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Review

Supply chain resilience: A review from the inventory management perspective

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ABSTRACT

The COVID-19 pandemic has exposed vulnerabilities in global supply chains, leading to economic damage and product shortages caused by demand surges and supply disruptions. Concurrently, geopolitical conflicts and the rising frequency of natural disasters due to climate change have amplified the urgency to develop strategies for building resilient supply chains. This article presents a comprehensive literature review on inventory management strategies for enhancing supply chain resilience, such as stockpiling, multi-sourcing, capacity reservation, and flexible supply contracts. We classify these strategies into two categories: one deals with supply-side disruption risks, and the other deals with demand-side disruption risks. For each category, we summarize the practical challenges, the state-of-art research, and potential avenues for future research.

1. Introduction

1.1. Supply chain resilience

Supply chain resilience refers to the ability of a supply chain "to return to its original state or move to a new, more desirable state after being disturbed" [1]. It implies the supply chain's ability to mitigate, respond to, and recover from risks that cause mismatches between demand and supply. Therefore, the supply chain is more resilient if the possibility of mismatches is lower, the duration is shorter, or the state after recovery is better.

As the world grows increasingly interconnected, global disruptions such as the Coronavirus (COVID-19) significantly and lastingly impact supply chain logistics, suppliers, and workforce [2]. Local disturbances, including natural disasters such as earthquakes and floods, as well as sudden shifts in inflation, market trends, political policies, and climate changes, can similarly influence global supply chain operations due to their cascading effects [3]. Concurrently, pervasive digital technologies are reshaping supply chain processes and configurations [4]. These transformations, however, may lead to heightened risks of supply disruptions due to increased coordination complexity inherent in Industry 4.0 designs and potential interruptions in information flow stemming from data security issues [5]. Additionally, dramatic changes in consumer behavior, particularly following the pandemic, pose further challenges [6]. Such shifts can disrupt supply chains as unpredictable demand creates substantial mismatches between supply and demand. Moreover, supply chain members are increasingly encountering events for the first time, where neither the probability nor the impact of risks is known, thereby escalating uncertainties and disruption risks towards unknown unknowns [7]. These developments underscore the ongoing and critical challenge of building a more resilient supply chain.

1.2. Existing reviews on supply chain resilience

The growing significance of supply chain resilience has attracted the attention of many scholars. A number of surveys provide an overview of the academic literature from different perspectives. For example, Kamalahmadi and Parast [8] review works focusing on the definition and principles of resilience. They define supply chain resilience as "*The adaptive capability of a supply chain to reduce the probability of facing sudden disturbances, resist the spread of disturbances by maintaining control over structures and functions, and recover and respond by immediate and effective reactive plans to transcend the disturbance and restore the supply chain to a robust state of operations*". They identify foundational supply chain

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resilience principles, including supply chain reengineering, collaboration, agility, and the development of a supply chain risk management culture. Finally, they summarize key elements of a resilient supply chain, such as flexibility and redundancy for supply chain reengineering, trust and information sharing for collaboration, visibility and velocity for agility, leadership and innovation for supply chain risk management culture. Emphasizing analytical decision-making, Snyder et al. [9] and Hosseini et al. [10] review the literature focusing on quantitative models for developing supply chain resilience. They discuss the objective functions, decision variables, and constraints of mathematical models addressing various resilience challenges such as supplier segregation, inventory location, order quantity, and restoration capacity of disrupted primary supplier. Hosseini et al. [11] review works that focus on resilience of supply networks. They discuss how to detect bottlenecks and how risk propagates in a supply network and comb through mitigation strategies for network disruptions. They emphasize that supply network topology design, redundancy and proactive and reactive flexibility for supply network reengineering can help avoid and postpone disruptions, or alleviate the impacts of the disruptions. They incorporate multiple stakeholders roles in supply network decisions.

Several surveys have further elucidated the roles of specific strategies such as procurement, collaborative actions, and Industry 4.0 technologies in enhancing supply chain resilience. For instance, Roberta Pereira et al. [12] emphasize procurement as a crucial interface that rapidly communicates market demand changes to suppliers. They explore how various procurement activities address key intra- and inter-organizational challenges in implementing supply chain resilience strategies. The procurement activities include establishing supplier bases, developing supplier selection criteria, building supplier relationships, setting up network configurations, reserving knowledge backups, and managing internal stocks. Scholten and Schilder [13] highlight the collaboration for building a resilient supply chain as the “glue that holds supply chain, organizations together in a crisis”. They unravel in detail how the collaborative activities of information sharing and collaborative communication, joint relationship efforts (decision synchronization, resource sharing and incentive alignment), and mutually created knowledge enable supply chain resilience. Based on discussions of previous literature, Spieske and Birkel [14] investigate the relationships among seven technologies of industrial 4.0 – artificial intelligence, big data analytics, blockchain, cloud computing, cyber physical systems, the Internet of Things, and additive manufacturing (e.g., 3D printing) – and supply chain resilience antecedents distinguished by supply chain reengineering, agility, collaboration, and supply chain risk management culture.

1.3. Inventory-related strategies on supply chain resilience

Effective inventory management at different levels of supply chain is an essential strategy to build supply chain resilience. Research by Remko [2] reveals that since the onset of COVID-19, 47% of respondents are considering holding more inventory, and 58% intend to diversify their sourcing strategies to mitigate supply chain risks. When demand surges occur, inventory provides immediate availability to fill the need. Similarly, in the event of supply disruptions, on-hand inventory serves as a buffer to continue serving demand. Therefore, inventory held in an organization plays a pivotal role in cushioning supply chain disruptions.

In this paper, we review inventory-related strategies that are applied to mitigate the impact of supply chain disruptions. Inventory management fundamentally aims to strike a balance between costs and service levels, which necessitates a detailed understanding of both demand-side and supply-side information. Consequently, inventory management strategies for hedging against demand-side and supply-side disruptions often differ due to their distinct advantages. Accordingly, our discussion separately addresses how strategies hedge against risks from disruptions on the demand side and the supply side, exploring these areas distinctly to highlight their unique challenges and solutions.

Specifically, to hedge against demand-side disruptions, firms often employ pre-positioning of emergency supplies. This strategy enables immediate response to demand surges, significantly reducing shortage impacts on customer service. Ergun et al. [15] note that pre-positioned inventories are particularly effective in mitigating frequent, large demand surges, as they substantially decrease the response time needed.

Conversely, to guard against supply-side disruptions, firms might adopt multiple sourcing strategies. This approach ensures that companies can maintain material inflows even if some suppliers face disruptions. For instance, if a supplier fails to deliver materials on time due to supply uncertainty, companies can procure from alternative suppliers or the spot market to stabilize material flow. Song et al. [16] highlight that multiple sourcing is especially advantageous for mitigating risks associated with suppliers’ production or transportation disruptions.

However, relying solely on inventory pre-positioning or multiple sourcing has its limitations in managing disruption risks. For instance, while pre-positioning can hedge against demand-side disruptions, maintaining large stockpiles is often costly. Alternatives like reserving capacities-referred to as virtual inventory-can be more cost-effective [15,17]. This approach, complemented by sharing inventory data, implementing Vendor-Managed Inventory (VMI) programs, or engaging in collaborative inventory planning, allows stakeholders to work together to enhance supply chain resilience. Thus, reserved capacity and flexible cooperation contracts serve as ideal supplements to physical inventory pre-positioning.

Conversely, when hedging against supply-side disruptions, placing additional orders with regular or emergency suppliers typically involves lead times. Therefore, maintaining inventory reserves is crucial to prevent the risk of supply disruptions from propagating through the supply chain during these lead times [15]. Moreover, cultivating flexible relationships can encourage suppliers to prioritize a company’s needs during disruptions, based on trust and reliability [9]. Consequently, combining inventory reserves with flexible sourcing contracts effectively supports multiple sourcing strategies in mitigating supply-side disruptions.

Compared to traditional inventory management literature, the discourse on inventory-related strategies in supply chain resilience primarily focuses on mitigating the impacts of demand surges and supply disruptions. For instance, within the framework of supply chain resilience, the quantity of pre-positioned inventories is typically greater than what is maintained for regular demand, and these inventories are often stored in dedicated warehouses. Additionally, it is generally preferable to source supplies from a diverse array of suppliers to ensure shorter lead times for arrivals [16], rather than prioritizing the lowest cost acquisitions. However, conventional inventory models that account for uncertainty could still be adapted to enhance supply chain resilience [18,19].

1.4. A framework for bridging research and practice

Recognizing the critical role of inventory management in enhancing supply chain resilience, this paper seeks to systematically review relevant scientific research. Our goal is to evaluate current inventory strategies that bolster resilience and identify significant research gaps. By synthesizing existing literature, we aim to provide actionable insights for managers to make better decisions and offer scholars a clearer understanding of crucial research areas.

We propose a framework shown in Fig. 1, to bridge theoretical developments and practical applications, facilitating comprehension of how robust inventory management practices contribute to a resilient supply chain.

The top portion of Fig. 1 illustrates the core strategies employed to build supply chain resilience against disruptions from the demand side, which include inventory pre-positioning and its supporting tools–reactive capacity and flexible cooperation contracts. In the bottom portion, we demonstrate widely used strategies to cope with supply

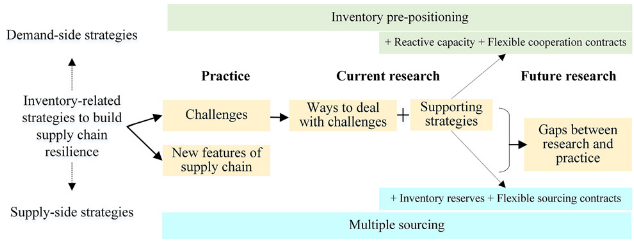

Fig. 1. A framework for practice and research.

uncertainties, i.e., multiple sourcing and its supporting tools–inventory reserves and flexible sourcing contracts.

The middle portion of Fig. 1 indicates the logic flow of our review. That is, we begin with identifying the practical challenges in implementing the core strategies across different phases of supply chain disruptions: pre-event, during, and post-event. We then analyze how current research tackles these periods with specific focus on mitigating risks from both demand and supply perspectives. Furthermore, we discuss the supporting tools that enhance the effectiveness of these primary strategies. Finally, we point out future research opportunities.

To conduct the review based on the framework outlined above, we selected papers indexed in INFORMS and Web of Science within the fields of Operations Research and Management Science. These papers contain keywords such as "resilience/resilient" "risk" "disruption" "demand surge" "uncertain" "emergency" or "breakdown" in their titles or abstracts. We also searched for Chinese references through Google Scholar and the China National Knowledge Infrastructure (CNKI). Our search was supplemented with ChatGPT, which significantly aided the process.

The databases contain thousands of journal articles, from which we initially selected the top 300 based on relevance and journal quality rankings. We then narrowed this selection to works focusing on inventory management decisions related to sourcing, storing, and fulfillment, resulting in approximately 168 papers. Each paper was evaluated based on its research questions, contributions, methodological rigor, and conclusions. Papers that did not provide information relevant to the purpose of this literature review were excluded. Additionally, we directly collected some papers from the references of review articles on supply chain resilience, inventory management, pre-positioned inventory, and multiple sourcing, including works by Roberta et al. [12], Balcik et al. [20], Song et al. [4], Xin et al. [21], Spieske et al. [14], Cohen et al. [22], and Ergun et al. [15].

In total, we selected 102 articles for an in-depth review, with 37 on pre-positioning, 36 on multiple sourcing, 17 on the supporting strategies for pre-positioning, and 12 on the supporting strategies for multiple sourcing.

In Section 2 we review the inventory-related strategies that are applied to deal with demand uncertainties. In Section 3 we review the inventory-related strategies that are applied to deal with supply uncertainties. In Section 4 we propose future research opportunities on inventory management strategies from demand-side and supply-side to improve supply chain resilience. Finally, we conclude the paper.

2. Demand-side strategies

If a demand shortage occurs, the first line of defense is often inventory. Thus, stockpiling inventories for demand surges has become a common practice. For instance, during the COVID-19 pandemic, Sam's Club increased its reserves of household-use items to 3-5 times the usual amount, enabling immediate responses to demand spikes (Sina Finance, 2022).[1] Similarly, governments establish strategic national stockpiles, such as the U.S. Strategic National Stockpile, which stores emergency supplies including oil, food, medical supplies, and personal protective equipment (PPE) to assist in disaster relief and prevent disease transmission [23].

Additionally, the slow yet steady capability of reactive capacity complements the inventory pre-positioning that is quick yet with limited capacity, making it a vital support strategy [15]. Furthermore, the integration and coordination of external resources with partners become necessary to supplement limited or cost-inefficient in-house efforts [24].

In this section, we explore three inventory-related strategies to manage demand uncertainties: inventory pre-positioning, reactive capacity, and flexible cooperation contracts. We first detail the challenges and current solutions associated with inventory pre-positioning, followed by an analysis of how supporting strategies enhance pre-positioning and their combined effectiveness in mitigating demand-side disruptions.

2.1. *Inventory pre-positioning*

Although inventory pre-positioning improves the responsiveness of the supply chain, there are many challenges when implementing this strategy. We summarize these challenges in Table 1 according to whether they occur before, during, or after the demand surge, as illustrated in Section 2.1.1, and the associated ways to solve these challenges are also presented in Table 1. Furthermore, we divide the existing research into different ways to deal with challenges, as discussed in Section 2.1.2.

2.1.1. *Challenges*

Inventory pre-positioning before a demand surge involves critical decisions on how much to order, when to order, and where to store. These measures require accurate information on potential demand surges, such as the location and distribution of demand. However, predicting the exact location, timing, and magnitude of an emergency is highly challenging, making it difficult to accurately estimate demand surge information [18,48]. For example, despite Japan's advanced monitoring systems and seismic analysis in a region prone to earthquakes, the massive 2011 earthquake and subsequent tsunami were unexpected.[2]

Moreover, pre-positioned inventories can perish or become obsolete if demand surges are infrequent [29,30,32]. For instance, millions of masks stockpiled in Ontario, Canada, after the SARS outbreak expired before the coronavirus pandemic.[3] This perishability presents a significant challenge in formulating inventory policies, even for a single location, due to the "curse of dimensionality" [32].

During a demand surge, swiftly delivering limited pre-positioned inventories is crucial, yet there are significant challenges to achieving this. First, evaluating response objectives that allocate these goods involves navigating conflicting goals [49]. For example, the impact of unmet demand during disasters extends beyond financial losses to include threats to life and health [15,50]. In addition, excess inventory can harm social welfare; notably, over 1.56 billion face masks used in 2020 to combat COVID-19 may end up polluting the oceans, raising public concerns.[4]

Second, delivery times may be impeded by factors such as traffic congestion or labor shortages [37,38]. Additionally, the facilities storing pre-positioned inventories face risks of damage or destruction due to wars, earthquakes, or severe weather [25,27,48].

Lastly, the unpredictable nature of demand surge trajectories—characterized by explosive growth or sudden disappearance—further complicates the fulfillment process [51].

[1] https://finance.sina.com.cn/chanjing/cyxw/2022-04-26/doc-imcwipii6527394.shtml.

[2] Rafferty, John P. and Pletcher, Kenneth. "Japan earthquake and tsunami of 2011". Encyclopedia Britannica, 16 Jul. 2023, https://www.britannica.com/event/Japan-earthquake-and-tsunami-of-2011.

[3] https://singapore.timesofnews.com/breaking-news/millions-of-masks-stockpiled-in-canadas-ontario-expired-before-coronavirus-hit.html.

[4] https://oceansasia.org/covid-19-facemasks/.

Table 1
Challenges of inventory pre-positioning under different phases.

Phases	Challenges	Ways to deal with challenges
Before demand surge Preparation phase	Lack of demand surge location information: Difficult to decide on pre-positioning location Lack of demand distribution information: Difficult to decide on pre-positioning quantity due to poor demand forecasting Inventories may perish before being used: Difficult to decide on the amount of goods to stockpile	Multiple warehouse locations [24,25] Robust stochastic facility location model [26] Scenario-based stochastic model [27] Distributionally robust model [18,26] Predictive analytics and data-driven methods [28] Inventory rotation [29,30] Inventory sharing [31,32] Data-driven dynamic ordering [6] Approximation policy to deal with the curse of dimensionality [32,33]
During demand surge Response phase	Complex objectives: Difficult to balance response time, shortage, equity, sustainability, cost, etc. Long response time: Difficult to deliver the pre--positioned goods High fulfillment uncertainty: Warehouses may be destroyed, trajectory of demand surges may not be assessed correctly, and demand loss disparity	Multi-objective planning [18,34] Membership-type agreement [35] Incentive mechanism [36] Mobile warehouse [37] Unmanned aerial vehicles [38] Two-stage programming [39] Dynamic deployment model [40,41]
After demand surge Recovery phase	Lack of control during rehabilitation: The duration of the recovery phase is difficult to control Heavy burden on disposal of pre-positioned goods: Difficult to measure social value of old products Lack of information for reconfiguration under new environment: Reposition inventory for future demand surges; Innovative operational tools for upgrading inventory management systems	Risk Exposure Index (REI) [42,43] Inventory model incorporating disposal [44] Matching mechanism for reallocation [45] Technology-driven inventory model [46] Dynamic structural-logical constraints [47]

After pre-positioned inventory is deployed to meet demand, the supply chain enters the recovery phase. This phase extends the responsibility of stakeholders from merely mitigating impacts to enhancing long-term resilience and performance. However, it is challenging to predict the time required to recover from a demand surge and the state of the supply chain post-recovery [43]. This uncertainty complicates decisions related to ordering and discontinuing inventory pre-positioning, especially in complex situations like the COVID-19 pandemic.

Another concern arises if pre-positioned inventories exceed the demand. Managing surplus humanitarian supplies becomes a perplexing issue for managers.[5] Disposing of excess inventory is problematic, as efficiently distributing leftover supplies to organizations that need them is difficult [45].

In the recovery phase, supply chains often transit into a “new normal” situation, where some critical but vulnerable suppliers may have ceased operations [43]. This shift can complicate inventory repositioning, as supply chains must adapt to new environmental forces and immature reconfigured networks.

2.1.2. Current research

Table 1 shows that extensive research has been conducted on the inventory pre-positioning. We proceed from summarizing studies that address challenges in the preparation phase to those addressing challenges in the recovery phase, as detailed in Table 1.

Preparation phase. During the preparation phase, choosing the optimal warehouse location for handling future demand emergencies is critical. This decision must balance the benefits of fast delivery against the costs and risks associated with warehouse vulnerability [27,48]. Davis et al. [24] suggest prioritizing the nearest warehouse to meet demand surges quickly, with reserved capacity transshipped from other locations as needed. The classical P-median model, assuming that customers always get service from the facility that minimizes their travel cost, is developed in the warehouse location problem by introducing a reliability aspect [52,53], where a pre-specified number of facilities may be disrupted with a probability.

However, when faced with uncertain demand locations, robust optimization methods become essential. For example, Lu et al. [25] apply distributionally robust optimization (DRO) to determine optimal facility locations under correlated disruptions, while Liu et al. [26] enhance location decisions using a state-wise robust stochastic facility location model with a state-wise ambiguity set of demand distributions. Lu et al. [25] verify that the robust model based on the worst-case correlation outperforms the traditional model even when disruptions are only mildly correlated, and Liu et al. [26] investigate the location policies in different models–state-wise ambiguity set model, the distributionally robust optimization counterpart model, and the stochastic average approximation counterpart, and shows that the state-wise robust stochastic facility location model indeed enhances the quality of the location decision.

Alongside location decisions, determining the optimal inventory level is crucial to balance holding costs with the risk of demand shortfall [20,48]. The newsvendor model is frequently used to calibrate the pre-positioned inventory levels for uncertain demand surges [15,20]. Scenario-based stochastic models are also common, where uncertainties are represented by a finite number of scenarios with known probabilities [18]. For instance, Mete and Zabinsky [27] model different disaster scenarios based on urban fault lines and time of day, and Balcik and Ak [54] use historical data and expert opinion to determine disaster probabilities.

Distributionally robust optimization (DRO) methods are increasingly utilized. Ni et al. [18] propose a min-max robust model that requires only the most likely values, upper, and lower bounds of random inputs, adjusting the level of conservatism through an uncertainty budget to match the decision-maker’s risk tolerance. They find that robust models often outperform deterministic and stochastic counterparts. Additionally, motivated by the growing availability of advanced demand forecast tools, Hu et al. [28] introduce a two-stage pre-positioning framework that integrates predictive analytics and data-driven demand forecasting into inventory sizing, achieving near-optimal performance with their prediction-driven decisions.

In order to enhance the effectiveness of future responses, it is crucial to consider the perishability of items when making inventory pre-positioning decisions. Various strategies have been proposed in the literature to mitigate expiration issues. For instance, Shen et al. [55] examine the management of perishable inventory at a pharmaceutical com-

[5] https://www.npr.org/sections/goatsandsoda/2019/02/26/691598686/from-trailers-to-tents-what-happens-to-leftover-aid-supplies.

pany using a deterministic Economic Manufacturing Quantity (EMQ) model with a minimum volume constraint at a single location. Their approach allows for the rotation of perishable stockpiles through regular market demand, maintaining freshness and usability. Zhou and Olsen [29,30] explore the rotation strategy of national emergency medical supplies to hospitals, finding that implementing a rotation policy after a critical period is effective. Specifically, they recommend an order-up-to policy for ordering decisions and a rotate-up-to policy for rotation decisions, which can also address the problem of outdated masks in strategic national stockpiles during pandemics. Furthermore, Liu et al. [31] and Zhang et al. [32] demonstrate that sharing perishable inventory in the face of highly variable demand can significantly reduce obsolescence.

In addition, managing perishable inventory systems involves complex challenges such as the “curse of dimensionality” which complicates inventory management. To address this, Zhang et al. [33] designed a truncated balancing policy that simplifies balancing underage and overage costs, offering a worst-case performance bound of two. Zhang et al. [32] also propose a myopic inventory sharing policy that uncovers a simple structure for optimal transshipment direction and provides lower and upper bounds on the optimal transshipment quantity.

Response phase. During a demand surge, multiple objectives must be balanced when making inventory deployment decisions, including minimizing both logistics and deprivation costs [34,49,56]. Holguín-Veras et al. [49] and Ni et al. [18] address these by jointly minimizing the logistics and deprivation costs. To quantify deprivation costs, Holguín-Veras et al. [57] employ contingent valuation techniques, calculating these costs as a function of deprivation time.

Challenges also arise from the need to coordinate among hundreds of organizations with potentially conflicting objectives during emergencies. To navigate this complexity, Liu et al. [35] propose a multi-period membership-type agreement and develop a dynamic principal-agent model to facilitate partnerships among independent entities. This model is particularly applicable to relationships between multiple humanitarian organizations during crises.

Addressing response times is crucial, especially when warehouses are distant from the demand surge areas or labor shortages occur. Sodhi and Tang [17] advocate for using locally pre-positioned inventories to enhance last-mile deliveries during regular disasters like floods. Similarly, Eftekhar et al. [58] note the advantages of local purchasing from suppliers near affected areas to increase responsiveness. Several innovative solutions have also been proposed. For example, Srinivas and Marathe [37] introduce the “mobile warehouse” concept, where trucks dedicated to specific geographic locations carry inventories to meet demand quickly. The recently developed unmanned aerial vehicles (UAVs), which can improve the speed of data collection and save travel time without following the physical road network, motivated Zhang et al. [38] to solve the drone routing problem by introducing two types of edges, actual ground network and airspace. Wang et al. [36] demonstrate that providing incentives through bonus contracts to suppliers immediately after a disaster can significantly reduce delivery lead times.

Furthermore, sophisticated optimization techniques like two-stage stochastic programming, robust optimization, and dynamic models are extensively used to enhance response effectiveness during surges [18,27,39,41,59]. For instance, Mete and Zabinsky [27] and Ni et al. [18] employ two-stage stochastic models where initial decisions about warehouse selection and inventory pre-positioning are followed by subsequent transportation and demand fulfillment decisions. Guo et al. [39] also use a two-stage stochastic model to investigate where to pre-position and how to deploy the inventories to minimize the expected demand loss during a disaster assuming that the demand surge may occur at random locations and the demand arrives sequentially over time. They find that the optimal deployment policy is a “nested” policy with respect to the shadow price at each demand location. More studies on two-stage programming for disaster management can refer to the review paper of Grass and Fischer [59]. A dynamic deployment model that incorporates the time profile of a demand surge may be a more efficient tool to deal with an uncertain trajectory. In Uichanco [40], the trajectory of a demand surge may be changing in an unknown fashion. As such, they develop a practically relevant stochastic pre-positioning model where the probability models of municipality-level demand and of supply damage are both dependent on the typhoon outcome. Alternatively, Liu et al. [41] investigate dynamic capacity planning and deployment model to deal with demand trajectory variation. They design an adaptive allocation policy that is near optimal with perfect information.

Recovery phase. Following a demand surge, Simchi-Levi [43] outlines five steps supply chain executives should take to develop an effective recovery plan. He emphasizes the importance of the time-to-recover (TTR) metric, which helps companies determine when to rebuild their warehouse capacities. Utilizing TTR parameters, Gao et al. [42] analyze the risk-exposure index that reflects the cascading effects of disruptions within supply chains, allowing for modeling of optimal recovery operations to minimize total sales loss during disruptions.

As the supply chain returns to full functionality, the management of remaining pre-positioned inventories, including their efficient disposal and return, becomes crucial to sustaining supply chain resilience. Stauffer and Kumar [44] examine how incorporating returns and disposal into the initial deployment decision can influence pre-positioning strategies, finding that it tends to increase the initial deployment level. Further addressing the management of excess inventories, Zhang et al. [45] describe how medical surplus recovery organizations (MSROs) can repurpose medical surplus products to meet the needs of healthcare facilities in underserved regions. They introduce a simple scoring mechanism that utilizes detailed inventory and recipient information to optimize the disposal process, thus maximizing the value of leftover inventories.

Unlike traditional static supply chain designs, the increasingly volatile market conditions and frequent disruptions necessitate dynamic network structures to enhance resilience management. Hong et al. [11] highlight that adapting to these dynamic environments is crucial for maintaining supply chain functionality as challenges and demands evolve. In response to these changes, the adoption of advanced technologies has accelerated, reshaping various aspects of supply chain management. Ivanov [46] discusses how technology-driven inventory management can significantly enhance supply chain resilience. This approach not only enables rapid collection of inventory data but also supports automatic handling of warehouse operations. Further advancing this area, Ivanov et al. [47] propose a mathematical model to address dynamically changing constraints within supply chains. Their model, which tackles structural-terminal-logical constraints, is complemented by a decomposition-based algorithm designed to efficiently manage these complexities.

2.2. Reactive capacity and flexible cooperation contracts

2.2.1. Relationship with the inventory pre-positioning strategy

Pre-positioned inventories are crucial for promptly addressing demand surges but often fall short during exceptionally high-demand scenarios, such as those experienced during global crises like the COVID-19 pandemic. The fast-but-finite nature of physical inventory highlights the need for complementary strategies that enhance flexibility and extend capacity beyond what static stockpiles can provide. Two primary strategies that effectively complement inventory pre-positioning are the establishment of reserved capacities [23] and the facilitation of resource sharing through tailored contracts between warehouses [60].

Reserved capacities: During the initial outbreak of COVID-19, the demand for N-95 masks quickly exceeded the available stockpiles, causing severe shortages. Companies like Ford and Burberry exemplified the strategic use of reserved capacities by adapting their production lines to manufacture masks, supplementing the overwhelmed pre-positioned inventories [61]. This adaptation underlines the necessity of reserved capacities that allow for dynamic adjustment of production processes in response to fluctuating demands [23]. However, the effectiveness of such capacities can be challenged by rapid demand surges that outpace production capabilities, leading to potential delays [15], as was observed with mask production in China during the early pandemic stages.[6] So the pre-positioned inventory and reactive capacity planning are interactive based on the demand rate of surges [51].

Flexible cooperation contracts: The collaborative inventory strategy further supports the rapid deployment of supplies by maintaining a cumulative stock in strategically located warehouses [60]. Through flexible cooperation contracts, organizations pursue common goals by centralizing resources, which reduces the need for large individual inventory holdings [13]. These contracts lead to more cost-efficient and effective pre-positioning inventory planning, including decisions about the number and location of warehouses and the amount of inventory each should hold. For instance, Balcik et al. [60] propose an innovative insurance contract to allocate costs among partner countries collaboratively establishing inventory pre-positioning. This strategy not only reduces fixed warehouse costs but also significantly lowers inventory levels and required investments. The collaborative network established through these contracts also enhances the overall response capacity. Another notable example is the employee-sharing schemes among Chinese companies during COVID-19, which effectively mitigated the challenge of labor shortages,[7] showcasing the benefits of resource sharing as a strategic response [60].

2.2.2. Current research

Zooming in on the strategies for hedging against demand surges, we review the streams of studies on reserved capacity and flexible cooperation contracts that complement and support flexibly the pre-positioning in mitigating the risk of the demand surges.

Reserved capacity approach. Reserved production capacity allows manufacturers to scale up production rates above normal levels when necessary, achieving higher service levels during demand surges [51]. Scholars have explored the joint strategy of combining pre-positioned inventory with reactive production capacity, noting how the characteristics of demand surge trajectories—such as duration, intensity, and volatility—affect the preference between these strategies. For example, reactive production is preferred for less volatile surges, while pre-positioning is advantageous when demand is more unpredictable [51]. Furthermore, when inventory holding costs and capacity reservation costs are low, combining reserved production capacity with inventory shows superior performance compared to an inventory-only strategy [51,62]. Chaturvedi and Martínez-de-Albéniz [63] argue that the average reserved production capacity and stockpile can act as economic substitutes given a certain demand distribution, while Song et al. [4] suggest that inventory and production capacity can be either substitutes or complements, depending on their positional relationship.

Local procurement also supports reactive capacity by enhancing responsiveness and providing culturally appropriate products, especially when transportation to the demand area is costly or inaccessible [58]. Policies such as the tailored base-surge (TBS) approach leverage nearby emergency facilities quick-response capabilities dynamically, ensuring high service levels during random demand surges [64,65].

Flexibility cooperation contract approach. Flexibility cooperation contracts typically involve agreements among two or more autonomous organizations to collaboratively work towards common goals [13]. This form of horizontal cooperation among pre-positioned inventories is recognized as an effective reactive strategy for managing demand surge risks [60]. Liu et al. [31] introduced a virtual stockpile pooling strategy among multiple warehouses to enhance the supply network's responsiveness and cost-efficiency. Similarly, Zhang et al. [32] show that inventory sharing can increase optimal inventory levels, and Rodríguez-Pereira et al. [66] have designed cost-sharing mechanisms for collaborative inventory pre-positioning among humanitarian organizations, boosting their response capabilities.

Moreover, appropriate coordination contracts between relief suppliers and humanitarian organizations can significantly aid in procuring extra needed relief items post-disaster. These include quantity flexibility contracts [54], option contracts [67], bonus contracts [36], compensation contracts [68], and insurance contracts [60]. Li et al. [69] also explore buyback contracts and capacity reservation contracts, which help to coordinate the supply chain effectively against demand uncertainty.

2.3. The gap between existing research and practices

Despite the strategic benefits of inventory pre-positioning supported by reactive capacities and flexible cooperation contracts, significant gaps remain between theoretical frameworks and practical implementations. These strategies are designed to alleviate the impacts of demand shortages effectively, yet they are often not pre-established prior to disruptions, particularly in scenarios involving unprecedented challenges. This disconnection highlights the need for more robust preparations and adaptive strategies that can preemptively address the demands of unforeseen disruptions.

2.3.1. New features of demand-side practices

The dynamics of the supply chain continue to evolve, introducing new features that significantly alter the landscape of supply chain resilience. Numerous disruptive factors give rise to unpredictable demand surges with unknown probability and unknown impact [70]. For example, the COVID-19 pandemic triggered unprecedented demand surges for household goods and protective equipment [15]. Similarly, the rare cold-driven climate catastrophe in Texas sparked a demand surge for home-based electrical heating, resulting in widespread power outages.[8] These events underscore the difficulties in predicting surge occurrences and their probabilities, as new demand-side features bring formidable challenges in managing demand-side disruptions.

Moreover, shifts in consumer behavior following the COVID-19 pandemic have further complicated supply chain dynamics [6]. Consumers are increasingly favoring online shopping, and their expectations for corporate social responsibility are growing. Companies failing to align their operations with these new consumer preferences face the risk of significant disruptions in their supply chains due to a sharp drop in demand [71]. These dramatic shifts in demand after such disruptive events create substantial challenges for optimizing ordering and allocation decisions for inventory pre-positioning, especially when the duration and magnitude of demand shifts cannot be inferred simply from past information [15].

2.3.2. The gap in demand-side strategies

While many studies employ advanced optimization techniques (such as robust models, data-driven dynamic methods, and approximation algorithms) and operating mechanisms (such as inventory sharing, information disclosure, and mobile warehouse design) to address inventory pre-positioning challenges, an appropriate level of supply chain resilience is often not established prior to optimizing these decisions [15]. Resilience is typically measured by the probability of meeting demand, with costs of demand shortages and enhancements considered as preliminary inputs. This approach, however, may overlook the interconnected impacts of demand behaviors, such as the spread of infectious diseases when calculating the costs of shortages, despite the inclusion of individual deprivation costs in many analyses, i.e., the economic valuation of the human suffering [15,36,49,57].

Additionally, although DRO is a widely adopted method for decision making in response to disruptive scenarios, it can lead to models

[6] https://www.sixthtone.com/news/1005781.

[7] https://www.sixthtone.com/news/1005235.

[8] https://corporatesolutions.swissre.com/insights/knowledge/polar-vortex-a-counter-intuitive-threat-of-climate-change.html.

Table 2
Challenges of multiple sourcing under different phases.

Phases	Challenges	Ways to deal with challenges
Before supply disruption Preparation phase	Lack of supply risk information: Difficult to select suppliers	Auctions [73] Contracts negotiations [74] Distributionfree approach [75] Advanced blockchain [76] Order-tracking [77]
	High complexity of supply chain: Costly to maintain more than one supplier	Redesign supply chains [71,78] Simulating disruption propagation [3]
	Non-trivial optimal ordering policy: Suppliers have different leadtimes and selling prices	Approximate newsvendor model [79,80] Model structures [64,81]
	Complex supply disruption risks: Suppliers have correlated risks; Supply disruption risks may come from high-tier suppliers	Model correlated disruption risks [82] Multi-tier supply chain model [83]
During supply disruption Response phase	Scarcity of raw materials: Emergency source has uncertain capacity and a higher price	Order splitting [84,85] Evaluate alternative materials [86]
	Lack of supply disruption information: Hard to know whether the order is executable	Intensify contact with supplier [87] Data-driven sourcing model [88,89] Advanced technologies [14]
After supply disruption Recovery phase	Lack of control during supplier recovery: Supplier diversification may hurt recovery	Enhance long-term relationship [90] Restoring design information stock [91]
	High network reconstruction uncertainty: Supply chain network dynamically changes; More stakeholders such as governments may guide supply chain networks with complex interactive behaviors	Technology-driven multi-sourcing model [92] Dynamic rules in network [11]

that diverge significantly from actual conditions, potentially resulting in unnecessary pre-positioning costs [11]. Moreover, challenges like the curse of dimensionality in optimizing inventory decisions remain daunting, especially when considering practical factors such as budget constraints [58], connetabilities between stakeholders [56], and perishability rates of pre-positioned inventory [32]. Thus, there is a clear need for further research to develop new methods and resilience measurement techniques that can effectively tackle these complex yet practical challenges.

The effectiveness of reactive capacity and flexible contracts in supporting inventory pre-positioning rests on their ability to enable supply chains to ramp up production or secure external inventories in response to a surge in demand. However, in reality, these strategies may be inadequate during sudden demand shifts or significant changes in consumption behavior, as evidenced at the onset of the COVID-19 outbreak. For example, BYD Auto had to reconfigure its automobile manufacturing capacity to produce face masks, establishing an ad hoc supply chain [11]. Furthermore, the demand for different products can be highly correlated, complicating the implementation of mixed strategies that do not consider these connections. Dynamic and transformable capacities or contracts are essential to manage such complexities, though achieving such flexibility is challenging due to high requirements for resources, information, and expertise [4,46,72]. Therefore, more effective designs for reactive capacities and flexible cooperation contracts are needed to support inventory pre-positioning strategies against unknown and correlated demand surges.

3. Supply-side strategies

Multiple sourcing is a critical strategy that companies utilize to hedge against potential disruptions in their suppliers production or transportation processes [16]. This approach ensures that companies can maintain a stable flow of materials even if the primary supplier fails to deliver on time. To bolster multiple sourcing, maintaining an inventory reserve is crucial. This reserve acts as a buffer to prevent supply shortages from impacting downstream operations in the supply chain [15]. In addition, sourcing contracts related to suppliers' production, financing, supply network, and so on, are also necessary to mitigate supply disruption risks [9]. This section will discuss how multiple sourcing, inventory reserves, and flexible sourcing contracts are strategically combined to manage and mitigate supply uncertainties effectively.

3.1. *Multiple sourcing*

To implement the multiple sourcing strategies to strengthen supply chain resilience, managers need to decide how to source from the two or multiple suppliers. The problem turns out to be quite complex and challenging, as summarized in Table 2. Given these challenges before, during, and after the supply disruption, multiple sourcing has drawn the attention of many researchers over several decades, also as combed in Table 2.

3.1.1. *Challenges*

Similar to the categorization in Table 1, we organize the challenges of multiple sourcing into three phases in Table 2, based on when they typically occur.

Preparation phase. In the preparation phase, supplier selection is influenced by factors such as sourcing price, reliability, service, product quality, lead times, and organizational culture [93]. However, obtaining accurate information on aspects like a supplier's reliability can be challenging, as suppliers may withhold private information to maintain competitive advantages [9].

Additionally, Ang et al. [83] demonstrate that manufacturers may rely less on dual sourcing when disruption risks arise from secondary (tier 2) suppliers, especially if there is significant overlap in the supply chain. Political and economic factors also complicate supplier selection and sourcing strategies, as they can drive substantial reforms in supply chain structures [71,94]. Furthermore, the upfront costs associated with diversifying suppliers and the potential diseconomies of scale make investing in supplier diversification costly [95]. Dong et al. [96] find that higher fixed ordering costs can deter firms from relying on dual sourcing strategies.

Moreover, the landscape of supply networks is rapidly evolving due to globalization and significant technological advancements in the last decade. For instance, additive manufacturing is emerging as a viable dual-sourcing option for producing spare parts on demand, thereby reducing dependency on traditional suppliers [92].

Political uncertainties also play a crucial role in reshaping the global supply chain network. Recent geopolitical tensions, such as the China-U.S. trade tensions and the Russia-Ukraine conflict, have prompted countries to incentivize domestic production or realignment of supply chains toward allied nations, particularly in critical sectors like semiconductors and pharmaceuticals [11]. These incentives, along with the need to navigate complex political landscapes, add another layer of complexity to managing global supply chain resilience, involving multiple stakeholders including governments and industry groups.

In terms of sourcing optimization, deciding on order policies from multiple suppliers is technically challenging due to variations in lead times and prices [16,81]. These complexities require companies to carefully balance costs, supplier capabilities, and potential supply chain disruptions in their strategic planning.

Response phase. During a supply disruption, it is important to recognize that the disruption in any link of a supply chain can trigger a ripple effect, impacting downstream operations [3]. Many products require a large number of components, often resulting in supply chains that span 5–10 tiers with numerous suppliers at each tier [22]. Consequently, a company may face disruptions originating from tier-2 or even higher-tier suppliers, complicating the management of supply risks [83].

Real-world supply risks are often correlated and strategically timed, adding layers of complexity to supply chain management. For instance, labor strikes may be scheduled during peak demand periods or when inventories are low, maximizing the bargaining power of striking workers [9]. These intricately linked supply disruption scenarios pose significant challenges to implementing effective multiple sourcing strategies.

During the recent COVID-19 pandemic, for example, border closures aimed at controlling the virus spread led to severe shortages of raw materials, which in turn caused dramatic price increases for medicines and semiconductors. The scarcity affected not only industries relying on wood and steel but also those dependent on rubber and plastics, leading to widespread sourcing bottlenecks.[9] This created enormous uncertainty in the supply capacity, even for emergency or backup suppliers.

Moreover, the asymmetry of disruption information between companies and their suppliers adds another layer of difficulty. Firms often struggle to respond effectively to supply failures due to incomplete information about the extent and duration of disruptions [9]. For example, when Ericsson faced production issues due to a fire at a key component supplier, the uncertainty regarding the disruption's duration led to significant operational and financial setbacks, eventually causing the company to exit the cell phone market in 2001 after a staggering 2.34 billion loss.[10]

Recovery phase. After a supply disruption, employing multiple sourcing strategies can complicate the recovery process. While diversifying suppliers is generally beneficial for risk mitigation, it can also result in lower purchasing volumes from each supplier, which might hinder their motivation or ability to prioritize the recovery needs [90]. Additionally, each supplier might have different capabilities and timelines for recovery from disruptions, making it challenging for companies to synchronize recovery efforts or predict recovery timelines effectively [90].

Compounding these challenges, the dynamics within the supply chain network can frequently shift due to factors such as bankruptcies, layoffs, or other economic pressures, further complicating the maintenance of stable supplier relationships and making it even more difficult for firms to resume normal operations promptly.

3.1.2. Current research

We now review the existing works related to the supply-side strategies according to the three phases of the supply disruption as presented in Table 2.

Preparation phase. To motivate suppliers to disclose their supply information, Chaturvedi and Martínez-de-Albéniz [73] analyze a two-part payment auction, encouraging truth-telling about production costs and reliability through strategic payment timing—one before and one after delivery. This mechanism eliminates the need for the buyer to pay extra for information on suppliers' reliability when they know the production costs but not the reliability. Gao [74] also advocates using contracts to curb opportunistic behavior from suppliers in a dynamic context where an unreliable supplier's private state of production is vulnerable to random shocks and evolves over time. The author reveals that the optimal contract has a semi-stationary structure: a supply-state-dependent base-stock or (s, S) policy, leading an easy-to-implement, dynamic long-term revenue-sharing contract.

Advanced technologies like blockchain also play a crucial role in mitigating information asymmetry within the supply chain. Dong et al. [76] show that while blockchain-*diminished* visibility helps manufacturers make informed decisions, its benefits across the supply chain depend on the specific structural arrangements. Similarly, Song et al. [77] find that order-tracking information becomes particularly valuable in dual-sourcing decisions when supply lead times are highly uncertain, emphasizing the importance of timely and accurate information in managing supply disruptions.

Distribution-free approach is another effective tool for sourcing decisions amidst supply disruptions when distributional information about supply is limited [75]. Furthermore, Xiong et al. [88] employ a data-driven approach to construct uncertainty sets for solving dual sourcing problems in the presence of limited historical data about sourcing price and demand uncertainties.

The complexity of the supply chain itself presents additional challenges. Bimpikis et al. [78] describe how certain network structures can amplify shocks to production output. They find that in the absence of disruptive events, the resulting equilibrium networks take the form of a box, i.e., the number of firms with the same cost coefficient in each tier is the same, whereas more firms tend to enter upstream stages of the production process when disruption probabilities increase. To enhance monitoring and mitigate disruption risks, Charoenwong et al. [94] and Xu et al. [71] advocate for simplifying supply chain structures by reducing the overseas supplier base and increasing reshoring or local sourcing. Charoenwong et al. [94] provide empirical evidence that, in response to uncertainties in complex trade relationships, firms with significant domestic sales are inclined to decrease their reliance on foreign suppliers. Additionally, Xu et al. [71] argue that reshoring and local sourcing serve as proactive strategies to bolster supply chain resilience in the face of escalating geopolitical and economic uncertainties.

Federgruen and Yang [79] and Federgruen and Yang [80] use the newsvendor model to identify the optimal set of suppliers under supply disruption risks, aiming to minimize total procurement costs while satisfying uncertain demand at a specified probability level. In Federgruen and Yang [79], the exact analysis of the model is challenging due to the multiplicative uncertainty in shortfall probability, which follows a general distribution. To address this, the authors propose two approximations: an upper-bound approximation using the large-deviations technique, and an asymptotic approximation that applies the central limit theorem as the number of suppliers approaches infinity. Federgruen and Yang [80] modify the earlier model by assuming zero fixed costs and heterogeneous per-unit costs. They develop two variations: a service constraint model and a total cost model that incorporates a stock-out penalty. They demonstrate that the optimal cost value functions, given effective supply, are strictly convex and differentiable, allowing for the determination of a unique minimum.

After determining the supply base, deciding when and how much to order from two or more suppliers is critical to balancing inventory cost and service levels. This problem is complex and has been extensively explored in the literature. For a comprehensive overview, we recommend the recent surveys by Svoboda et al. [97] and Xin and Van Mieghem [21].

Notably, due to distinct lead times and prices from different suppliers, the form of the optimal policy for general multi-sourcing models remains largely unknown. Consequently, researchers have developed several effective heuristic policies to address this challenge. These include single and dual index policies [81], Tailored Base Surge (TBS) policies [64], and Capped Dual-Index Policies [98].

[9] https://www.jaegergroup.com/en/blog/raw-material-shortages-due-to-corona-how-manufacturing-companies-should-react/.

[10] https://covid-19.mitpress.mit.edu/pub/4138hanq/release/1.

More recently, there has been some progress in understanding the optimal policy form. Considering a dual sourcing system with endogenous stochastic lead times, Song et al. [16] characterize optimal ordering policies as consisting of a constant threshold and a switching curve dependent on outstanding orders. Additionally, Federgruen et al. [99] find that optimal procurement strategies for dual sourcing with general lead time combinations exhibit monotonicity and limited sensitivity properties. Song et al. [77] verify that the value function of the dual-sourcing inventory dynamic program is supermodular in the net inventory and the outstanding orders, and convex in the outstanding orders and the emergency inventory position.

Response phase. When responding to supply disruptions within a multi-sourcing system, it is common for studies to assume that supply disruption risks at different suppliers are independent. However, risks may actually be correlated among suppliers. Shan et al. [82] investigate a scenario where a retailer deals with competing suppliers who have correlated default risks. Interestingly, they find that the retailer might prefer a supply network where supply disruption risks are positively correlated, despite the loss of diversification benefits, because this increases competition among suppliers.

For more intricate supply chains with multi-tier supplier risks, Ang et al. [83] explore how manufacturers can provide contract terms to motivate Tier 1 suppliers to optimally source from Tier 2 suppliers in an asymmetric information setting. They demonstrate that with price and quantity contracts, manufacturers can encourage Tier 1 suppliers to engage in dual sourcing to mitigate supply disruption risks, albeit at a higher price.

Another critical focus for managers is determining how to allocate orders among suppliers to minimize the impacts of disruptions. Hu and Kostamis [84] use an approximation model that overlooks the possibility of simultaneous disruptions at multiple suppliers and find that the optimal order allocations are best ranked by the ratio of each unreliable suppliers cost advantage over a reliable one to their disruption probability. When ordering from one reliable and one unreliable supplier, the total order quantity and its allocation between the two are independent decisions. Considering simultaneous supply disruptions, Khojasteh-Ghamari [85] advocates for order splitting across suppliers from different regions to diversify risk.

Addressing raw material scarcity resulting from supply disruptions involves evaluating alternative materials and collaborative problem-solving. A survey by MIT and PriceWaterhouseCoopers reports that 48% of 209 respondents use some form of product substitution to mitigate supply risks [86]. Freeman et al. [86] develop a single-period stochastic linear program with a sample average approximation to calculate the manufacturer's expected profit, demonstrating through Monte Carlo experiments that substitution helps ensure sufficient capacity to convert orders into finished products. However, manufacturers often encounter significant challenges in developing alternatives and adjusting their product portfolios. For instance, case studies of disaster recoveries at Aisin Seiki and Riken Corporation reveal that temporary sourcing may not be feasible if specific design and manufacturing methods are required [100]. Alternatively, Saghafian and Van Oyen [101] suggest contracting with or establishing a flexible backup resource to insure the supply stream operationally against future disruptions. Moreover, Xue et al. [87] design option and order commitment contracts as emergency backups to mitigate the effects of price fluctuations in a volatile spot market when disruptions occur.

Xiong et al. [88] tackle dual sourcing challenges with limited historical data using a data-driven robust approach. They introduce a robust dual-sourcing rolling horizon formulation and construct an uncertainty set of random variables based on historical observations. Additionally, advancements in information technology, particularly those that expedite shipping options, can overcome these challenges [93]. Spieske and Birkel [14] highlight how Industry 4.0 technologies enhance risk transparency, supporting better sourcing decisions in the face of supply disruptions. Furthermore, using technologies like GPS, RFID, and blockchain, Song et al. [89] develop smart ordering and dynamic expediting policies that utilize real-time supply information. They show that two special cases of their general policy, Policy-M and Policy-E, can be efficiently evaluated using product-form solutions involving only marginal distributions of the state variable. Policy-M retains full sourcing flexibility and makes expediting decisions while ignoring upstream congestion. Policy-E only orders from the normal, farthest source and makes expediting decisions based on both upstream and downstream information. They demonstrate the relative advantage of policy-E and hence reveal the value of dynamic expediting.

Recovery phase. Jain et al. [90] provide extensive empirical evidence showing that, for faster recovery from disruptions, maintaining long-term relationships with a few selected suppliers is more beneficial than diversifying across more suppliers. As such, there is a downside to diversification when taking recovery into account. Similarly, Scholten and Schilder [13] find that coordination among stakeholders significantly enhances the speed of recovery, highlighting the importance of collaborative relationships in resilient supply chain management.

From a different perspective, Fujimoto and Park [91] analyze how manufacturers manage and process the flow of value-carrying design information to customers. They argue that a supply chain disruption can be viewed as an interruption in the flow of this critical design information. To address this, they propose methods for restoring essential design information either at the site of destruction or at alternative production lines, thereby facilitating the recovery of the damaged supply chain.

In dynamic sourcing environments, dual sourcing models are increasingly integrated with emerging technologies to enhance supply chain flexibility and responsiveness. Song and Zhang [92] investigate the application of 3D printing technology within a spare parts supply chain, where parts are either sourced traditionally from a distant supplier or printed on-demand locally using a 3D printer with limited capacity. They find that 3D printing offers a viable solution for producing parts on demand, particularly when the printing times are short. However, they also highlight a crucial consideration: because multiple parts may compete for the same finite printing capacity, it is vital to maintain a low utilization rate of the printer to avoid excessive waiting times.

Looking forward, Hong et al. [11] recommend focusing on dynamic rules for modeling risk propagation and developing mitigation strategies. They advocate for more attention to network reconstruction post-disruption and incorporating interactive behaviors of stakeholders into supply chain models. These approaches aim to adapt more effectively to the evolving supply chain environment and enhance the overall resilience.

3.2. Inventory reserves and flexible sourcing contracts

3.2.1. Relationship with the sourcing strategy

As previously discussed, sourcing from multiple suppliers alone may not quickly and completely halt the propagation of supply disruptions downstream. To enhance the effectiveness of multiple sourcing in mitigating supply disruption risks, strategies such as inventory reserves and flexible sourcing contracts are crucial. For example, many manufacturers maintain stockpiles of key components as a hedge against supply disruptions [31]. Furthermore, flexible sourcing contracts can act as both incentives, such as advance payment contracts that encourage suppliers to invest in proactive risk mitigation [76], and mechanisms to ensure truthful reporting of supplier reliability, thus optimizing the supply network for profit and resilience [9].

Inventory reserves: In contrast to the immediate availability of inventory, sourcing from multiple suppliers can be time-consuming due to the lead times associated with placing additional orders with backup or emergency suppliers [15]. To counteract these delays, companies may produce or order in advance of actual demand and hold products in inventory, thus shortening the response time to supply disruptions [15]. Lücker and Seifert [102] numerically demonstrate that even with a dual sourcing strategy covering 100% of demand, inventory reserves remain essential for maintaining high resilience levels. They also find that the quantity of inventory reserves decreases with disruption time, but only when the disruption duration is already sufficiently long.

Flexible sourcing contracts: Building contractual relationships between buyers and their suppliers is another vital strategy for reducing operational and disruptive supply risks [9]. Huawei, for example, enhances supplier relationships through regular training and coaching to mitigate risks and increase efficiency, and by establishing contractual backup supply networks that guarantee the supply of core chips.[11] Sourcing contracts, such as incentive contracts (e.g., investment subsidies) and capacity reservation contracts (also known as option contracts), are designed to minimize supply disruption risks by enabling choices among multiple unreliable suppliers and facilitating the swift arrival of emergency sourcing orders following a disruption [9,101]. The specific sourcing policies and supplier selection and ordering decisions are heavily influenced by the type of sourcing contracts [9], indicating that there is no one-size-fits-all rule for flexible sourcing contracts to achieve a mutually beneficial outcome in supporting multiple sourcing strategies.

3.2.2. Current research

Scholars have extensively studied the roles of inventory reserves and flexible sourcing contracts in complementing multiple sourcing strategies to mitigate supply-side disruption risks.

Inventory reserve approach. Inventory reserves are critical for fulfilling customer demand during supply chain disruptions [103]. Ergun et al. [15] point out that the fast-but-finite nature of inventory reserves makes them ideal complements to other strategies, helping to mitigate the mismatch between demand and supply. Lücker and Seifert [102] explore the combined effect of multiple sourcing and inventory reserves in a pharmaceutical supply chain facing deterministic demand and supply disruption risk. Their numerical results indicate that in a dual sourcing system, maintaining higher inventory reserves is increasingly beneficial as the likelihood or duration of disruptions grows. Furthermore, Rozhkov et al. [104] demonstrate that increasing stockpiles at upstream suppliers also enhances disruption mitigation and service levels during pandemics. Craig et al. [105] analyze the positive correlation between a suppliers inventory service level and the demand it receives from retailers, showing that a supplier's inventory reserves can significantly reduce a buyer's supply uncertainty.

Flexible sourcing contract approach. Flexible sourcing contracts are essential for ensuring reliable supplies. Handfield et al. [106] discuss how companies like Honda, Intel, Toyota, and BMW invest heavily in enhancing their suppliers' reliability and restoring their capacities after disruptions. Kim et al. [107] investigate performance-based contracts that tie compensation to agreed-upon performance metrics, which can effectively address system disruptions. Jia and Zhao [108] design contracts that not only improve supply reliability but also address quality-related disruptions in the pharmaceutical supply chain by adjusting purchase prices and compensation terms. Dong et al. [76] examine advance payment and wholesale contracts designed to optimize sourcing in multi-tier supply chains to reduce disruption risks. Gao [74] develops a dynamic long-term revenue-sharing contract that encourages suppliers to disclose true risk information, facilitating better supply risk management. Additionally, Xue et al. [87] highlight how option and order commitment contracts can allocate supply disruption risks either to the supplier or the buyer, leading to a more effective risk management.

3.3. The gap between existing research and practices

Existing literature has identified key benefits of multiple sourcing and its supporting strategies—such as inventory reserves and flexible sourcing contracts—in mitigating supply-side disruptions. These benefits include reduced emergency costs [87], shortened supply lead times [16], enhanced supply reliability [75], and improved flexibility [101]. Despite these advancements, significant gaps remain between current research and the practical implementation of these strategies within dynamic supply disruption contexts.

3.3.1. New features of supply-side practices

Recent years have seen supply chains becoming increasingly globalized and complex, often spanning multiple countries and multi-tier sectors. This complexity heightens their vulnerability to disruptions [72]. For example, localized lockdowns in China during the COVID-19 pandemic had cascading effects on global multinationals like Apple, Tesla, General Electric, Amazon, and Adidas, all warning of potential disruptions to their operations.[12] Additionally, geopolitical instabilities such as the U.S.-China trade conflict and the Russia-Ukraine war pose substantial risks to supply stability [4]. Addressing these challenges requires building resilience at broader system levels, considering the complexity of partnerships in an interconnected supply network.

Technological advancements are also reshaping supply processes. Innovations like drone deliveries by Amazon and Walmart, and Audis use of 3D printing for tail light covers, represent structural shifts in supply chain operations [4]. While digital technologies enable real-time, data-driven decision-making, issues with data quality can adversely affect these decisions, increasing coordination complexity across supply channels [5]. Furthermore, data security concerns introduce additional disruption risks, challenging the reliability of data-driven models.

3.3.2. The gap in supply-side strategies

Practical implementation of multiple sourcing strategies faces numerous challenges. Suppliers varying backgrounds and operational scales complicate the adoption of uniform sourcing policies. Existing research often focuses on routine scenarios with predictable variables like yield or lead times [9], but does not adequately address extreme cases such as suppliers engaging in unethical practices. This gap highlights the need for more comprehensive strategies that account for potential negative impacts, including increased risk of supplier violations.

Additionally, the complexity of managing partnerships for manufacturers relying on thousands of components poses significant barriers to implementing effective multiple sourcing. While heuristic policies proposed by researchers such as Allon and Van Mieghem [64], Hua et al. [81], Song et al. [16], and Sun and Van Mieghem [98] aim to address these complexities, the roles of various stakeholders—government, investors, NGOs, and media—in influencing supply disruptions remain underexplored.

Digital technologies enable multi-tier suppliers, manufacturers, logistics providers, and other stakeholders to interact with each other on a platform [4], creating new supply interaction structures and sourcing processes. These evolving dynamics necessitate further research into how digital platforms can support or complicate multiple sourcing strategies. Emerging issues such as data licensing, data security, and the management of virtual relationships also demand closer examination.

Supporting strategies such as inventory reserves and flexible sourcing contracts are increasingly challenged by complex political factors that impact supply chain configurations. Recent developement s, such as alliance relationships, trade policies, international environmental and labor regulations, and political dynamics, play greater roles in shaping supply chains.

For example, the China-U.S. trade war has posed significant risks for companies like Huawei, threatening the continuity of input flows for 5G network equipment and smartphones once existing inventories are depleted.[13] This situation underscores the need for multinational firms to dynamically adjust inventory reserves, considering special regulations

[11] https://www.huawei.com/en/sustainability/sustainability-report.

[12] https://www.ft.com/content/9318db50-e0c3-4a27-9230-55ff59bcc46e.

[13] https://arstechnica.com/gadgets/2020/08/chip-and-phone-supply-chain-shaken-as-huawei-faces-mortal-threat/.

and the shifting political landscape, such as ally sourcing and relationship restoration. This dynamic setting of inventory reserves in response to political changes is an emerging area of interest.

Moreover, there is a growing body of research focusing on how contractual relationships can mitigate operational supply risks [9]. However, if a supplier fails to provide essential raw materials following a disruption, the sourcing relationship may be suspended, and firms might need to develop new relationships. This transition can be particularly challenging for firms with dominant positions in their industries, as they might find flexible contracts less effective [109].

Additionally, while data analytics is commonly used for demand prediction, the application of computing power and AI to support operational decisions on the supply side is less developed. This discrepancy highlights a significant gap between research and practice, necessitating further exploration into how dynamic and intelligent supply relationships can enhance the effectiveness of inventory reserves and flexible sourcing contracts in combating supply disruption risks.

4. Future research opportunities

Significant progress has been made in addressing the challenges outlined in Table 1 and Table 2. However, as discussed in Sections 2.3 and 3.3, considerable gaps remain between current research and practical implementation, necessitating further investigation. Additionally, the supply chain landscape has undergone unprecedented changes during and after the COVID-19 pandemic, introducing new complexities such as increased frequency of unforeseen disasters, evolving demand behaviors, shifting cross-border relationships, and the adoption of data-intensive policies. These transformations are prompting a reformation of supply chain networks, as evidenced by recent scholarly work [43,46]. As a result, new issues and challenges have emerged, particularly in the realm of inventory management, affecting both the supply and demand sides.

4.1. Research directions for demand-side strategies

As highlighted by the gap between current research and practical needs, it is crucial—and increasingly urgent—for researchers to establish a consensus on identifying optimal resilience levels in the face of "unknown unknowns." Additionally, there is a pressing need to develop hybrid human-AI models that can effectively predict and adapt to rapidly changing consumer behaviors.

Exploiting an approach for setting resilience targets. Constructing robust methods for measuring resilience is fundamental to defining and optimizing inventory-related decisions. However, with unknown unknowns, determining the appropriate level of resilience is particularly challenging due to the unpredictable nature of black swan events and the absence of known distribution functions. Although Ergun et al. [15] provide a thorough discussion on quantifying the appropriate level of supply chain resilience and utilize the basic newsvendor model to balance shortage costs against protection costs, their approach has limitations. Specifically, their model does not adequately address the difficulty in obtaining accurate demand distribution functions or in accurately defining the costs associated with shortages and overages.

Furthermore, robust optimization methods, commonly employed to address parameter and distributional uncertainty, also present challenges. Establishing a reliable uncertainty set can be problematic due to limited understanding of potential black swan events. Additionally, the real-world application of inventory pre-positioning systems introduces greater complexity. Factors such as the intercorrelation of multiple products, budget constraints, perishability of inventory, the reverse logistics of reusable resources, disposal of remaining items, and public interventions further complicate the resilience measurement and optimization process [15,44]. Therefore, unforeseeable demand surges and inventory system complexities would lead to a resilience measurement model that may require new tools from multiple disciplines to analyze.

Developing human-AI prediction models for demand behaviors. Abnormal events often lead to deviations from typical consumer behavior, such as the panic buying or hoarding observed during the COVID-19 pandemic [15]. Similarly, subjective emotions can influence decision-makers, leading to inefficiencies such as the over-distribution of masks by the Red Cross Society in Hubei, which hindered the response to COVID-19.[14]

Understanding these demand behaviors is crucial for formulating more realistic mathematical programming problems and addressing challenges associated with calculating the shortage costs of surging demands in pre-positioning-related policies. However, during turbulent times, firms often lack perfect information about the rapidly changing consumer expectations or demand surges, making it difficult to use traditional models.

Robust optimization is one approach to handle uncertainties caused by limited information. More recently, with advances in AI and machine learning, data-driven predictive models have become popular for anticipating demand based on historical data. However, for unprecedented events ("unknown unknowns") with little or no historical data, leveraging AI to predict the likelihood of demand surges from big data becomes challenging. AI excels in processing and analyzing large datasets and could potentially inform dynamic capacity or contractual adjustments that depend on real-time demand and resource flow data.

Nevertheless, the integration of AI predictions in supply chain management must consider human factors. Humans often have "private" information not accessible to algorithms [110] and may override AI recommendations [111]. This highlights the need for effective collaboration between smart AI algorithms and human judgment.

Therefore, exploring how AI prediction models can enhance the management of demand-side disruptions, and determining the best methods for integrating these models with human insights are critical areas for future research. This exploration should focus on developing hybrid systems that effectively combine human strategic thinking and AI's analytical power to improve inventory pre-positioning and other supportive strategies.

4.2. Research directions for supply-side strategies

Similarly, on supply side, we suggest that future research directions need more consideration of interactions of many stakeholders and smart data-driven forces to optimize supply management under continually dynamic and digital-developed environment.

Incorporating more stakeholders' behavior in disruption contexts. The wave of supply chain disruptions, fueled by events such as the COVID-19 pandemic and the China-U.S. trade war, has made global sourcing shift towards ally-sourcing or friend-sourcing. This trend illustrates the increasing impact of government policies and geopolitical issues on supply chain performance [71]. Charoenwong et al. [94] empirically demonstrate that as uncertainty in U.S. trade policy grows, firms with high domestic revenue shares tend to reduce their number of foreign suppliers, while those with significant foreign sales might increase them. Considering that ally-sourcing reduces geopolitical conflict risks, this deglobalization scenario poses several new research questions: What are the differences in supply disruption risk propagation between within-region and across-region supply networks? How do national powers influence flexible sourcing contracts and supplier shifts? How can optimal resilience levels be adjusted to account for political relationships?

Furthermore, local or friendly sourcing enables buyers to develop deeper, more meaningful relationships with their suppliers and exert

[14] https://news.cgtn.com/news/2020-02-01/Hubei-Red-Cross-faces-scrutiny-over-whereabouts-of-donations-NJGbCJxb9u/index.html.

greater control,[15] potentially enhancing stakeholder interactions including cultural exchanges, R&D incentives, and compliance with sustainability and ethics standards [11]. Future research should explore how these enriched buyer-supplier relationships and enhanced stakeholder interactions influence supply disruption risks and affect the effectiveness of multiple sourcing and its supporting strategies.

Embedding smart data-driven forces into conceptual models. Designing and operating sourcing contracts manually can be challenging due to the dynamic status and irrational behaviors of stakeholders within the supply chain. Utilizing data-driven technologies such as blockchain to construct smart contracts between buyers and suppliers holds promise for enhancing future flexible coordination strategies. The availability of large-scale, dynamic datasets from systems like ERP and blockchain enables the development of data-driven models that support the creation of supply resilience strategies using real-time supply information [112].

This shift from model-driven to data-driven approaches offers greater flexibility and alignment with practical evidence. Such models can aid in evaluating complex supply-side disruption risks involving multiple supplier interactions, enhancing supply resilience assessment, and optimizing sourcing strategies. However, challenges remain in effectively utilizing real-time supply information during disruptive events, as companies may be overwhelmed by requests from logistics providers and customers [89]. Furthermore, data-intensive inventory models risk data contamination, which can lead to inaccurate operational and management parameter estimations. While existing studies emphasize robust inventory models and heuristic solutions, consensus on model validation is lacking. Liu et al. [113] propose a globalized distributionally robust counterpart that ensures no constraint violation for distributions within the ambiguity set and accounts for potential deviations outside this set. More research is needed to integrate data-driven approaches with smart policies effectively. Additionally, designing trust mechanisms to prevent data contamination and developing smart policies for multi-source inventory systems remain critical areas for future research, especially as the impacts of digital technology on supply chain resilience continue to evolve [14,46].

These considerations highlight the need for a robust dialogue on integrating advanced technologies and AI with traditional supply chain practices to address the complexities of modern supply disruptions effectively.

5. Conclusion

The COVID-19 pandemic has significantly disrupted supply chain operations, compelling both practitioners and researchers to devise and refine inventory-related strategies that bolster supply chain resilience. This paper has reviewed various strategies, pinpointed their implementation challenges, and proposed future research directions. From our discussions, we have distilled several critical insights.

5.1. Strategic insights

Pre-positioning and multiple sourcing: Pre-positioning is effective for rapid response to demand shortages by immediately deploying prestored relief items during a demand surge. However, it requires significant coordination among various stakeholders to maintain a continuous supply. Multiple sourcing, in contrast, ensures a stable supply when certain suppliers fail to deliver, and like pre-positioning, it benefits greatly from stakeholder coordination. The integration of pre-positioning with multiple sourcing can significantly enhance overall supply chain resilience.

Supporting strategies: While powerful, both pre-positioning and multiple sourcing have limitations that can be mitigated through supporting strategies. For instance, the costly nature of maintaining large inventory reserves can be offset by strategies like capacity reservation, which provides buffer against demand surges. Similarly, inventory reserves can help mitigate the ripple effects of supply disruptions. Strategic flexibility, such as the kind suggested by Tang and Tomlin [114] and Tomlin [115], where even a small degree of flexibility can significantly reduce disruption impacts, is crucial. Investments in flexible supply contracts can elevate resilience levels at a relatively low cost. However, strategies requiring longer lead times, such as reactive capacity and coordination supply contracts, need to be employed judiciously to maximize their effectiveness.

Integrating flexibility and redundancy: A mix of inventory-related mitigation strategies with elements of redundancy and flexibility forms a cornerstone of a cost-effective resilience strategy. This approach not only addresses the immediate impacts of disruptions but also prepares the supply chain for future uncertainties.

Role of new technologies: Emerging data-driven technologies are redefining supply chain resilience. The adoption of digital supply chain solutions, Industry 4.0 technologies, and blockchain enhances resilience by reducing reliance on human labor, improving demand forecast accuracy through big data, and ensuring more reliable, transparent supply processes.

5.2. Looking ahead

In the post-pandemic world, the supply chain landscape faces new vulnerabilities due to changes in consumer behavior and prolonged supply disruptions. Pre-positioning and multiple sourcing remain pivotal in mitigating these risks. Complementary strategies that enhance these core approaches include enhancing supplier networks, adopting flexible production capabilities, optimizing corporate financing, and refining governance mechanisms. Additionally, broader aspects such as the production network, supply chain finance, and the structure of supply networks play instrumental roles in fostering supply chain resilience.

Ultimately, inventory-related strategies are crucial in crafting a more resilient supply chain capable of withstanding and adapting to the dynamic global market landscape. Further research should continue to explore and refine these strategies, ensuring they evolve in tandem with emerging global challenges and technological advancements.

Declaration of competing interest

The authors declare that they have no conflicts of interest in this work.

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