shows that they are defined as a scenario dependent integer or continuous variables that determine the number of products sent to customers or other facilities in any disruption scenario. Transportation costs, selling price, unit purchasing cost of materials, distance between facilities and customers, and expected defect rate of products supplied by each supplier are related parameters that makes it possible to optimise the integration of this strategy by taking into account the objective function (column 4, Table 7). Capacity at each facility is the most commonly applied constraint in models and scenario-based modelling is the dominant method in this strategy.

SC design quality strategies are used before disruptions, increasing resilience and robustness. To explore how such strategies are integrated into mathematical models focus was placed on the two strategies identified as most efficient in research articles, D2 and D5 (see Sect. 4.2). Table 7 shows the characteristics of the mathematical models applying these strategies. IF (Snyder & Daskin, 2005; Chen et al., 2011; PrasannaVenkatesan & Goh, 2016, Enayati et al., 2024) and SB (Dupont et al., 2018; Feng et al., 2023; Sawik, 2020) are among the modelling approaches being applied to model D2, and D5. The goal of strategy D2 is to reduce the potential effects of disruptions on the SC by selecting the best combination of suppliers to allocated customer demand. To include this strategy in mathematical models, similar to proactive strategies, non-scenario dependent binary variables are used for supplier selection (column 2 of Table 7). Continuous variables, such as 'Fraction of total demand assigned to each supplier' determine demand attributed to suppliers (PrasannaVenkatesan & Goh, 2016; Sawik, 2014, 2020). Supplier capacity and demand satisfaction constraints are key limitations frequently used to regulate this strategy. IF is the only modeling approach used for D5, defined by binary variables such as 'assigning customers to a facility at different levels,' or continuous variables like 'the probability that a facility is assigned a customer at different levels' (see column two of Table 7 for the full list of variables). The objective function defined for modelling this strategy mainly includes the minimisation of the expected transportation cost. In some of the presented models, assignment of customers to the facilities is limited by their capacity. The mathematical formulation for this strategy must include constraints such as 'each customer can only be assigned to one facility at each assignment level' and 'customers must be assigned to facilities that have been opened.' IF models are not applicable in modelling reactive strategies since they do not explicitly define failure scenarios. However, unlike SB models that can exponentially increase numbers of variables and constraints, IF models are more compact, polynomial in size, so produce solutions more quickly (Cui et al., 2010).

5 Future research directions

5.1 Disruption types

The Covid-19 pandemic demonstrated how global disruption can cause all sections of a SC to fail simultaneously. These types of disruptions in supply chain networks can be studied either separately or in an integrated manner. Scenario-based (SB) and robust optimization (RO) approaches have the potential to model these disruptions on a semi-global or global scale. However, only a few studies have investigated these scenarios, whether separately or in an integrated manner. Integrated global or semi-global disruption types, alongside regional ones, are often addressed in RSS problems; however, designing RLND networks demands even greater attention. Furthermore, studies focusing on RFL and IRFL problems that integrate such disruption events are also limited (Table 3) meaning further research in this area is required in future studies. In a multi-period stochastic setting, the accommodation of multiple disruptions occurring in succession during the recovery process in all decision-making problems addressed by SCND has not been studied. By incorporating this capability into the expanded framework, a deeper analysis of the sequential disruptions and their cumulative effects on the supply chain can be conducted (Azad & Hassini, 2019; Sawik, 2021). It is essential to recognize that different types of disruptions can have varying impacts on different regions. The effects of disruptions can be heterogeneous, with some regions experiencing more severe consequences than others, so insights into the relationship between supply chain resilience and robustness require exploration of such situations (Fahimnia et al., 2018).

5.2 Vulnerable sections

Our analysis revealed researchers focus on suppliers and plants as vulnerable sections of SCs. In retail SCs distributors and retailers are at risk of disruption, and this area warrants further attention. Moreover, in much of the analyzed research, it is assumed that customer demand remains independent of supply chain disruptions. However, during regional or global disruptions, simultaneous changes in customer demand are likely to occur, as evidenced by the increased demand for essentials like pasta and rice during the Covid-19 pandemic. This issue deserves particular attention in the context of RSS, IRFL, and RFL problems.

The possibility of local, regional or global disruptions occurring in the transportation routes or modes in RFL and RSS problems has not been considered until now and should be addressed in future research. Disruption in SC transportation sectors significantly impact on performance since meeting customer demand for physical products is only possible when this sector is operative. Future research should address disruption at transportation nodes and the implications of port congestion as a significant source of delays on supply chain performance (Namdar et al., 2021). This entails exploring mitigation strategies, operational adjustments, and decision-making frameworks to enhance resilience in the face of such disruptions. For instance, studying the coordination and synchronization of port operations, or optimizing resource allocation can help alleviate the negative impact of port congestion on supply chains.

Finally, the impact of facility disruptions on reachability and access distances presents an intriguing avenue for future research (Yan & Ji, 2020). Disruption, reachability and access distances opens opportunities to explore integrated RSCND problems, along with other optimization problems such as routing optimization under disruption scenarios. A comprehensive understanding of the performance of supply chain networks, requires consideration of the wider effects of disruptions, including the impact of disruptions on critical factors such as lead time or capacity of different sections of SCs (Hasani & Khosrojerdi, 2016).

5.3 Mitigation strategies

Suggestions for future research in this section are made by comparing the results obtained in this research and the aspects of the triple capabilities presented in Chowdhury and Quaddus (2017).

5.3.1 Proactive strategies

Proactive strategies related to disaster readiness capabilities of SCs including readiness resource, disruption detection, and security, is under researched. Specifically, when considering digital technologies now central to all supply chains in practice, greater focus needs to be placed upon cyber attacks and proactive cybersecurity strategies within the models. Our analysis in Table 8 reveals that only one study has proposed a cybersecurity strategy in modelling RLND problems. This strategy deserves greater attention, and incorporating this into future models across all types of resilient supply chain network design problems will advance understanding.

Few studies consider product substitution in RFL and assign flexibility indices to facilities in RLND problems. Exploring other types of flexibility strategies, such as time flexibility (the ability to adjust production lead times) and production volume flexibility, could open new avenues for future research. Flexibility in the workforce, products and production has not been considered too.

Efficiency gains from increased productivity and hardworking employees, and quality control are among the SC proactive capabilities that can be used as the basis of improving the resiliency of SCs by introducing suitable mitigation strategies. Another proactive strategy that requires more attention is the application of insurance as a mitigation strategy. Investigating the impact of insurance on supply chain resilience and developing insurance strategies could yield valuable insights.

A review of the mitigation strategies listed in the Table 8 shows that the application of proactive strategies for different vulnerable sections of SCs have not been equal. For suppliers, plants and manufacturers, and DCs, more than 10% of the reference articles applied proactive strategies, while for general facilities, retailers, and the transportation section, this number is reduced to below 5%. Proactive strategies have not been employed for geographically defined areas of customer demand. Future studies should investigate the effectiveness of proactive strategies for vulnerable SC sectors that have received little attention. In particular, future studies should explore approaches to enhance the robustness and resilience of arcs and transportation routes (Meng et al., 2021). This may involve evaluating alternative routes, and optimizing resource allocation for route protection, or implementing real-time monitoring systems to detect and respond to disruptions promptly. In addition, collaboration has been limited to suppliers, facilities, and DCs but it is increasingly recognized that the involvement and support of all supply chain partners are critical to the success of the proposed strategy. To address capability maintenance and control challenges, it is advisable to focus future efforts on the development of a comprehensive monitoring framework. This framework can leverage potential solutions from recent advancements in Internet-based technologies, including the Internet of Things (IoT), blockchain technology, artificial intelligence, and other related fields (Vishnu et al., 2021).

5.3.2 Reactive strategies

A number of reactive strategies have been proposed to increase the response capability of SCs (e.g., Alikhani et al., 2021; Sawik, 2013a, 2019, 2021; Tucker et al., 2020). However, several research avenues remain in this area. First, by replenishing capacity through non-disrupted facilities and maintaining customer allocations, companies can effectively navigate challenges and maintain operational capabilities (Lu & Cheng, 2021). Secondly, in the event of disruptions, the availability of parts in the inventory for transhipment can be compromised (Sawik, 2019). To address these issues, analysis is required of contingency plans that can effectively deal with part non-availability for transhipment and constraints on the transhipment process. The analysis provided in Table 8 indicates that limited research has been conducted on applying reactive strategies to increase resilience in general facilities, retailers, transportation modes, routes, and customer zones within supply chains. More exploration is needed to understand how reactive strategies can be tailored and implemented at the facility level, within retail operations, for transportation modes and routes, and in customer zones. The concept of relocating DCs has recently been examined by Maliki et al. (2022) within the scope of dynamic RFL problems. Their sensitivity analysis revealed that utilizing mobile facilities can result in cost savings by eliminating the extra expenses of opening and closing facilities associated with dynamic relocations during each period of a finite planning horizon. Further exploration is necessary to determine if similar cost savings and operational efficiencies can be achieved within the context of other types of reverse supply chain network design (RSCND) problems, such as reverse logistics network design (RLND) and integrated reverse flow logistics (IRFL) problems.

Limited research has been done in the field of recovery related strategies. This group of strategies has only been applied where suppliers, manufacturers, DCs are the vulnerable sections of SC. Recovery strategies have not been examined in other sections defined as vulnerable and could be examined in future research.

5.3.3 SC design quality:

SC design quality related strategies are most often employed to improve the complexity related capabilities of SCs when suppliers, general facilities, plants, DCs and retailers are vulnerable to disruption. The greatest attention is given to strategies at transportation modes and routes, and customer demand disruptions. There is a knowledge gap related to capabilities that further improve resilience, such as SC node density, critically for suppliers, general facilities, plants, DCs and retailers, customer demand, and complexity for transportation modes and routes. Strategies can then be devised to enhance the robustness and redundancy of these critical nodes, ensuring uninterrupted flow of materials and minimizing disruptions. There is a notable lack of studies focusing on modeling facility segregation and dispersion strategies, despite their critical importance, particularly in addressing vulnerabilities among manufacturers, DCs, and retailers within supply chains (see Table 8). Currently, there is a lack of studies addressing mitigation strategies that prioritize the resilience of demand nodes. Future research could explore the advantages of having multiple buyers instead of relying heavily on a few large buyers. Another compelling area for further investigation is comparing strategies in concentrated markets versus diversified markets within different node density groups.

5.3.4 Mitigation strategy combinations

Several authors have attempted to integrate diverse mitigation strategies from various categories. However, it is evident that only one paper (Alikhani et al., 2023a, 2023b) provides justifications for these integrations, specifically studying the synergistic effects of combining resilience strategies. A promising direction for future research entails conducting a qualitative study to delve into the underlying reasons behind these combinations, complemented by a quantitative analysis of their overall performance.

When combining resilience strategies, only a limited number of studies have explored the integration of supply chain design quality resilience strategies. Moreover, there is a scarcity of studies that combine proactive and reactive strategies. Therefore, in the future, authors can focus their efforts on proposing models that leverage the advantages of combining such strategies and investigate both their potential benefits and drawbacks. For example, among these strategies listed in Table 8, *facility collaboration* (SP11, PP10, and DP9), *cybersecurity* (SP4, and DP3)—proactive approaches—and *facility dispersion* (SD2, PD1, and DD1)—a SC design quality approach—have shown promising results when integrated with other proactive or reactive strategies. Their integration can also be studied alongside approaches from supply chain design quality and reactive strategies to explore their effectiveness in enhancing supply chain resilience.

5.4 Mitigation strategies relative performance

The results of the analysis presented (Sect. 4.2) shows that in most research the effectiveness of strategies and their relative performance has not been investigated, or is only compared against a SC model not employing resilience strategies. Future research should focus on the relative effectiveness of different strategic options. The findings in Sect. 4.2 show that the performance of resilience strategies can depend on objective functions. The efficiency of strategies with both monetary and non-monetary objective functions such as visibility, responsiveness, social and environmental performance measures should be considered. Very little research exists where models are defined as multi-objective.

Exploration of the relative performance of mitigation strategies in different contexts, taking into account various objective functions, is required to develop knowledge in this area. Such studies will contribute to developing standardized approaches for selecting mitigation strategies tailored to specific types of supply chains.

5.5 Modelling

First, in multi-objective models presented using IF, RB, SSO, RO and SP, the objective functions are defined to minimise SC disruption costs, where usually the disruption cost is defined as the expected cost of transportation. Going forward researchers should consider non-monetary objective functions such as environmental related criteria and green transportation (Erdoĝan & Miller-Hooks, 2012) as well as social criteria such as fairness (Jiang & Zografos, 2021). Taking into account a longer time horizon, it is valuable to explore the enhancement of visibility, agility, external flexibility, and integral integration through the utilization of objective functions, such as maximizing visibility and internal integration (Nooraie et al., 2020). Exploring the trade-offs between sustainability and resilience can provide valuable insights for businesses in making tactical and operational decisions, such as determining sales prices, discounts, and customer service levels (Jabbarzadeh et al., 2018).

Secondly, the majority of models focus on designing resilient supply chains (RSCs) for a single product and within a single time period. However, there is a need for the development of resilience strategies and quantitative models that address multi-period and multi-product problems. Multi-period models serve as a basis for studying the ripple effects (Dolgui et al., 2018; Gholami-Zanjani, et al., 2021a) and recovery options in supply chain design. Additionally, these models provide a foundation for analysing lead-time constraints, delays, and late orders in supply chain analysis (Kaur & Prakash Singh, 2021). To increase the realism and applicability of multi-period models across diverse industries, it is essential to incorporate seasonal products and consider factors such as inflation and the time value of money (Saha et al., 2020).

Third, few integrative models exist, and research could consider combining location problems with transportation planning, inventory management, and production scheduling. Integrating optimization problems across different planning horizons may prove an effective approach to system design.

Finally, the application of the developed model to real-life case studies within actual supply chains is crucial for advancing knowledge in the field. By conducting empirical studies in real-world contexts, researchers can refine the model, address practical considerations, and provide valuable guidance for industry practitioners seeking to apply the resilience strategies in their RSCND processes.

6 Conclusions, and managerial implications

6.1 Summary and conclusions

Events such as the Covid-19 pandemic highlighted the importance of resilience in SC design. Resilience strategies are key to protecting SC's through planning for pre- or post-disruption activities. This novel investigation used a systematic literature review method to investigate the mitigation strategies used in mathematical models of RSCND problems and the methods of integrating them in the proposed models to address several challenges in developing quantitative models for designing RSCs.

To address RQ1, 'What is the classification of disruptions according to the extent of their impact on vulnerable parts of SCs?' we classified disruptions events based on their geographic scope and the part of SCs they affect, and show that in most articles local disruptions are introduced as the main cause of facility failures, with fewer articles considering regional and global disruptions respectively. When addressing local disruptions, researchers more often considered RLND and RFL problems than RSS and RFL problems. Analysis shows that in the literature, little attention has been paid to the modelling of RSCND problems in the case of national and regional disruption events.

RQ2 asked "focussing on vulnerable SC sections, what strategies have been introduced to improve resilience?" This analysis found that SC design complexity related strategies are most commonly used to address vulnerabilities at suppliers, with general facilities and transportation also often used respectively. Reactive strategies are dominant in the other SC sections, except for retailers where proactive strategies are prevalent. This analysis also examines the performance of mitigation strategies in different SCND contexts by reviewing the efficiency of the most commonly employed strategies selected from proactive, reactive and SC chain quality categories. The results of this analysis show that the effectiveness of mitigation strategies in reducing the effects of disruption depends on the context of SCs.

RQ3 ‘Drawing on performance criteria from literature, how have these strategies improved the resilience of supply chains?’, required analyses of the performance of applied mitigation strategies in improving the resilience of SCs. Strategies D2 and P1 performed well in comparison to other strategies, regardless of context of industrial application, though there were exceptions (see for example (Fattahi et al., 2017). We found the relative performance of mitigation strategies related to the objective function, and that combined strategies often outperform discrete applications.

Finally, RQ4 asked ‘How are resilience strategies integrated into mathematical models?’. To address RO4, the proposed mathematical models that addressed RSCND were classified based on their modelling approaches. Our findings indicated that SB and RO modelling approaches from the STH category were the only methods used to model a wide range of disruptive events and resilience strategies. Reactive strategies can only be integrated into mathematical models such as SB and RO, which divide the problem solving process into two stages, pre- and post-disruption. IF and RB modelling approaches were mainly used for proactive and SC design quality strategies. SP and FUZ models were used in modelling RSCND with parameters following specified statistical distributions and fuzzy numbers respectively, while R&R models were applied to risk minimisation and reliability maximization strategies.

The findings of this review provide a basis for both academics and practitioners to utilise and undertake further research into the methods of integration of resilience strategies into mathematical models proposed for different version of RSCND problems to make further effective contributions to the field.

6.2 Managerial implications

This review paper provides several implications for managers, particularly in the design of RSCs. The review guides managers in the design of mathematical models, and in choosing among mitigation strategies for SCs. For example, in a scenario a manager intends to invest in a food SC in Cornwall, a coastal areas in the UK that is exposed to natural disasters such as floods and storms. The manager’s goal is to design a SC that includes suppliers, manufacturers, and distribution centres, with suppliers and manufacturers located in the Cornwall region and therefore vulnerable to disruption events. The analysis performed in Sect. 3 as a first step will assist the manager to address the appropriate optimization problem considering the identified vulnerable sectors of the SC. In addition, the analysis presented will help them to understand how to model the disruptions in terms of geographic scope. In this case, a RLND problem may be defined considering the possibilities of regional and local disruption affecting both suppliers and manufacturers. The second implication is that managers can identify resilient strategies to hedge SC’s against the possible disruptions. The analysis in Sect. 4.1 aids managers evaluation of resilience strategies proposed for given conditions they face. Further the analyses in both Sects. 4.1 and 4.2 can be used to compare the performance of mitigation strategies in a given context, supporting the choice of the most efficient strategy. Suppose P1 strategy is selected from the proactive category, which according to the analysis of Sect. 4.2 provides reasonable relative performance. The final implication is related to the design of a suitable mathematical model to solve this problem. The results of the investigations carried out in Sect. 5.1 then aid managers choice of modelling approach. Supplementing the choice of model, the main characterises of the model can be determined by referring to the analyses in Sect. 5.2.

Appendix

The list of articles are presented for each strategy based on the associated DM problem discussed in Sect. 2.3. The last column of the Table 8 represents how often each strategy is applied in models in the articles (as a percent of total). In order to refer to the strategies more easily, in Table 8, we have also assigned a code to each mitigation strategy e.g. SP1 is *suppliers protection or fortification* strategy.

Table 8 The list of resilience strategies

ID	FiCod	Strategies	RFL	IRFL	RSS	RLND	Summary (%)
Suppliers							
Proactive							21.36
SC readiness							6.80
1	SP1	Suppliers protection or fortification			[13, 27]	[46, 81, 100]	4.85
2	SP2	Supplier agility			[75]		0.97
3	SP3	Assigning anticipation index				[89]	0.97
4	SP4	Cybersecurity				[100]	0.97
Flexibility and reliability							8.84
5	SP5	Suppliers flexibility			[35, 60, 91]	[87]	3.88
6	SP6	External flexibility			[75]		0.97
7	SP7	Suppliers reliability			[75, 86]	[44, 74, 87, 101]	5.82
Reserve capacity							10.68
8	SP8	Additional extra production capacity			[60, 86]	[52, 53, 96]	4.85
9	SP9	Additional extra inventory capacity			[64]		0.97
10	SP10	Pre-positioned Inventory & holding safety and emergency stocks			[13, 27, 69, 77]	[81]	4.85
Integration							2.91
11	SP11	Suppliers collaboration			[56]	[96]	1.94
12	SP12	Suppliers internal integration			[75]		0.97

Table 8 (continued)

ID	FiCod	Strategies	RFL	IRFL	RSS	RLND	Summary (%)
Visibility							1.94
13	SP13	Suppliers visibility			[56, 75]		1.94
Reactive							31.07
Response							31.07
14	SR1	Reselection of suppliers				[65, 67]	1.94
15	SR2	Recalculating the possibility of locating a supplier to serve a customer by a given transportation mode				[34]	0.97
16	SR3	Recalculating the amount of products used from emergency stock or prepositioned inventory in suppliers			[13, 27, 69, 77]		3.88
17	SR4	Customers' demand reallocation or recalculation of purchase or shipment from primary or backup suppliers			[27, 55, 64, 91]	[9, 42, 43, 46, 54, 57, 67, 71, 81, 82, 89, 96, 97, 99, 100]	18.45
18	SR5	Recalculating the quantity of extra products purchased from primary and/or backup suppliers			[27, 86]		1.94
19	SR6	Order-to-period assignment			[14, 23, 36]		2.91

Table 8 (continued)

ID	FiCod	Strategies	RFL	IRFL	RSS	RLND	Summary (%)
20	SR7	Production rescheduling over a limited time planning period			[48]	[67]	1.94
21	SR8	Applying the lateral transhipment among suppliers			[69, 77]		1.94
22	SR9	Spot price purchasing			[56]		0.97
23	SR10	Direct-to-store delivery				[76, 81, 97, 100]	3.88
24	SR11	Recalculation of transfer price				[46]	0.97
25	SR12	Increasing responsiveness				[93]	0.97
Recovery							7.77
26	SR13	Recalculating the recovery or restoring level of suppliers' capacities			[27, 64]		1.94
27	SR14	Reselection of recovery suppliers			[48, 69, 77]	[67]	3.88
28	SR15	Recalculating the amount of order from backup or recovery suppliers (recovery supply portfolio)			[48, 69, 77, 91]	[67]	4.85
29	SR16	Assigning recovery rate index				[89]	0.97
30	SR17	Recalculating the capacity recovery time				[89]	0.97
SC design quality							43.68
Density							4.85
31	SD1	Segregation of suppliers			[64, 98]		1.94
32	SD2	Supplier dispersion or SC mapping				[46, 92, 100]	2.91

Table 8 (continued)

ID	FiCod	Strategies	RFL	IRFL	RSS	RLND	Summary (%)
Complexity							40.77
33	SD3	Using dual or multiple sourcing			[3, 6, 13, 14, 23, 35, 36, 41, 42, 48, 49, 55, 56, 60, 69, 75, 77, 79, 86, 91, 99]	[43, 46, 53, 57, 65, 68, 71, 74, 82, 88, 89, 93, 97]	33.0
34	SD4	Contracting with (reliable or unreliable) recovery or backup suppliers			[27, 48, 56, 64, 86, 91, 98]	[54, 67, 68, 88, 89, 90]	12.62
35	SD5	Customers' allocation to protected suppliers			[13]		0.97
36	SD6	r-level assignment of suppliers to customers			[103]	[76]	1.94
37	SD7	Backup supply route				[90]	0.97
Critically							1.94
38	SD8	Multiple set covering				[81, 100]	1.94
Operational vulnerability							3.88
39	SD9	Inventory control			[13, 79, 86]	[21]	3.88
General facilities							
Proactive							4.85
SC readiness							3.88
40	FP1	Facilities protection or fortification	[10, 16, 37]				2.91
Flexibility and reliability							
41	FP2	Producing substitute product		[73]			0.97

Table 8 (continued)

ID	FiCod	Strategies	RFL	IRFL	RSS	RLND	Summary (%)
Reserve capacity							1.94
42	FP3	Additional extra production capacity	[10]	[62]			1.94
Reactive							13.59
Response							13.59
43	FR1	Reassignment of customers to survived facilities	[8, 19, 25, 26, 28, 32, 63, 80, 85, 95]	[31]			10.68
44	FR2	Customers rerouting until receiving a service	[33]				0.97
45	FR3	Lateral transhipment among facilities	[66]				0.97
46	FR4	Recalculating of the shipment amounts of products to customers	[66]				0.97
47	FR5	Reassignment of demand nodes to *r* closer facilities (level-r)	[70]				0.97
SC design quality							19.42
Complexity							19.42
48	FD1	Assignment of demand nodes to *r* closer facilities (level-r)	[1, 2, 11, 15, 18, 20, 29, 30, 32, 38, 50, 51, 58, 63]	[7, 73]			15.53
49	FD2	Assignment of customers to both primary and backup facilities	[4, 16, 37]				2.91

Table 8 (continued)

ID	FiCod	Strategies	RFL	IRFL	RSS	RLND	Summary (%)
50	FD3	Assignment of customers to non-disrupted facilities after disruption of the primarily assigned facility	[10]				0.97
Operational vulnerability							
51	FD4	Inventory control		[73]			0.97
Plants, factories or manufacturers							
Proactive							11.65
SC readiness							2.91
52	PP1	Protection or fortification				[46, 99]	1.94
53	PP2	Calculating anticipation time				[89]	0.97
54	PP3	Calculating preparation time				[89]	0.97
Flexibility and reliability							4.85
55	PP4	Assigning flexibility index				[87]	0.97
56	PP5	Assigning reliability index			[60]	[44, 87, 101]	3.88
57	PP7	Production of semi-manufactured products				[46]	0.97
Reserve capacity							9.71
58	PP8	Adding extra production capacity			[60]	[52, 54, 68, 81, 84, 99]	6.80

Table 8 (continued)

ID	FiCod	Strategies	RFL	IRFL	RSS	RLND	Summary (%)
59	PP9	Pre-positioned Inventory & holding safety and emergency stocks in plants			[69, 77]	[96]	2.91
Integration							0.97
60	PP10	Facilities collaboration				[96]	0.97
Reactive							20.38
Response							20.38
61	PR1	Allowing the direct shipment of products from factories to customers				[68]	0.97
62	PR2	Considering primary and alternative BOM				[46]	0.97
63	PR3	Recalculating the amount of products transferred (received) from manufacturers (primary or backup suppliers)			[98]	[42, 45, 46, 54, 84, 89, 93, 99]	8.74
64	PR4	Recalculating the amount of products transferred from manufacturers through different routes				[22, 43, 59, 61, 68]	4.85

Table 8 (continued)

ID	FiCod	Strategies	RFL	IRFL	RSS	RLND	Summary (%)
65	PR5	Recalculating the amount of direct shipment from manufacturers to customers				[68]	0.97
66	PR6	Recalculating the transfer price from manufacturer				[46]	0.97
67	PR7	Recalculating the quantity of products produced in manufacturers			[69]	[43, 47, 54, 61, 68, 71, 84]	7.77
68	PR8	Recalculating the inventory position of products			[60]	[93]	1.94
69	PR9	Reassigning customers to other operating plants		[24]			
70	PR10	Applying lateral transhipment			[77]	[67]	1.94
Recovery							2.91
71	PR11	Assigning recovery rate index				[89]	0.97
72	PR12	Recalculating the capacity recovery time				[89]	0.97
73	PR13	Recalculating the amount of order from backup or recovery suppliers (recovery supply portfolio)			[77]		0.97
74	PR14	Recalculating the recovery or restoring level of capacities				[99]	0.97

Table 8 (continued)

ID	FiCod	Strategies	RFL	IRFL	RSS	RLND	Summary (%)
SC design quality							4.85
Density							0.97
75	PD1	Manufacturers dispersion				[46]	0.97
Complexity							2.91
76	PD2	Substitute or backup facilities within the chain				[52, 67]	1.94
77	PD3	Backup supply route				[90]	0.97
Operational vulnerability							0.97
78	PD4	Inventory control			[60]		0.97
Distributed centres, transfer centres, warehouses, or depots							
Proactive							16.50
SC readiness							6.80
79	DP1	Protection or fortification				[46, 47, 81, 82, 100, 102]	5.82
80	DP2	Soft hardening				[17]	0.97
81	DP3	Cybersecurity				[100]	0.97
Flexibility and reliability							3.88
82	DP4	Assigning flexibility index				[87]	0.97
83	DP5	Assigning reliability index				[44, 87, 101]	2.91

Table 8 (continued)

ID	FiCod	Strategies	RFL	IRFL	RSS	RLND	Summary (%)
Reserve capacity							9.71
84	DP6	Adding extra inventory capacity		[78]		[61, 72, 92]	3.88
85	DP7	Emergency or safety stock in the DCs				[46, 52, 81, 96, 100]	4.85
86	DP8	Adding extra throughput capacity				[84]	0.97
Integration							0.97
87	DP9	DCs collaboration				[96]	0.97
Reactive							27.18
Response							27.18
88	DR1	Applying lateral transhipments among DCs			[49]	[17, 68, 81, 88]	4.85
89	DR2	Reassigning the customers to DCs				[72, 88]	1.94
90	DR3	Recalculating the amount of products transferred from DCs	[94]	[78]		[12, 42, 43, 45, 46, 57, 81, 82, 84, 88, 93, 97, 100, 102]	15.52
91	DR4	Recalculating the amount of products transferred from DCs through different routes				[22, 59, 61, 65, 68]	4.85
92	DR5	Using temporarily mobile warehouses				[65]	0.97

Table 8 (continued)

ID	FiCod	Strategies	RFL	IRFL	RSS	RLND	Summary (%)
93	DR6	Recalculating inventory position		[78, 83]		[12, 46, 47, 59, 72, 81]	7.77
94	DR7	Modification of the amount of outsourcing for a DC		[78]			0.97
95	DR8	Moving DC from its current location to a new location in the next period	[94]				0.97
96	DR9	Opening a DC or warehouse in a new location during a specific time period	[94]			[65]	1.94
Recovery							1.94
97	DR10	Recalculating the recovery or restoring level of capacities				[102]	0.97
98	DR11	Recalculating the cost increase related to the SC operation during the recovery time of the SC				[72]	0.97
SC design quality							9.71
Density							1.94
99	DD1	Warehouses dispersion				[46]	0.97
100	DD2	Dynamic sourcing				[12]	0.97
Complexity							1.94
101	DD3	r-level assignment of DCs to customers	[39]	[40]			1.94

Table 8 (continued)

ID	FiCod	Strategies	RFL	IRFL	RSS	RLND	Summary (%)
Critically							0.97
102	DD4	Multiple set covering				[81]	0.97
Operational vulnerability							4.85
103	DD5	Inventory control		[78, 83]	[49]	[12, 72]	4.85
Retailers							
Proactive							2.91
SC readiness							1.94
104	RP1	Protection or Fortification				[81, 100]	1.94
105	RP2	Cybersecurity				[100]	0.97
Reserve capacity							2.91
106	RP3	Adding extra inventory capacity				[81]	0.97
107	RP4	Pre-positioned Inventory & holding safety and emergency stocks				[53, 100]	1.94
Reactive							2.91
Response							2.91
108	RR1	Recalculating the amount of unused capacity				[81]	0.97

Table 8 (continued)

ID	FiCod	Strategies	RFL	IRFL	RSS	RLND	Summary (%)
109	RR2	Recalculating the amount of products transferred from retailers				[81, 100]	1.94
110	RR3	Assigning responsiveness index		[83]			0.97
SC design quality							3.88
Density							0.97
111	RD1	r-level assignment of retailers to customers				[76]	0.97
Critically							2.91
112	RD2	Multiple set covering				[81]	0.97
Operational vulnerability							
113	RD3	Inventory control				[5, 21]	1.94
Transportation modes, 3P logistics, paths, and routes							
Proactive							4.85
114	TP1	*SC readiness*					0.97
115	TP2	Protection or fortification				[102]	0.97
Flexibility and reliability							2.91
116	TP3	Assigning flexibility index				[87]	0.97

Table 8 (continued)

ID	FiCod	Strategies	RFL	IRFL	RSS	RLND	Summary (%)
117	TP4	Assigning reliability index				[44, 52, 87]	2.91
Reserve capacity							0.97
118	TP5	Fleet size expansion				[34]	0.97
Reactive							7.77
Response							7.77
119	TR1	Using an alternative unscheduled vehicle		[24]			0.97
120	TR2	Penalising adding an alternative vehicle		[24]			0.97
121	TR3	Rerouting of vehicles		[31, 62]		[65]	2.91
122	TR4	Recalculating the flow of products through paths				[53, 100]	1.94
123	TR5	Coalition formation among carriers				[97]	0.97
Recovery							
124	TR6	Recalculating the recovery or restoring level of capacities				[102]	0.97
SC design quality							6.80
Density							1.94
125	TD1	Reliable backup routes				[17, 90]	1.94

Table 8 (continued)

ID	FiCod	Strategies	RFL	IRFL	RSS	RLND	Summary (%)
Complexity							0.97
126	TD2	Backup supply route				[90]	0.97
Critically							4.85
127	TD3	Multiple transportation routes or channels				[59, 61, 68]	2.91
128	TD4	Multiple transportation modes				[34, 74]	1.94
129	TD5	Multiple set covering					
Demands							
Reactive							25.24
Response							25.24
130	MR1	Recalculating the amount of lost sales or unmet demand to apply penalties	[25, 66, 80]	[78, 83]	[13, 55, 64, 69, 77, 91]	[12, 43, 46, 54, 57, 61, 68, 81, 84, 89, 96, 99, 100]	23.3
131	MR2	Recalculating responsiveness level of the SC				[47]	0.97
132	MR3	Recalculating the retail price for a customer				[88]	0.97
SC design quality							0.97
Critically							0.97
133	MD1	Assigning a fraction of demand to subcontracting facilities	[66]				0.97

Table 9 Resilience strategies used in the models proposed in reference articles

Ref	Proactive	Reactive	SC quality
1			FD1
2			FD1
3			SD3
4			FD2
5			RD3
6			SD3
7			FD1
8		FR1	
9		SR4, DR3	
10	FP1, FP3		FD3
11			FD1
12		DR3, DR6, MR1	DD2, DD5
13	SP1, SP10	SR3, MR1	SD3, SD5, SD9
14		SR6	SD3
15			FD1
16	FP1		FD2
17	DP2	DR1	TD1
18			FD1
19		FR1	
20			FD1
21			SD9, RD3
22		PR4, DR4	
23		SR6	SD3
24		PR9, TR1, TR2, MR1	
25		FR1, MR1	
26		FR1	
27	SP1, SP10	SR3, SR4, SR5, SR13	SD4
28		FR1	
29			FD1
30			FD1
31		FR1, TR3	
32		FR1	FD1
33		FR2	
34	TP5	SR2	TD4
35	SP5		SD3
36		SR6	SD3
37	FP1		FD2
38			FD1

Table 9 (continued)

Ref	Proactive	Reactive	SC quality
39			DD3
40			DD3
41			SD3
42		SR4, PR3, DR3	SD3
43		SR4, PR3, PR7, DR3, MR1	SD3
44	SP7, PP5, DP5, TP4		
45		PR3, DR3	
46	SP1, PP1, PP7, DP1, DP7	SR4, SR11, PR2, PR3, PR6, DR3, DR6, MR1	SD2, SD3, PD1, DD1
47	DP1	PR7, DR6, MR2	
48		SR7, SR14, SR15	SD3, SD4
49		DR1	SD3, DD5
50			FD1
51			FD1
52	SP8, PP8, DP7	TR4	PD2
53	SP8, RP4	TR4	SD3
54	PP8	SR4, PR3, PR7, MR1	SD4
55		SR4, MR1	SD3
56	SP11, SP13	SR9, MR1	SD3, SD4
57		SR4, DR3, MR1	SD3
58			FD1
59		PR4, DR4, DR6	TD3
60	SP5, SP8, PP5, PP8		SD3, PD4
61	DP6	PR4, PR7, DR4, MR1	TD3
62	FP3	TR3	
63		FR1	FD1
64	SP9	SR4, SR13, MR1	SD1, SD4
65		SR1, DR4, DR5, DR6, DR9, TR3	SD3
66		FR3, FR4, MR1	MD1
67		SR1, SR4, SR7, SR14, SR15, PR10	SD4, PD2
68	PP8	PR1. PR4, PR5, PR7, DR1, DR4, MR1	SD3, SD4, TD3
69	SP10, PP9	SR3, SR8, SR14, SR15, PR7, MR1	SD3
70		FR5	
71		SR4, PR7,	SD3
72	DP6	DR2, DR6, DR11	DD5

Table 9 (continued)

Ref	Proactive	Reactive	SC quality
73	FP2		FD1, FD4
74	SP7		SD3, TD4
75	SP2, SP6, SP7, SP12, SP13		SD3
76		SR10	SD6, RD1
77	SP10, PP9	SR3, SR8, SR14, SR15, PR10, PR13, MR1	SD3
78	DP6	DR3, DR6, DR7, MR1	DD5
79			SD3, SD9
80		FR1	MR1
81	SP1, SP10, PP8, DP1, DP7, RP1, RP3	SR4, SR10, DR1, DR3, DR6, RR1, RR2, MR1	SD8, DD4, RD2
82	DP1	SR4, DR3	SD3
83		DR6, RR3, MR1	DD5
84	PP8, DP8	PR3, PR7, DR3, MR1	
85		FR1	
86	SP7, SP8	SR5	SD3, SD4, SD9
87	SP5, SP7, PP4, PP5, DP4, DP5, TP3, TP4		
88		SR4, DR1, DR2, DR3, MR3	SD3, SD4
89	SP3, PP2, PP3	SR4, SR16, SR17, PR3, PR11, PR12, MR1	SD3, SD4
90			SD4, SD7, PD3, TD1, TD2
91	SP5	SR4, SR15, MR1	SD3, SD4
92	DP6		SD2, SD3
93		SR12, PR3, PR8, DR3	
94		DR3, DR8, DR9	
95		FR1	
96	SP8, SP11, PP9, PP10, DP7, DP9	SR4, MR1	
97		SR4, SR10, DR3, TR5	SD3
98		PR3	SD1, SD4
99	PP1, PP8	SR4, PR3, PR14, MR1	SD3
100	SP1, SP4, DP1, DP3, DP7, RP1, RP2, RP4	SR4, SR10, DR3, RR2, TR4, MR1	SD2, SD8
101	SP7, PP5, DP5		
102	DP1, TP2	DR3, DR10, TR6	
103			SD6

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Data availability Data supporting the findings of this study are available on a reasonable request from the authors.

Declarations

Conflict of interest The authors declare that there is no conflict of interest regarding the publication of this paper.

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