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Flying through uncertainty: Air transportation's impact on supply chain resilience and inventory efficiency☆

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ABSTRACT

The COVID-19 pandemic revealed critical vulnerabilities in global supply chains, highlighting the need for innovative approaches to enhance resilience and operational efficiency. This study addresses the dual challenge of managing global supply chain risks and disruptions while improving inventory efficiency. Specifically, it investigates how transportation modal flexibility—the strategic use of air versus ocean freight—mitigates these challenges. Leveraging industry-level data from U.S. manufacturing sectors spanning 2003 to 2021, this research demonstrates how firms utilized air transport to counteract disruptions, maintain operational continuity, and sustain inventory performance. Findings reveal that while global supply chain risks and disruptions adversely affect inventory efficiency, unique features of air transport offer critical mitigation strategies. This study not only contributes to the discourse on supply chain risk management by emphasizing transportation modal flexibility but also provides actionable insights for firms aiming to adapt to crises and enhance supply chain resilience.

1. Introduction

The research agenda of global supply chain management has gained traction largely due to its competitive advantages for firms, such as cost reduction, enhanced access to production resources and consumer markets, exposure to advanced research and development (R&D), and improved service levels (Bozarth & McDermott, 1998; Nassimbeni & Sartor, 2006; Rodríguez & Nieto, 2016). However, global supply chains carry greater risks than domestic ones due to the numerous interconnected global links that create a complex network of firms, and are more susceptible to disruptions, such as unpredictable and adverse events including natural disasters, supply–demand mismatches, and shipping failures (Christopher & Holweg, 2017; Ketokivi et al., 2017; Manuj & Mentzer, 2008a, 2008; Jain et al., 2014; Lorentz et al., 2015; Tang & Tomlin, 2008). The heightened vulnerabilities and risks associated with global supply chains have led recent studies to focus on global supply chain risk management strategies to reduce risks, mitigate disruptions, and build resilience.

The COVID-19 pandemic exposed the fragility of global supply chains, highlighting the susceptibility of these complex networks to major disruptions (Gurbuz et al., 2023; Kulpa et al., 2024). As economies worldwide came to a halt due to lockdowns and travel restrictions, supply chains faced unprecedented challenges, including severe supply interruptions, port congestion, and abrupt shifts in consumer demand. These disruptions not only led to supply shortages and lost sales but also significantly impacted inventory

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efficiency. The interconnected nature of global supply chains magnified these challenges, especially for manufacturing industries, underscoring the need for risk mitigation strategies and enhanced resilience.

In response to these challenges, firms may consider various risk mitigation strategies, including risk avoidance, postponement, speculation, hedging, control, risk transfer and sharing, security, and flexibility (Cho et al., 2017; Ke et al., 2022; Shekarian et al., 2020; Manhart et al., 2020). This study focuses on the role of flexibility in global supply chain risk mitigation.

Although substantial research has examined various dimensions of global supply chain flexibility (Bernabei et al., 2022; Kochan & Nowicki, 2018; Montoya-Torres et al., 2023; Heydari et al., 2020; Ogunranti et al., 2021; Pellegrino et al., 2024), the role of transportation modal flexibility remains underexplored, leading to an underestimation of its impact on global supply chain performance. Previous studies indicate that firms facing demand uncertainty increasingly rely on air freight, which enhances global supply chain performance (Bertazzi et al., 2021; Ke et al., 2015; Kulpa et al., 2024; Park et al., 2018; Sreedevi & Saranga, 2017). However, few studies provide empirical support for air transport, particularly its capacity for more frequent, faster shipments in smaller batch sizes compared to ocean transport. Thus, existing debates and gaps in the literature necessitate conceptual and empirical investigation of the impact of transportation modal flexibility—particularly shifting from ocean to air freight—on firms' inventory performance during major global supply chain disruptions. This study seeks to address this gap.

Practically, port congestion during the COVID-19 pandemic incentivized firms with transportation modal flexibility to shift from ocean to air transportation due to (1) potential inventory shortages and lost sales and (2) a reduced gap between air and ocean shipping rates. As depicted in Fig. 1, the time required for a vessel to secure a berth at the Port of Los Angeles reached 25 days in November 2021, 20 days longer than the pre-pandemic average (Ke et al., 2023). This delay negatively impacted various manufacturing industries, including electronics, furniture, and clothing. For instance, Adidas reported shipping delays due to port congestion at the Ports of Los Angeles and Long Beach, which hindered timely product delivery to retailers, leading to inventory shortages and lost sales (Adidas, 2022). Meanwhile, port congestion significantly impacted shipping rates during the pandemic. Fig. 2 presents the ocean and air shipping rate index from 2013 to 2023. In August 2021, ocean shipping rates surged by 170% year-over-year, while air shipping rates rose by 60 % during the same period. Fig. 3 compares air cargo's chargeable weight rate per kilogram versus container shipping (FreightWaves, 2021). Before the pandemic, air cargo transportation typically cost 13 to 15 times more than ocean freight, but this price differential narrowed to just three to five times more by the second half of 2021.

Firms that shifted from ocean to air transportation reportedly mitigated the impact of global supply chain risks and disruptions during the COVID-19 pandemic. For example, during the COVID-19 pandemic, Amazon significantly increased its reliance on air freight to meet the surge in online shopping and address supply chain disruptions. The company expanded its daily flight operations from 85 flights in April 2020 to 133 flights in August 2020, marking a 56% increase (FOX Business, 2020). These business practices during the pandemic emphasize the relevance of this study and highlight the need for insights to build more resilient and sustainable supply chains through transportation modal flexibility.

Therefore, drawing on a dataset comprising 1,546 industry-year observations across 85 manufacturing industries from 2003 to 2021—including both pre-pandemic and pandemic periods—our empirical analysis aims to answer the following questions:

1. How does firms' exposure to global supply chain risks impact their inventory performance?

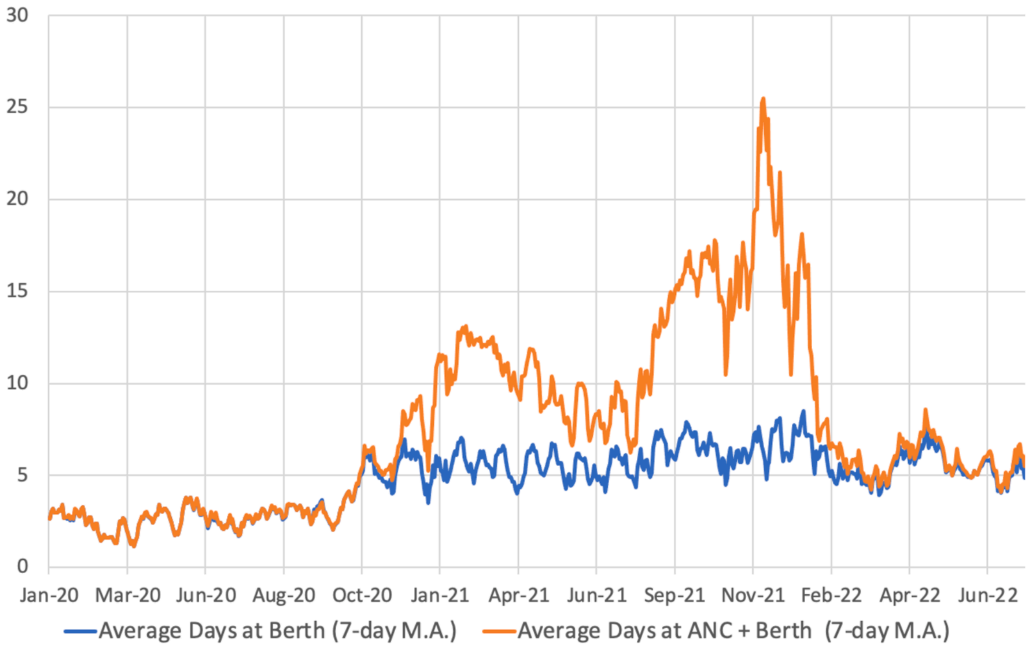

Fig. 1. Average Days at Berth and Anchored at the Port of Los Angeles.

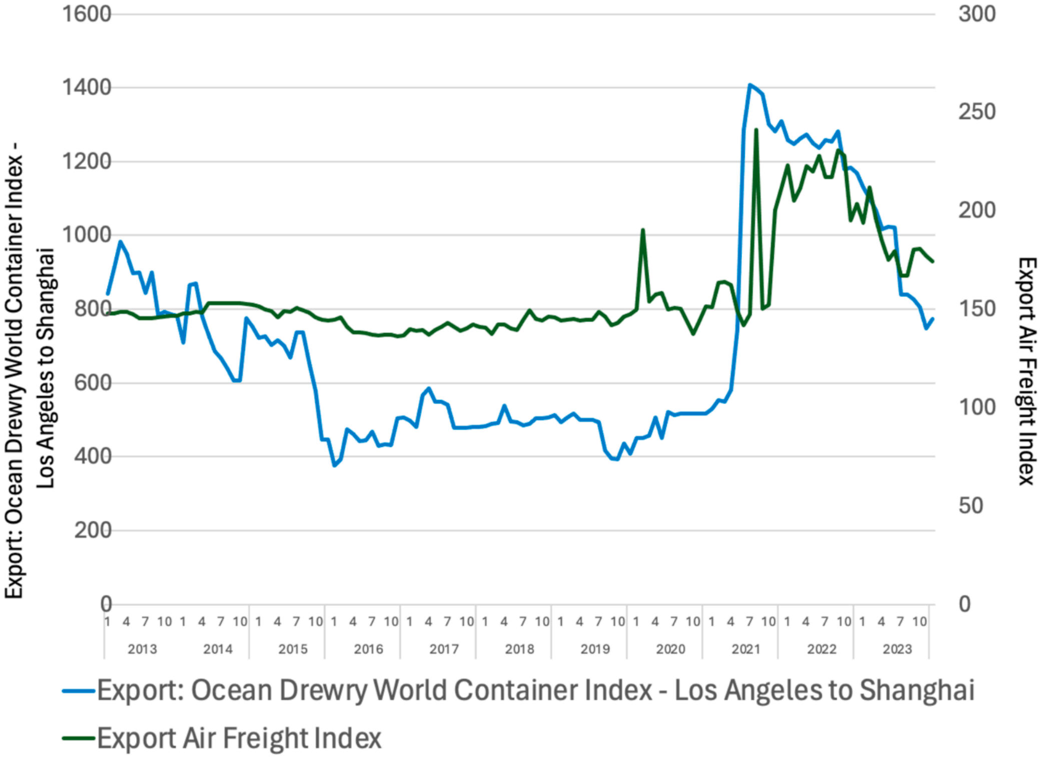

Fig. 2. Trends of Ocean and Air Shipping Rates during 2013–2023.

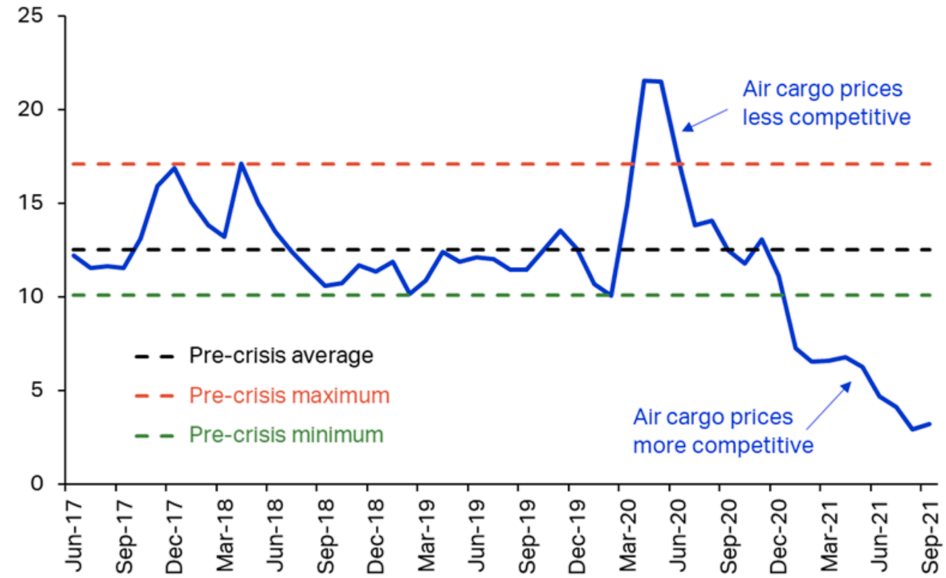

Fig. 3. Ratio of Chargeable Weight Rate per Kilogram for Air Cargo and Container.

2. How do global supply chain disruptions impact firms' inventory performance?
3. Does the transportation modal flexibility (increased use of air transport) mitigate the impact of global supply chain risks and disruptions on firms' inventory performance?

This study offers several significant contributions to the existing body of research. First, it advances the global supply chain risk management literature by underscoring the pivotal role of transportation modal flexibility in mitigating disruptions and enhancing resilience (Jain, 2018; Fan et al., 2018; Shekarian et al., 2020; Park et al., 2018; Sreedevi and Saranga, 2017; Kulpa et al., 2024). While prior studies have predominantly focused on strategies such as supplier diversification and operational flexibility, this research highlights the importance of transportation modal switching, particularly to air transportation, in addressing supply chain risks and improving inventory efficiency under dynamic conditions. Second, this study addresses a notable gap in the literature on transportation mode flexibility, where empirical support is limited and ambiguous. Finally, our study contributes to the growing body of research on reshoring (Cheng et al., 2024; McLaughlin & Peterson, 2023; Pal et al., 2018; Pedroletti & Ciabuschi, 2023), a trend increasingly adopted by U.S. manufacturers as a response to supply chain risks, including rising labor costs, logistical bottlenecks, and geopolitical uncertainties.

From a practical perspective, the findings offer actionable strategies for supply chain managers. By leveraging transportation modal flexibility, firms can adapt swiftly to disruptions, whether from global crises, reshoring transitions, or unexpected demand spikes. This adaptability allows businesses to balance cost efficiency and resilience, maintaining continuity and avoiding costly delays. These insights are particularly valuable for firms navigating the logistical challenges posed by reshoring and evolving global supply chain conditions.

The remainder of this paper is organized as follows: Section 2 and 3 summarize global supply chain risk literature and present the development of hypotheses, respectively. Section 4 outlines the data collection process and research methodology. Section 5 provides data descriptive information and presents the regression results. Section 6 provides an ad hoc analysis and discusses managerial implications. Finally, Section 7 concludes with a summary of theoretical and managerial contributions, research limitations, and directions for future research.

2. Literature review

The proposed research question explores risk mitigation strategies emphasizing flexibility, specifically increased use of air transportation mode, from the global supply chain perspective. It draws upon relevant literature that focuses on global supply chain, risk mitigation strategies (Christopher & Holweg, 2017; Cho et al., 2017; Ke et al., 2022), transportation flexibility (Jain, 2018; Shekarian et al., 2020; Sreedevi & Saranga, 2017; Kulpa et al., 2024), and inventory performance (Ak & Patatoukas, 2016; Miller & Peters, 2024; Jain et al., 2014). A summary of recent and relevant literature follows.

2.1. Global supply chain

2.1.1. Competitive advantage

An extensive body of literature continuously underscores the competitive advantages associated with globally extended supply chains (Trent & Monczka, 2003; Nassimbeni & Sartor, 2006; Mihalache et al., 2012; Rodríguez & Nieto, 2016). Since the 1980s, as emerging markets rapidly grew, researchers have emphasized the benefits that firms can achieve by organizing business activities across borders to leverage unique and specialized resources available in different countries (Carter & Narasimhan, 1996; Fayerweather, 1982; Ferdows, 1997; Kogut, 1984). Firms operating globally benefit from (1) cost-effectiveness achieved through economies of scale, (2) access to competitive resources, and (3) responsiveness to market changes through flexibility within an integrated network (Kogut, 1984). Lower labor costs and other operational savings in countries with reduced overhead (e.g., utilities and land) help yield cheaper parts and materials within the global supply chain network (Trent & Monczka, 2003). While cost saving is recognized as one of the most compelling motivators for adopting global supply chains (Nassimbeni & Sartor, 2006), exposing companies to new trends, more unique suppliers, and access to skilled labor including offshoring R&D activities can enhance firm performance as well (Mihalache et al., 2012; Rodríguez & Nieto, 2016).

2.1.2. Inherent risk and disruption

Despite the considerable benefits aforementioned, global supply chains carry greater risks and experience more disruptions than domestic supply chains due to the interconnected nature of heterogenous and unsynchronized transboundary networks (Christopher & Holweg, 2017; Ketokivi et al., 2017; Manuj & Mentzer, 2008a, 2008b). Accordingly, a notable shift of focus from advantages to potential disadvantages associated with global supply chains is observed in literature (Stanczyk et al., 2017). Empirical studies showed that extensive and cross-border structures lead to longer transit times and increased complexity, which can diminish operational efficiency and increase exposure to unexpected disruptions (Han et al., 2008; Ke et al., 2022). These disruptions, including environmental, socioeconomic, regulatory, network, and political risks, are inescapably faced by firms managing international partnerships (Handfield et al., 2020). Additionally, global supply chains often lack visibility, involve longer and more steps in transit, and are more prone to negative performance in business (Cho et al., 2017; Gurbuz et al., 2023; Manhart et al., 2020). Ketokivi et al. (2017) argue that global supply chain design, a geographic decision at its core, critically impacts time-based competition, a factor often overlooked by managers. Golini and Kalchschmidt (2015) found that firms sourcing more from global suppliers tend to maintain higher inventory levels. Similarly, fluctuating demand adds further complexity, often resulting in lost sales and customers (Jabbarzadeh et al., 2016). Excessive buffer inventory, meant to absorb disruptions, has been criticized for concealing quality failures and inefficiencies in the supply chain (Scheibe and Blackhurst, 2017), highlighting risks and disruptions inherently embedded in lengthened supply chain but often hidden by extra inventory.

2.2. Risk mitigation strategies in global supply chain

Given the inevitable risks of global supply chains, researchers explore various risk mitigation strategies that enable firms to prevent, respond to, and manage a range of risks that could disrupt their operations (Christopher & Holweg, 2017; Kochan & Nowicki, 2018; Montoya-Torres et al., 2023). Common strategies include diversification and associated flexibility in multiple areas (e.g., production, sourcing, and delivery) (Bernabei et al., 2022; Sreedevi & Saranga, 2017). For production, volume flexibility enables firms to shift production across facilities in different countries in response to changes in market conditions or operational constraints (Heydari et al., 2020). Cho et al. (2017) showed that the geographical spread of a manufacturer's production bases, often reflected in foreign investments, increases inventory levels during stable periods while providing resilience during crises, resulting in a significant alleviation of the adverse impact of supply chain risks. Sourcing flexibility also helps mitigate supplier dependency risks, as firms can select from a diverse supplier base to maintain stable supply (Sreedevi and Saranga, 2017). Flexibility in sourcing contracting allows firms to share or absorb price volatility with suppliers, stabilizing costs (Ogunranti et al., 2021). The critical role of flexibility in sourcing is also supported by the Real Option theory as it enables firms to switch options among suppliers across countries and respond to risks associated with foreign exchange uncertainties (Pellegrino et al., 2024). In terms of delivery, flexibility among shipping markets is discussed, entailing procuring transportation options from the spot market carriers or the Safety Net carriers, a network of carriers (Pellegrino et al., 2021). Similarly, the most effective recycling channel strategy for the remanufacturer is argued to collaborate with both traditional recyclers and smart recyclers (Wang et al., 2023b). Additionally, diversification in demand across customer market countries enhances resilience, especially during global disruptions, by allowing firms to balance customer concentration and increase inventory efficiency (Ke et al., 2022). All of these studies position various flexibility measures as a critical enabler of global supply chain risk mitigations, offering scalable solutions for businesses facing mismatches between supply and demand.

2.3. Transportation flexibility

Transportation flexibility is a multi-faceted concept and covers various research streams that focus on adaptability in logistics (Naim et al., 2006; Tang & Tomlin, 2008). One stream aims at proposing optimum solutions for logistics service through minimized cost, emission, and resource use. Popular themes include vehicle routing and scheduling problems. For example, the application of heuristic algorithms can improve cost-effectiveness and degree of synchronization by enabling dynamic adjustments to time-dependent constraints and service windows (Wang et al., 2020). Further studies include both dynamic routing and resource-sharing strategies to enhance efficiency and operational responsiveness (Wang et al., 2024a,b). Using numerical analysis, these studies continuously underscore the importance of flexibility by collaboratively sharing transportation resources across multiple depots or centers.

Transportation modal flexibility stands out as an effective approach for adapting to changing market conditions among the risk mitigation strategies in the literature. It enables firms to select among transportation modes, thereby strengthening their ability to manage supply chain risks effectively (Ishfaq, 2012; Tang & Tomlin, 2008). Quantitative studies using numerical analysis allow researchers to significantly contribute to the literature by identifying optimal transportation modes under specific circumstances. Through numerical analysis, Bertazzi et al. (2021) investigate the flexibility of transportation modes in international shipping. Given the shipment frequencies and lead times set in the study, the authors identified optimal scenarios that minimize costs, recommending a strategic combination of full-container road transport and less-than-container load (LCL) or air freight shipments.

Notably, numerical studies have begun incorporating a supply chain risk perspective into this transportation mode flexibility literature. For example, adjusting speed by changing transportation modes (e.g., low-speed mode vs. high-speed mode) may help increase flexibility, which arises from the inherent time buffers present in slower transportation modes can be leveraged by expediting transport activities depending on product stages (raw material, semi-finished product, and final product) (Fan et al., 2017). Similarly,

Table 1
Summary of Selected Recent Studies on Supply Chain Risk Mitigation using Transportation Mode Flexibility.

Author	Year	Risk Types	Mitigation Measures	Methodology	Data
Sreedevi and Saranga	2017	supply risk, manufacturing process risk, delivery risk	flexible logistics / transportation (multi-modal, −carrier, −route)	structural equation model (SEM)	Indian data from International Manufacturing Strategy Survey (IMSS)
Jain	2018	mismatch between demand and supply	logistics flexibility (multiple shipments via multiple routs and transportation modes)	numerical analysis	–
Fan et al.	2018	short-term and long-term supply chain disruptions	diverse transportation modes (low-speed mode vs. high-speed mode)	numerical analysis	–
Park et al.	2018	demand uncertainty in humanitarian logistics	Surface vs. air shipment	numerical analysis	–
Shekarian et al.	2020	disruptions in supply and demand	flexibility and agility through multi-sites, – transportation modes (road and air), and –product planning	numerical analysis / example	data from Nooraie and Parast (2015) / based on the observation of a global manufacturing firm
Kulpa et al.	2024	demand and lead time uncertainty, based on product attributes	use of air freight vs. Ocean for intermediate inputs	regression	the US Census Bureau's USA Trade Online database

two different speeds of transportation modes (air vs. road) are introduced into the analytical models, assuming that two different modes heterogeneously affect the impact of disruptions and supply chain responsiveness (Park et al., 2018; Shekarian et al., 2020). Further, the flexibility consistently lowers optimal order-up-to levels, with greater reductions achieved under full lead-time visibility, suggesting the varying impacts of transportation modes across different scenarios of lead-time visibility (Jain, 2018). These studies numerically demonstrate that the advantages derived from transportation modal flexibility exceed the associated costs. Table 1 summarizes selected recent studies on risk types and their corresponding mitigation measures using transportation modal flexibility.

To complement reservation introduced by particular experiment settings in quantitative studies, the concept of transportation flexibility by multi-mode is also tested empirically in the literature. As a potential moderator in the relationship between environmental uncertainty and various supply chain risks—such as supply disruptions, manufacturing process challenges, and delivery issues—the firm's survey responses were utilized to assess its level of flexibility in transportation modes (Sreedevi & Saranga, 2017). However, this flexibility tested in the study was found to have no statistically significant effect. The authors attributed this insignificant result to the limitations of national or state-level logistics infrastructure and practices, suggesting that inefficiencies at the macro level could not be effectively mitigated by firm-level transportation flexibility measures. On the contrary, Kulpa et al., (2024) argued that air freight may be more demanded to minimize delays in manufacturing production at specific stages of the production process, implying that switching to a faster and reliable transportation mode may provide critical flexibility that buffers against demand shocks and supply chain interruptions during the time of unexpected events.

Despite the potential value of these studies, few empirical support demonstrates the value of transportation mode flexibility as an effective mitigation strategy against supply chain risks and disruptions in inventory performance. This gap in the literature indicates a vague understanding of the effectiveness of a risk mitigation approach that emphasizes flexibility, particularly in transportation modes, during major global supply chain disruptions.

2.4. *Inventory performance*

2.4.1. *Inventory performance Determinants*

Inventory performance is influenced by both internal and external factors that shape operational and strategic decisions. Internally, inventory management aligns with broader business strategies, with lean supply chains reducing costs via just-in-time approaches and agile supply chains using buffer stocks to adapt to demand variability (Fisher, 1997; Tang, 2006a). Leadership and culture of data-driven decision-making further enhance inventory practices (Flynn et al., 2010). Advanced technologies like RFID, warehouse management systems, IoT, and big data analytics improve forecasting, traceability, and efficiency while minimizing errors (Baker & Canessa, 2009; Ben-Daya et al., 2019; Sarac et al., 2010).

Externally, factors beyond a firm's control, such as natural disasters, geopolitical instability, and macroeconomic changes, disrupt supply chains and require safety stock to mitigate risks (Croson & Donohue, 2006). These disruptions, while challenging, also necessitate precise demand forecasting, which can lead to faster inventory turnover (Cheng, 2019; Dbouk et al., 2020). Reliable suppliers with consistent lead times and quality deliveries further enhance inventory efficiency by reducing buffer stock requirements (Lin et al., 2021; Wagner & Bode, 2006).

2.4.2. *Inventory performance metrics*

Evaluating inventory performance is crucial in supply chain management, as it directly affects efficiency, cost control, and customer satisfaction. Inventory Turnover, calculated as the ratio of a firm's cost of goods sold to its average inventory level, is a widely used metric (Gaur et al., 2005). Higher turnover generally indicates effective inventory management and strong sales, while lower

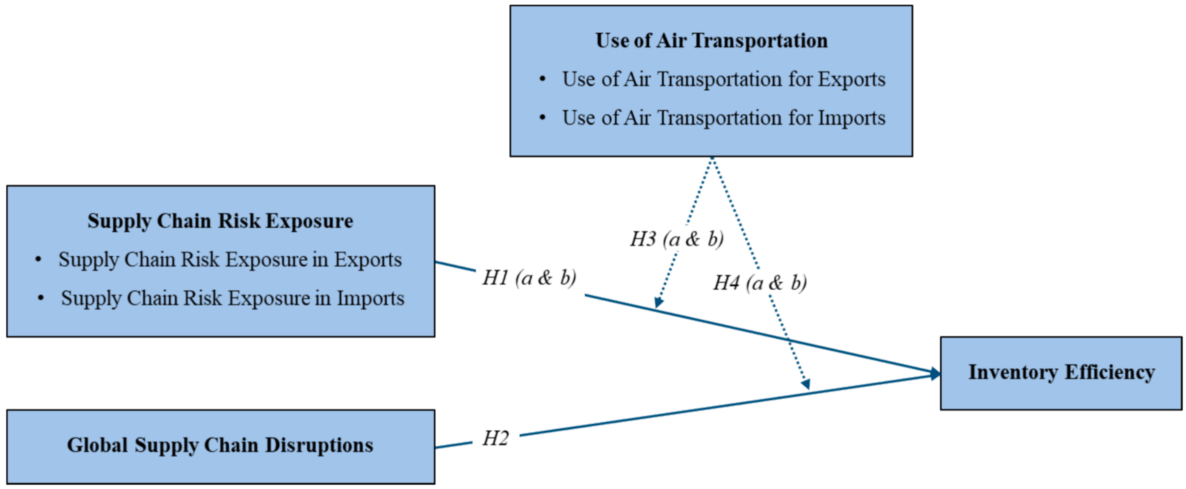

Fig. 4. Research Framework.

turnover suggests overstocking or weak demand. This metric has been applied in industries such as retail (Gaur et al., 2005; Kesavan et al., 2016), manufacturing (Eroglu & Hofer, 2011; Wang et al., 2023a), healthcare (Alnaim & Kouaib, 2023; Balkhi et al., 2022), and aviation (Narendran et al., 2024). Days in Inventory, or Days Inventory Outstanding, measures the average time required to sell inventory. It complements turnover by assessing efficiency and sales velocity (Chen et al., 2022). The choice between these metrics depends on whether the focus is on operational efficiency or sales performance. The Fill Rate metric evaluates how much customer demand is met directly from available stock, serving as a key indicator of service levels (Bijvank & Vis, 2012; Santos et al., 2020). High fill rates reflect well-maintained inventory, while low rates may point to stockouts or inaccurate forecasting. Order Fulfillment Cycle Time, or lead time, captures the period from order placement to fulfillment. Effective management of cycle time enhances responsiveness, reduces costs, and improves customer satisfaction (Cotteleer & Bendoly, 2006; Hult et al., 2002). Shorter cycle times enable firms to better address demand changes and maintain a competitive advantage.

Building on global supply chain risk management literature, this study empirically examines two key areas: (1) the impacts of global supply chain risks and disruptions on manufacturing inventory performance, and (2) the role of transportation modal flexibility—specifically the shift from ocean to air freight—in supporting inventory performance during major disruptions.

3. Hypotheses

Fig. 4 presents a comprehensive research framework that highlights the interconnections among global supply chain risk exposure, supply chain disruptions, the use of air transport, and inventory efficiency, serving as a conceptual roadmap for this study.

3.1. Supply chain risk exposure and inventory efficiency

With emerging economies in Asia, such as China, India, and Vietnam, increasingly becoming global manufacturing hubs, firms have strategically globalized their supply chains. This globalization has contributed to reduced production costs, expanded access to international markets, and improved responsiveness to market demands. However, these benefits come with inherent risks, particularly a heightened vulnerability to supply chain disruptions, which can negatively impact inventory efficiency for the following reasons.

First, the extended lead times inherent in global supply chains complicate accurate demand forecasting for retailers over long periods. Inventory theory suggests a positive correlation between lead time length and variability in order quantities from retailers to manufacturers (Chen et al., 2000; Lee et al., 1997). As a result, longer lead times and greater fluctuations in orders often require higher inventory levels, thereby reducing inventory efficiency.

Second, global supply chains are inherently more complex and vulnerable to supply chain disruptions than domestic ones. These disruptions can be caused by both natural events—such as tsunamis, typhoons, and earthquakes—and man-made factors, including terrorist attacks, port strikes, and customs delays, all of which pose significant threats to supply chain continuity. To address these elevated risks, firms may implement various risk mitigation strategies, such as purchasing business interruption insurance, maintaining higher inventory levels, adopting multiple-supplier sourcing, rerouting shipments, and employing proactive demand management techniques (Tomlin, 2006). Consequently, global supply chains are often associated with reduced inventory efficiency and higher inventory levels compared to domestic supply chains (Han et al., 2008; Jain et al., 2014; Ke et al., 2022; Levy, 1997; Rajagopalan & Malhotra, 2001).

Based on these arguments, we propose the following hypotheses:

Hypothesis 1a Greater supply chain risk exposure in exports decreases manufacturers' inventory efficiency.

Hypothesis 1b: Greater supply chain risk exposure in imports decreases manufacturers' inventory efficiency.

3.2. Global supply chain Disrupions and inventory efficiency

The COVID-19 pandemic introduced an unprecedented disruption to global supply chains, creating both demand and supply shocks (Federal Reserve Bank of St. Louis, 2020; Meester & Ooijens, 2020). A demand shock occurs when consumers' ability or willingness to purchase goods and services at current prices decreases. Conversely, a supply shock arises when the economy's capacity to produce goods and services at existing prices is compromised. Although demand for personal protective equipment (PPE) and essential goods surged, lockdowns and factory closures significantly reduced overall consumer and corporate spending. Many industries faced operational constraints due to these lockdowns and social distancing measures, with medium-scale enterprises, in particular, experiencing severe impacts on production processes. This led to a marked decline in inventory efficiency across manufacturing industries during the pandemic.

Furthermore, to achieve pre-pandemic sales levels, manufacturers had to bear higher inventory levels due to several critical factors. First, the global shortage of microchips impeded the production of finished goods, as essential components became unavailable, stalling sales. Second, substantial quantities of inventory remained immobilized on ships, in ports, and in warehouses due to severe port congestion. In particular, congestion at the Ports of Los Angeles and Long Beach stemmed from a combination of factors, including blocked railroads, a shortage of truck drivers, near-capacity warehouses, and insufficient chassis availability (Mongelluzzo, 2020; U.S. Department of Transportation, 2022). The rail and truck system connecting the Port of Los Angeles to the broader U.S. market was hindered by labor shortages, a lack of capacity, and delays caused by importers not retrieving goods from the port. Additionally, unprecedented demand from third-party logistics and e-commerce providers during the pandemic occupied most warehouse space. This shortage led retailers to store goods in containers in parking lots rather than unloading them into warehouses, prolonging the duration that chassis remained in use before being returned.

This study posits that global supply chain disruptions, such as the COVID-19 pandemic, have decreased inventory efficiency in manufacturing industries due to operational constraints, microchip shortages, port congestion, and shipping delays. This leads to the following hypothesis:

Hypothesis 2 Global supply chain disruptions decrease manufacturers' inventory efficiency.

3.3. The impact of using air transportation on global supply chain risk exposure

Compared to ocean transport, air transportation offers significantly shorter transit times, more frequent departures, smaller capacity, and higher per-unit transportation costs. Inventory theory suggests that shifting from ocean to air transport in global supply chains may reduce inventory holdings, thereby enhancing inventory efficiency. The rationale is as follows.

Longer forecast horizons complicate the accuracy of demand predictions while shorter lead times allow retailers to make more precise forecasts. This shorter timeframe enables retailers to forecast demand more accurately, allowing them to place orders with smaller deviations from actual demand, thus improving inventory efficiency (Lee et al., 1997; Chen et al., 2000). Shorter replenishment lead times with air transportation may reduce this order variability, enabling manufacturers to maintain lower safety stock levels for finished goods. It is numerically shown that firm's inventory levels generally remain higher without logistics flexibility such as an alternative mode of transportation less prone to shipment delays (Jain, 2018).

Moreover, in-transit inventory levels are directly tied to transit time and lot size. Miller and Peters (2024) find that transport mode choices significantly impact inventory management, as they affect cost, lead time, and service level. Air transport, though more expensive, offers shorter lead times, smaller batches, and lower safety stock requirements, enabling faster response to demand with less inventory on hand. In contrast, ocean shipping is more cost-effective but requires higher inventory investments due to its longer transit times and increased lead time variability, resulting in higher overall carrying costs. Industries relying more on air transport for exports are expected to maintain lower in-transit inventory levels, leading to improved inventory efficiency. Consequently, using air transportation may help offset the negative impact of supply chain risk exposure in both exports and imports on inventory efficiency. In the meantime, the flexibility in transportation mode was found to have no statistically significant effect (Sreedevi & Saranga, 2017).

Based on these arguments, we propose the following hypotheses:

Hypothesis 3a Increased use of air transportation offsets the negative impact of supply chain risk exposure in exports on inventory efficiency.

Hypothesis 3b: Increased use of air transportation offsets the negative impact of supply chain risk exposure in imports on inventory efficiency.

3.4. The impact of using air transportation on global supply chain disruptions

While the COVID-19 pandemic led to decreased inventory efficiency due to factors such as microchip shortages, port congestion, and shipping delays, firms with greater transportation modal flexibility could perform better than those without it. According to real options theory (Gorupec et al., 2022; Trigeorgis & Tsekrekos, 2018), firms with contracts across multiple transportation modes demonstrate higher resilience during supply chain disruptions, as they can swiftly switch modes to adapt to changing conditions. Achieving transportation modal diversification may involve expanding transportation options, forming alliances with multiple carriers, and operating across different shipping routes to maintain a continuous logistics flow (Ishfaq, 2012; Tang & Tomlin, 2008). Flexibility, although it may lead to a reduction in the optimal price, enhances resilience, which can significantly benefit systems operating in uncertain and volatile environments (Bernabei et al., 2022). Increased preference for air shipping during the pandemic period implies that the faster and more reliable transportation mode absorbs in part the negative impact of the supply chain disruptions (Kulpa et al., 2024).

Conventional wisdom suggests that transportation costs and service time are the main factors driving modal decisions. However, Ke et al. (2015) argue that industry characteristics play a more significant role. They propose that transportation mode usage in global supply chains is strategically aligned with industry-specific factors and supply chain objectives. For instance, manufacturing industries are more likely to rely on air transport in response to positive sales surprises, high demand variability, high gross margins, capital intensity, and increased competition. During the pandemic, marked by high demand uncertainty and competition for essential components, firms with access to air transportation were able to bypass delays and respond to customer demand more swiftly, resulting in improved inventory efficiency.

Additionally, a firm's routine use of air transportation can serve as a strategic asset during supply chain disruptions. As air transport is considerably faster than ocean transport, it becomes especially advantageous when avoiding delays outweighs the additional cost. Particularly during disruptions, switching from ocean to air cargo is generally more feasible than the reverse. Consequently, firms with access to both air and ocean transport demonstrate greater responsiveness under disruption. Firms that regularly use both modes face lower costs when shifting from ocean to air transport, as their freight forwarders likely already have contracts and reserved space with airlines. During the pandemic, manufacturing industries that leveraged air transportation could respond to fluctuating demand more effectively than those reliant on ocean transport, leading to better inventory efficiency.

Based on this reasoning, we propose the following hypotheses:

Hypothesis 4a Increased use of air transportation for exports offsets the negative impact of supply chain disruptions on inventory efficiency.

Hypothesis 4b: Increased use of air transportation for imports offsets the negative impact of supply chain disruptions on inventory efficiency.

4. Data and methodology

4.1. Data

This study utilizes industry-level data from the USA Trade Online database and the Annual Survey of Manufactures (ASM), covering 75 four-digit North American Industry Classification System (NAICS) manufacturing industries over a 20-year period (2002–2021). Data from 2002 is used specifically to calculate sales growth for 2003, resulting in a final dataset spanning 2003 to 2021. This panel dataset comprises 1,375 industry-year observations, capturing both pre-pandemic and pandemic periods.

Industry-level analysis provides a broader perspective by aggregating data across firms within a sector, reducing noise from firm-specific factors such as management practices and competitive strategies (e.g., pricing and promotions) and enabling generalizable insights. Prior studies on aggregated inventory performance (Eroglu & Hofer, 2011; Moser et al., 2017; Rumyantsev & Netessine, 2007) highlight its ability to minimize variability and inconsistencies often found in firm-level data. This approach also captures the widespread impacts of disruptions, such as the COVID-19 pandemic, offering a clearer view of how industries collectively adapt to challenges and implement resilience strategies. By focusing on industry-wide trends rather than intra-industry competition, this study examines resilience and adaptation strategies without the influence of firm-level rivalry or concerns about inconsistent measurement definitions across firms (Shah & Shin, 2007), making it particularly relevant for assessing sector-wide inventory performance. Additionally, industry-level data, often available longitudinally, enables the analysis of both immediate and long-term impacts, providing valuable insights for policymakers and stakeholders.

This approach is particularly suitable for the research objective, which seeks to demonstrate how inventory performance is influenced by shipping modes. Shipping modes, including air and ocean freight, are largely shaped by industry-level attributes that are exogenous to individual firms' decisions. Industry-level data is thus more appropriate for this analysis and complements prior research relying on firm-level data. Moreover, this dataset uniquely provides directional shipment value information, separating exports and imports (Svensson, 2002). This granularity enables a deeper analysis of the interplay between inventory performance and transportation decisions, particularly the trade-offs between transportation costs and inventory costs (Berman & Wang, 2006; Mason et al., 2003; Zhao et al., 2010).

4.2. Variables

Consistent with prior research by Gaur et al. (2005) and Ke et al. (2022), this study uses inventory turnover (INVT) as the dependent variable, serving as a proxy for inventory efficiency, with higher inventory turnover indicating greater efficiency.

The analysis focuses on three explanatory variables and their interaction terms.

First, supply chain risk exposure, as discussed by Han et al. (2008) and Jain et al. (2014), is quantified using the export ratio (ER) and import ratio (IR). The ER is calculated as the ratio of export value to total shipment value, using data from USA Trade Online and the Annual Survey of Manufactures (ASM). The IR represents the share of imported content relative to raw material costs, derived from data provided by the U.S. Bureau of Economic Analysis (BEA) and ASM. Calculating the IR is more complex, as industries often source raw materials from multiple sectors. We determine the value of an industry's imported content using the BEA's annual input–output accounts, available at the three-digit NAICS industry level. To estimate import content at the four-digit NAICS level, we used data from the 2007, 2012, and 2017 U.S. Economic Censuses, which provide input–output accounts at this level. For non-census years, we imputed values by assuming minimal shifts in industry composition within two years before and after each census year.

Second, the Global Supply Chain Pressure Index (GSCPI) is a time-variant, industry-invariant measure developed to capture global supply chain disruptions and constraints. Created by the Federal Reserve Bank of New York, the GSCPI combines various data sources into a single metric, incorporating information from shipping costs, transportation prices, and supply chain-related surveys, including the Baltic Dry Index (BDI), Harpex Index, airfreight costs, and the Purchasing Managers' Index (PMI). It aggregates data on delivery times, backlogs, and transportation prices, providing a comprehensive overview of global supply chain conditions. A higher GSCPI value indicates increased supply chain pressures, such as longer delivery times or higher shipping costs, often arising from disruptions like pandemics or geopolitical events. Conversely, a lower GSCPI suggests smoother supply chain operations with fewer bottlenecks. The GSCPI index helps policymakers, businesses, and analysts track global trade dynamics and supply chain health over time, identifying periods of stress or recovery within the network. Recent studies have utilized this GSCPI to show the relationship between disruptive events and key economic indicators such as inflation rates, producer price indices, and industry performance (Benigno et al., 2022; Ren et al., 2024; Ye et al., 2023). This study considers the aggregate impact of other significant events within the study period that may have influenced transportation usage and overall supply chain efficiency. Given that the Federal Reserve Bank of New York reports monthly GSCPI deviations from its historical average, this study uses the average of these deviations over 12 months to assess the annual impact of supply chain disruptions.

Additionally, this study includes two moderating variables: the value shares of air transportation in exports and imports. The air transportation value share, relative to the combined air and ocean transport, is calculated separately for exports (EXAIR) and imports (IMAIR) at the four-digit NAICS industry level using data from the USA Trade Online database. Shipments by truck and rail are excluded, as these modes are generally unavailable for most international trade routes.

EXAIR represents the proportion of export value transported by air relative to the total value transported by both air and ocean. Calculating IMAIR, the air transportation share for imports, is more complex because industries may import commodities from multiple sectors. First, we used the BEA's annual input–output accounts to calculate each imported commodity's share, which serves as its weight. Next, we determined each commodity's share of air transportation in imports from the USA Trade Online database. Finally, IMAIR for a three-digit NAICS industry is derived as a weighted share by multiplying each commodity's weight by its air transport share. For simplicity, we assume a uniform air transportation share across all four-digit industries within the same three-digit NAICS industry.

This study includes additional control variables: gross margin ratio (lagGM), capital intensity (CI), industry sector size (SZ), and shipment value growth (SG), all derived from ASM data at the four-digit NAICS industry level. To mitigate endogeneity concerns, the gross margin ratio (lagGM) is lagged by one year and calculated as the difference between shipment value and the cost of goods sold, divided by total shipment value. Capital intensity (CI) is defined as shipment value per employee, while industry size (SZ) is measured by the number of employees (in thousands). Shipment value growth (SG) is determined by the year-over-year growth rate of shipment values.

4.3. Estimation strategy

Various methodologies have been performed to investigate similar research questions in previous papers. The methodology include but not limited to momentum approach for prospecting scenarios (i.e., desired, undesired and the trend) (Rodrigues et al., 2021), Data Envelopment Analysis (Ribeiro et al., 2023), Structure Equation Model (Sreedevi and Saranga; 2017), numerical modeling (Fan et al. 2018; Heydari et al., 2020; Ogunranti et al.), qualitative case studies (Pellegrino et al., 2024), simulation experiments (Pellegrino et al., 2024), and regressions (Lorentz et al., 2021; Ke et al., 2022; Kulpa et al., 2024). In this study, we used the regression method for our archival data to develop a fixed-effects inventory model. Our analysis is unique in that it predicts inventory turnover with the newly introduced variables.

To determine the most suitable model for our analysis, we conducted a Hausman test to compare fixed and random effects specifications. The test produced a chi-squared statistic of 43.23 with 11 degrees of freedom and a p-value of 0.0000, indicating a significant difference between the fixed and random effects estimates. Given that the p-value is well below the 0.05 threshold, we reject the null hypothesis that the random effects model is appropriate. This result suggests that unobserved characteristics associated with each entity are correlated with the independent variables in our model, making the fixed effects approach more suitable. Consequently, we selected the fixed effects model for this study, as it provides unbiased estimates by controlling for time-invariant characteristics specific to each industry, enhancing the reliability of our findings.

To assess the impact of supply chain risk exposures and disruptions on inventory efficiency, we use *Equation (1)* to construct a regression model for testing Hypotheses 1a, 1b, and 2.

$$INVT_{it} = \beta_0 + \beta_1 ER_{it} + \beta_2 IR_{it} + \beta_3 GSCPI_t + \beta b_4 lagGM_{i(t-1)} + \beta_5 CI_{it} + \beta_6 SZ_{it} + \beta_7 SG_{it} + \mu_i + \omega_t + \varepsilon_{it} \tag{1}$$

In this model, i represents the four-digit NAICS industry level, t represents the years 2003–2021, μ_i represents the fixed effect of four-digit NAICS industry i, and ω_t represents the fixed effect of year t.

Equation (2) is used to estimate the moderating effect of air transportation on the relationship between supply chain risk exposures and inventory efficiency, thereby testing Hypotheses 3a and 3b.

$$\begin{aligned} INVT_{it} = {} & \beta_0 + \beta_1 ER_{it} + \beta_2 IR_{it} + \beta b_3 GSCPI_t + \beta_4 ER_{it} \times EXAIR_{it} + \beta_5 IR_{it} \\ & \times IMAIR_{it} + \beta_6 lagGM_{i(t-1)} + \beta_7 CI_{it} + \beta_8 SZ_{it} + \beta_9 SG_{it} + \mu_i + \omega_t + \varepsilon_{it} \end{aligned} \tag{2}$$

Equation (3) estimates the moderating effect of air transportation on the relationship between global supply chain disruptions and inventory efficiency, thus testing Hypotheses 4a and 4b.

$$INVT_{it} = \beta_0 + \beta_1 ER_{it} + \beta_2 IR_{it} + \beta_3 GSCPI_t \times EXAIR_{it} + \beta_4 GSCPI_t \times IMAIR_{it} + \beta_5 lagGM_{i(t-1)} + \beta_6 CI_{it} + \beta_7 SZ_{it} + \beta_8 SG_{it} + \mu_i + \omega_t + \varepsilon_{it} \tag{3}$$

Table 2
Descriptive Statistics.

Variable	Observations	Mean	Std. Dev.	Min	Max
INVT	1,375	6.21	3.99	1.17	30.35
ER	1,375	21.5 %	17.7 %	0.4 %	99.2 %
IR	1,375	22.7 %	13.1 %	3.7 %	103.4 %
GSCPI	1,375	0.08	0.85	−0.67	3.01
EXAIR	1,375	32.0 %	29.2 %	0.0 %	97.9 %
IMPAIR	1,375	26.9 %	13.4 %	0.1 %	67.3 %
lagGM	1,375	0.39	0.10	0.12	0.80
CI	1,375	533.85	733.73	126.28	8509.64
SZ	1,375	149.15	132.58	11.92	676.14
SG	1,375	0.02	0.12	−0.99	0.68

5. Regression results

5.1. Descriptive statistics

Tables 2 and 3 present the descriptive statistics and correlation coefficients for all variables used in the regression models. As shown in Table 2, average inventory turnover stands at 6.21, indicating that each dollar of inventory generates approximately $6.21 in sales based on costs. Additionally, around 21.5 percent of the total shipment value from U.S. manufacturers is exported to international markets, while about 22.7 percent of raw material costs are attributed to imports. The value shares of exports and imports conducted through air transportation are 32% and 26.9%, respectively.

In Table 3, the shares of air transportation in exports and imports also show a high correlation with the gross margin ratio, which is negatively associated with inventory turnover. Moreover, the relationships between various control variables and inventory turnover are generally consistent with previous studies (Ak & Patatoukas, 2016; Casalin et al., 2017; Gaur et al., 2005; Han et al., 2008; Jain et al., 2014; Ke et al., 2022; Rumyantsev & Netessine, 2007), indicating that higher inventory turnover is associated with greater capital intensity, increased sales growth, and larger industry size. The highest correlation value is found between ER and EXAIR (0.66), suggesting that multicollinearity is not a concern for this data.

Table 4 provides yearly descriptive statistics, highlighting the distinct impact of the COVID-19 pandemic. Inventory turnover in manufacturing industries, which had been declining since 2015, dropped further during the pandemic. The GSCPI reflects the intensity of supply chain disruptions, increasing from 1.63 standard deviations above the average in 2020 to 3.01 in 2021. While export and import ratios remained relatively stable, there was a notable increase in the use of air transportation for both exports and imports in 2020 and 2021, suggesting that some industries turned to air transport to meet demand and acquire raw materials more quickly. The growth in shipment value (SG) illustrates high uncertainty during COVID-19.

The COVID-19 pandemic first emerged in China in December 2019, with the first confirmed U.S. case reported on January 20, 2020, in Washington state. By March 2020, the virus had spread widely across the country, leading to widespread disruptions such as lockdowns, travel restrictions, and a national emergency declaration on March 13, 2020. As a result, the average shipment value declined by 7.3% in 2020 compared to the previous year. In 2021, the economy showed signs of recovery, supported by widespread vaccination efforts, additional government stimulus, and the gradual reopening of businesses. By the second quarter of 2021, U.S. GDP had returned to its pre-pandemic level. However, supply chain disruptions and labor shortages persisted. Manufacturing shipment value rose by 11.9% in 2021 compared to 2020, yet inventory turnover saw only a slight increase from 5.43 in 2020 to 5.73 (an increase of 5.5%) in 2021, indicating a rise in inventory levels due to ongoing supply chain disruptions.

5.2. Regression results

Table 5 presents the regression results from the time and industry fixed-effects inventory models used to test our research hypotheses. Variables and interaction terms were added sequentially across the models. Model (1) shows that the export ratio (ER) and the import ratio (IR) negatively affect inventory turnover, with significance levels of 0.01, supporting Hypotheses 1a and 1b. This result remains consistent across Models (2) and (3) when additional interaction terms are included. The findings suggest that industries with a higher share of sales and raw materials from foreign markets face increased supply chain risks, leading to higher inventory levels and lower inventory efficiency. Specifically, a ten-percentage-point increase in the share of export sales relative to the total shipment value results in a 0.1906 unit decrease in inventory turnover, supporting Hypothesis 1a. Similarly, a ten-percentage-point increase in the share of imported content relative to raw material costs results in a 0.5148 unit decrease in inventory turnover, supporting Hypothesis 1b.

The results from Model (1) also indicate that global supply chain disruptions, measured by the Global Supply Chain Pressure Index (GSCPI), have a significant negative effect on inventory turnover, supporting Hypothesis 2. Specifically, an increase of one standard deviation in global supply chain disruption pressure corresponds to a 0.0866 unit decrease in inventory turnover. Furthermore, while 2003 serves as the baseline year for time-fixed effects, the 2021 year dummy was excluded from the model. This is because Model (1) includes GSCPI, an industry-invariant variable that captures the substantial impact of the COVID-19 pandemic as a primary factor.[1]

Model (2) introduces two interaction terms: ER x EXAIR and IR x IMAIR. The results suggest that the shares of air transportation in exports and imports effectively mitigate the negative impact of supply chain risk exposures on inventory turnover. Specifically, a ten-percentage-point increase in the use of air transportation for exports significantly offsets the negative effect of the export ratio on inventory turnover by 0.9296 units, with a significance level of 0.01, controlling for industry and other variables. This result supports Hypothesis 3a. Additionally, a ten-percentage-point increase in the use of air transportation for imports significantly offsets the negative effect of the import ratio on inventory turnover by 0.8953 units, also at a significance level of 0.01, supporting Hypothesis 3b.

Model (3) includes two additional interaction terms related to supply chain disruptions: GSCPI x EXAIR and GSCPI x IMAIR. The results show that a ten-percent increase in air transportation usage for exports mitigates the negative impact of global supply chain disruptions at a significance level of 0.01, supporting Hypothesis 4a. However, increased air transportation usage for imports leads to higher inventory holdings and lower inventory efficiency, with a significance level of 0.1, which does not support Hypothesis 4b. This finding, though seemingly counterintuitive, can be explained by the circumstances during the COVID-19 pandemic. Due to surging

[1] We ran the models without GSCPI, and the year dummy 2021 remained with the negative sign.

Table 3
Correlation Table.

	INVT	ER	IR	GSCPI	EXAIR	IMPAIR	lagGM	SZ	SG
INVT	1.00								
ER	−0.29	1.00							
IR	−0.19	0.14	1.00						
GSCPI	−0.04	0.01	−0.01	1.00					
EXAIR	−0.47	0.66	0.10	0.05	1.00				
IMPAIR	−0.30	0.49	0.02	0.14	0.51	1.00			
lagGM	−0.50	0.19	−0.04	0.02	0.55	0.33	1.00		
CI	0.38	−0.03	0.12	0.03	−0.22	−0.16	−0.31		
SZ	0.13	0.01	−0.10	0.00	0.24	0.07	0.12	1.00	
SG	0.11	−0.05	0.03	0.13	−0.05	−0.13	0.00	0.03	1.00

Table 4
Descriptive Statistics – Mean by Year.

Year	INVT	ER	IR	GSCPI	EXAIR	IMPAIR	lagGM	CI	SZ	SG
2003	5.96	17.5 %	21.9 %	−0.25	31.5 %	27.9 %	40.1 %	342.79	155.21	0.7 %
2004	6.30	19.0 %	25.2 %	−0.06	32.6 %	26.0 %	39.9 %	394.37	149.69	5.5 %
2005	6.30	19.6 %	25.9 %	−0.53	32.1 %	24.9 %	39.9 %	452.46	147.57	7.8 %
2006	6.19	21.0 %	26.7 %	−0.25	31.9 %	24.8 %	39.4 %	491.18	145.86	4.3 %
2007	5.98	20.8 %	25.7 %	−0.46	31.3 %	24.0 %	39.1 %	504.60	153.34	3.8 %
2008	6.81	20.3 %	22.2 %	−0.16	30.4 %	23.0 %	39.0 %	539.29	162.25	7.8 %
2009	5.82	20.2 %	19.1 %	−0.33	31.6 %	27.8 %	37.7 %	470.27	143.50	−23.5 %
2010	6.46	21.5 %	20.4 %	0.25	31.6 %	27.0 %	39.2 %	531.24	140.64	6.3 %
2011	6.59	22.4 %	22.1 %	0.33	31.2 %	27.2 %	39.4 %	593.09	143.29	7.2 %
2012	6.55	23.7 %	21.4 %	−0.26	30.2 %	26.0 %	38.4 %	611.68	147.23	3.0 %
2013	6.53	23.9 %	21.8 %	−0.49	30.1 %	26.4 %	37.7 %	628.26	145.83	2.4 %
2014	6.62	23.2 %	22.4 %	−0.67	29.8 %	25.2 %	38.1 %	633.36	145.57	2.4 %
2015	6.28	22.6 %	22.6 %	−0.48	30.6 %	25.6 %	38.2 %	570.65	147.98	−2.1 %
2016	6.13	22.1 %	21.8 %	−0.36	31.5 %	28.5 %	39.0 %	544.45	147.28	−2.9 %
2017	6.25	22.6 %	21.9 %	0.30	32.4 %	26.2 %	39.7 %	550.46	153.00	2.7 %
2018	6.18	22.4 %	22.7 %	0.43	33.5 %	26.7 %	38.8 %	586.19	155.11	4.9 %
2019	5.77	22.4 %	23.1 %	−0.04	34.2 %	27.5 %	38.9 %	566.92	152.91	−2.6 %
2020	5.43	22.3 %	21.3 %	1.63	35.1 %	36.0 %	39.4 %	516.55	149.09	−7.3 %
2021	5.73	22.1 %	23.8 %	3.01	36.4 %	30.3 %	39.0 %	634.09	148.60	11.9 %

demand and port congestion in 2021, many U.S. manufacturers faced delays in obtaining key raw materials necessary for production. Firms that could not respond to supply chain disruptions quickly experienced lower inventory levels of raw materials. However, firms that increased air transportation to bypass ocean shipping and port congestion maintained higher inventory levels of raw materials, ensuring continuity in domestic production despite global disruptions.

5.3. Robustness check

As a robustness check, we replaced the value shares of air transportation in exports and imports with the weight shares of air transportation to verify the consistency of our findings. As reported in Table 6, the weight share metric offers an alternative perspective on the reliance of industries on air transport by measuring the proportion of total shipment weight that is transported by air. This measure provides additional insight, particularly in industries where the weight-to-value ratio may influence transportation mode selection. The main results remained consistent with those presented in Table 5.

In addition, the population average (PA) model is used as a robustness check to ensure that the findings are not dependent on the choice of estimation method. The results, as shown in Table 7, are consistent with those in Table 5. While the fixed-effects model controls for unobserved heterogeneity at the industry level, the PA model focuses on estimating the average effects across the population, accounting for within-group correlations without explicitly modeling individual-specific effects. This complementary approach helps validate that the relationships between explanatory variables and the dependent variable are consistent and generalizable at the population level.

6. Discussion

6.1. Ad hoc analysis

The inventory efficiency measure in Table 5 is based on total inventories, encompassing raw materials (RM), work-in-process (WIP), and finished goods (FG), which represent different production stages. Given that supply chain risk exposures and disruptions may impact each production stage differently, we further analyze how these risks and disruptions affect each inventory type and

Table 5
Regression Results.

	(1)	(2)	(3)
VARIABLES	INVT	INVT	INVT
ER	−1.906***	−8.149***	−2.115***
	(0.478)	(0.853)	(0.479)
IR	−5.148***	−6.855***	−5.189***
	(0.373)	(0.604)	(0.371)
GSCPI	−0.0866*	−0.159***	−0.126*
	(0.0490)	(0.0478)	(0.0765)
ER_EXAIR		9.296***	
		(1.061)	
IR_IMAIR		8.953***	
		(1.647)	
GSCPI_EXAIR			0.476***
			(0.110)
GSCPI_IMAIR			−0.413*
			(0.223)
lagGM	−1.963**	−2.709***	−1.582**
	(0.798)	(0.770)	(0.797)
CI	0.000780***	0.000742***	0.000772***
	(0.000120)	(0.000115)	(0.000119)
SZ	0.0121***	0.0107***	0.0125***
	(0.00103)	(0.00102)	(0.00103)
SG	2.557***	2.448***	2.590***
	(0.259)	(0.251)	(0.258)
Industry	Included	Included	Included
2004.year	0.456***	0.493***	0.463***
	(0.145)	(0.139)	(0.144)
2005.year	0.387**	0.422***	0.401**
	(0.158)	(0.152)	(0.157)
2006.year	0.434***	0.511***	0.453***
	(0.151)	(0.146)	(0.150)
2007.year	0.116	0.231	0.137
	(0.157)	(0.152)	(0.157)
2008.year	0.544***	0.715***	0.555***
	(0.150)	(0.146)	(0.149)
2009.year	0.500***	0.502***	0.531***
	(0.168)	(0.161)	(0.167)
2010.year	0.582***	0.674***	0.606***
	(0.143)	(0.138)	(0.142)
2011.year	0.728***	0.848***	0.754***
	(0.143)	(0.138)	(0.142)
2012.year	0.699***	0.824***	0.731***
	(0.159)	(0.153)	(0.158)
2013.year	0.696***	0.769***	0.729***
	(0.166)	(0.161)	(0.166)
2014.year	0.779***	0.845***	0.813***
	(0.172)	(0.165)	(0.171)
2015.year	0.590***	0.619***	0.622***
	(0.164)	(0.158)	(0.163)
2016.year	0.468***	0.413***	0.495***
	(0.159)	(0.154)	(0.158)
2017.year	0.462***	0.483***	0.483***
	(0.144)	(0.138)	(0.143)
2018.year	0.307**	0.299**	0.328**
	(0.142)	(0.136)	(0.141)
2019.year	0.113	0.0389	0.142
	(0.152)	(0.146)	(0.151)
2020.year	0.0479	−0.0995	0.109
	(0.136)	(0.133)	(0.137)
2021.year	–	–	–
Constant	5.875***	6.600***	5.703***
	(0.400)	(0.391)	(0.399)
Industry	Included	Included	Included
Observations	1,375	1,375	1,375
R-squared	0.412	0.458	0.421
Number of NAICS	75	75	75

Standard errors in parentheses.
*** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

Table 6
Regression Results – Using Weight Share of Air Transportation.

	(4)	(5)	(6)
VARIABLES	INVT	INVT	INVT
ER	−1.906***	−4.529***	−2.140***
	(0.478)	(0.665)	(0.481)
IR	−5.148***	−5.037***	−5.264***
	(0.373)	(0.467)	(0.373)
GSCPI	−0.0866*	−0.105**	−0.112**
	(0.0490)	(0.0488)	(0.0566)
ER x EXAIR_W		8.583***	
		(1.598)	
IR x IMAIR_W		8.466	
		(11.08)	
GSCPI x EXAIR_W			0.966***
			(0.230)
GSCPI x IMAIR_W			−3.881***
			(1.191)
lagGM	−1.963**	−1.911**	−1.818**
	(0.798)	(0.795)	(0.801)
CI	0.000780***	0.000779***	0.000775***
	(0.000120)	(0.000119)	(0.000119)
SZ	0.0121***	0.0119***	0.0127***
	(0.00103)	(0.00105)	(0.00104)
SG	2.557***	2.454***	2.568***
	(0.259)	(0.258)	(0.258)
Industry	Included	Included	Included
2004.year	0.456***	0.440***	0.457***
	(0.145)	(0.144)	(0.145)
2005.year	0.387**	0.367**	0.369**
	(0.158)	(0.157)	(0.158)
2006.year	0.434***	0.424***	0.439***
	(0.151)	(0.151)	(0.151)
2007.year	0.116	0.116	0.111
	(0.157)	(0.157)	(0.157)
2008.year	0.544***	0.574***	0.539***
	(0.150)	(0.150)	(0.150)
2009.year	0.500***	0.491***	0.504***
	(0.168)	(0.167)	(0.168)
2010.year	0.582***	0.606***	0.608***
	(0.143)	(0.142)	(0.143)
2011.year	0.728***	0.769***	0.758***
	(0.143)	(0.142)	(0.143)
2012.year	0.699***	0.756***	0.715***
	(0.159)	(0.158)	(0.158)
2013.year	0.696***	0.744***	0.705***
	(0.166)	(0.166)	(0.166)
2014.year	0.779***	0.815***	0.780***
	(0.172)	(0.171)	(0.171)
2015.year	0.590***	0.606***	0.598***
	(0.164)	(0.163)	(0.164)
2016.year	0.468***	0.477***	0.481***
	(0.159)	(0.158)	(0.159)
2017.year	0.462***	0.484***	0.481***
	(0.144)	(0.143)	(0.143)
2018.year	0.307**	0.313**	0.329**
	(0.142)	(0.141)	(0.141)
2019.year	0.113	0.0997	0.132
	(0.152)	(0.151)	(0.151)
2020.year	0.0479	0.0371	0.0792
	(0.136)	(0.135)	(0.136)
2021.year	–	–	–
Constant	5.875***	6.017***	5.806***
	(0.400)	(0.399)	(0.402)
Observations	1,375	1,373	1,373
R-squared	0.412	0.427	0.423
Number of naics	75	75	75

Standard errors in parentheses.
*** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

Table 7
Regression Results – Using the Population Average (PA) Method.

	(7)	(8)	(9)
VARIABLES	INVT	INVT	INVT
ER	−2.082***	−7.877***	−2.275***
	(0.469)	(0.809)	(0.473)
IR	−5.143***	−6.873***	−5.182***
	(0.373)	(0.572)	(0.372)
GSCPI	−0.0952*	−0.161***	−0.131*
	(0.0492)	(0.0458)	(0.0773)
ER x EXAIR		8.602***	
		(1.001)	
IR x IMAIR		8.833***	
		(1.563)	
GSCPI x EXAIR			0.454***
			(0.111)
GSCPI x IMAIR			−0.400*
			(0.226)
lagGM	−2.668***	−3.269***	−2.307***
	(0.788)	(0.729)	(0.791)
CI	0.000848***	0.000799***	0.000841***
	(0.000118)	(0.000109)	(0.000118)
SZ	0.0111***	0.00994***	0.0115***
	(0.000985)	(0.000940)	(0.000987)
SG	2.525***	2.437***	2.556***
	(0.261)	(0.241)	(0.261)
Industry	Included	Included	Included
2004.year	0.451***	0.490***	0.458***
	(0.146)	(0.134)	(0.145)
2005.year	0.374**	0.413***	0.388**
	(0.159)	(0.146)	(0.159)
2006.year	0.416***	0.497***	0.434***
	(0.152)	(0.140)	(0.152)
2007.year	0.0980	0.214	0.118
	(0.158)	(0.146)	(0.158)
2008.year	0.536***	0.702***	0.547***
	(0.151)	(0.140)	(0.151)
2009.year	0.453***	0.465***	0.482***
	(0.168)	(0.154)	(0.168)
2010.year	0.556***	0.649***	0.578***
	(0.144)	(0.132)	(0.144)
2011.year	0.705***	0.824***	0.729***
	(0.143)	(0.132)	(0.143)
2012.year	0.666***	0.792***	0.695***
	(0.159)	(0.147)	(0.159)
2013.year	0.653***	0.731***	0.684***
	(0.167)	(0.154)	(0.167)
2014.year	0.737***	0.810***	0.768***
	(0.172)	(0.158)	(0.172)
2015.year	0.554***	0.592***	0.584***
	(0.164)	(0.151)	(0.164)
2016.year	0.439***	0.394***	0.463***
	(0.160)	(0.147)	(0.160)
2017.year	0.452***	0.477***	0.471***
	(0.144)	(0.132)	(0.144)
2018.year	0.292**	0.290**	0.311**
	(0.142)	(0.131)	(0.142)
2019.year	0.0911	0.0286	0.118
	(0.152)	(0.140)	(0.152)
2020.year	0.0402	−0.100	0.0992
	(0.137)	(0.128)	(0.139)
2021o.year	–	–	–
Constant	6.404***	6.969***	6.246***
	(0.557)	(0.566)	(0.560)
Observations	1,375	1,375	1,375
Number of NAICS	75	75	75

Standard errors in parentheses.
*** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

Table 8
Regression Results by Inventory Type.

	(10)	(11)	(12)	(13)	(14)	(15)	(16)	(17)	(18)
VARIABLES	INVT_RM	INVT_ RM	INVT_ RM	INVT_WIP	INVT_ WIP	INVT_ WIP	INVT_ FG	INVT_ FG	INVT_ FG
ER	−2.893**	−19.72***	−3.435***	−2.28	−77.25***	−6.14	−9.247***	−26.91***	−9.726***
	(1.16)	(2.06)	(1.16)	(12.63)	(23.39)	(12.73)	(2.44)	(4.47)	(2.46)
IR	−12.56***	−17.00***	−12.67***	−46.96***	−59.94***	−47.90***	−15.93***	−24.32***	−16.03***
	(0.91)	(1.46)	(0.90)	(10.33)	(17.70)	(10.32)	(1.99)	(3.38)	(1.99)
GSCPI	−0.948***	−1.139***	−0.945***	1.25	0.51	0.09	−0.07	−0.33	−0.24
	(0.12)	(0.12)	(0.19)	(1.30)	(1.31)	(2.04)	(0.25)	(0.25)	(0.39)
ER_EXAIR		25.06***			111.5***			26.50***	
		(2.56)			(29.04)			(5.55)	
IR_IMAIR		23.57***			80.38*			36.64***	
		(3.98)			(46.13)			(8.81)	
GSCPI_EXAIR			1.439***			7.501**			0.955*
			(0.27)			(2.99)			(0.57)
GSCPI_IMAIR			−1.667***			−4.61			−0.54
			(0.54)			(5.93)			(1.14)
lagGM	−8.299***	−10.29***	−7.134***	−39.83*	−47.82**	(33.68)	7.342*	5.10	8.125**
	(1.94)	(1.86)	(1.93)	(21.16)	(21.11)	(21.27)	(4.08)	(4.03)	(4.10)
CI	0.00439***	0.00428***	0.00437***	−0.00531*	−0.00575*	−0.00549*	0.00211***	0.00199***	0.00209***
	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)
SZ	0.0244***	0.0206***	0.0256***	0.278***	0.265***	0.283***	0.0423***	0.0364***	0.0431***
	(0.00)	(0.00)	(0.00)	(0.03)	(0.03)	(0.03)	(0.01)	(0.01)	(0.01)
SG	4.589***	4.290***	4.688***	18.00***	16.40**	18.58***	10.12***	9.922***	10.19***
	(0.63)	(0.61)	(0.63)	(6.85)	(6.85)	(6.84)	(1.32)	(1.31)	(1.32)
Constant	16.94***	18.88***	16.40***	33.05***	40.75***	30.62***	11.64***	14.12***	11.30***
	(0.97)	(0.95)	(0.97)	(10.58)	(10.72)	(10.62)	(2.04)	(2.04)	(2.05)
Industry	Included	Included	Included	Included	Included	Included	Included	Included	Included
Year	Included	Included	Included	Included	Included	Included	Included	Included	Included
Observations	1,374	1,374	1,374	1,364	1,364	1,364	1,369	1,369	1,369
R-squared	0.459	0.51	0.471	0.132	0.144	0.136	0.245	0.268	0.246
Number of NAICS	75	75	75	75	75	75	75	75	75

Standard errors in parentheses.
*** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

the moderating effect of air transportation. Using the same model specifications in Equations (1) to (3), we replace the dependent variable with inventory turnover for raw materials (INVT_RM), work-in-process (INVT_WIP), and finished goods (INVT_FG), resulting in 9 additional Models (10) ~ (18), and report the results in Table 8. Inventory turnovers for RM, WIP, and FG are calculated as the cost of goods sold over the corresponding average inventory value.

The results from Models (10), (13), and (16) indicate that a higher export ratio increases inventory holdings for both raw materials and finished goods relatively compared to the cost of goods sold. This suggests that as industries have a higher proportion of overseas sales, extended supply chains amplify exposure to various risks. Consequently, U.S. manufacturers hold more finished goods to account for longer lead times and greater demand variability in international markets. The demand for raw materials rises correspondingly as it aligns with the production needs for finished goods.

Additionally, a higher import ratio significantly reduces inventory turnover across all inventory types due to relatively greater inventory holdings. Firms relying more heavily on global sourcing rather than local suppliers face longer lead times and greater supply uncertainty. This necessitates higher raw material inventory levels to mitigate risks associated with global sourcing. Additionally, increased unpredictability in supply schedules can disrupt production, requiring firms to account for longer and more variable lead times. Such disruptions often result in increased WIP and finished goods inventory, as production lines may pause while waiting for materials, accumulating both WIP and finished goods. Furthermore, when raw materials are delivered in large batches to reduce shipping costs, production may be organized in larger batches to minimize setup times, leading to higher levels of WIP and finished goods inventory.

Table 8 also shows that global supply chain disruptions led to a significant decrease in raw materials inventory turnover, while WIP and finished goods turnover remained unaffected. Several factors may explain this outcome. First, the severe disruptions during the COVID-19 pandemic forced companies to increase raw material inventories as a buffer against unpredictable lead times, lockdowns, and shortages. Second, supply chains became especially vulnerable for less replenishable or replaceable components often sourced from specific regions or single suppliers. Delays or unavailability of these components prevented production from proceeding as planned, resulting in an accumulation of replenishable or replaceable raw materials that could not be converted into WIP or finished goods. For example, semiconductor chips play a crucial role in modern vehicles, powering systems ranging from infotainment to essential functions like power steering and braking. Manufacturers like GM and Ford have faced challenges due to supply shortages during COVID-19, leading them to produce vehicles partially and store them until the necessary components become available (CNBC, 2021).

Models (11), (14), and (17) demonstrate the moderating effect of air transportation on supply chain risk exposures across inventory types. Increased air transportation use helps mitigate the negative effects of higher export and import ratios across all stages of inventories including raw materials, WIP, and finished goods. Faster export movement accelerates the sales and restocking cycles for finished goods and WIP, supporting higher turnover rates despite disruptions.

In contrast, Models (12), (15), and (18) indicate that using air transport for exports effectively mitigates the negative impact of global disruptions and accelerates the turnover for all stages of inventories, whereas air transportation only impacts raw materials inventory in the context of imports. While using air transport for imports allows firms to replenish raw materials and provide a strategic response to anticipated shortages and longer lead times, it increases raw material inventory, leading to lower efficiency. The result shows that ensuring raw material availability alone does not necessarily increase turnover for WIP and finished goods, as production may still face constraints from missing critical components.

7. Theoretical contribution

This study makes four significant theoretical contributions. First, toward supply chain risk management literature, our findings refresh the value of transportation mode flexibility, an element that has been relatively underexplored in the existing literature. We highlight its capacity to alleviate the negative impacts arising from inherent risk exposure and external disruptions associated with global supply chains (Cho et al., 2017; Bernabei et al., 2022; Gurbuz et al., 2023; Lorentz et al., 2015; Kulpa et al., 2024).

Second, this study contributes to extant numerical studies examining transportation mode flexibility (Ishifaq, 2012; Shekarian et al., 2021; Fan et al., 2017; Jain, 2018; Park et al., 2018) by providing empirical evidence that complements existing findings, which are primarily derived from simplified or assumed experimental settings devised by researchers. While previous numerical findings offer valuable insights, they can be highly sensitive to the input data and parameters used, implying their limited applicability to real-world scenarios. By incorporating factors often overlooked such as economic influences and management trends, our empirical study relatively better captures the complexity and variability of the real-world situation. Additionally, our study addresses the ambiguity in existing empirical studies, characterized by statistically insignificant or indirectly tested relationships (Sreedevi and Saranga, 2017; Kulpa et al., 2024), by showing the mitigating impact of transportation mode flexibility on the global supply chain risk and disruptions. Given the lack of empirical studies regarding transportation mode flexibility, our study contributes to both numerical analyses and empirical analyses in the literature by better understanding the full picture of this phenomenon.

Third, for inventory literature (Ak & Patatoukas, 2016; Miller & Peters, 2024; Jain, et al., 2014), we suggest critical factors that must be considered in predicting inventory performance. These factors include the split between domestic and global operations in firm's business, the influence of external events such as disruptions, and the dynamic allocation of transportation modes such as extent of integration between air and ocean shipping. By emphasizing these elements, our study advances literature that uses inventory performance, offering a nuanced perspective for future research and practice.

Lastly, our study complements recently increasing body of literature focusing on reshoring as another supply chain risk mitigation measure (Cheng et al., 2024; McLaughlin & Peterson, 2023; Pal et al., 2018; Pedroletti & Ciabuschi, 2023). Reshoring represents the firms' efforts to improve supply chain resilience. But our findings suggest that new ambiguities will be introduced in future research if the transportation mode flexibility is not properly considered given that these dynamics will likely drive greater international shipment volumes.

7.1. Managerial Implication

The extent to which air transport and ocean transport are hybridized for international shipping typically depends on speed and cost. Ke et al. (2015) suggest that transport mode decisions align strategically with industry characteristics, with industries facing greater supply chain uncertainties tending to use more air transportation—a trend seen in the increased share of air transport in exports and imports during the COVID-19 pandemic. According to Miller and Peters (2024), transport mode choices significantly impact inventory management, as they affect cost, lead time, and service level. Both Ke et al. (2015) and Miller and Peters (2024) recommend a mixed strategy: using ocean transport for regular shipments while reserving air transport as a backup for unexpected demand spikes. This approach balances the cost-effectiveness of ocean shipping with the flexibility of air transport.

As the global environment becomes increasingly volatile, uncertain, complex, and ambiguous (VUCA), firms need strategies for managing global supply chains effectively in this VUCA world. Building on previous studies, this study shows that relying on global markets for both revenue generation and sourcing amplifies supply chain risk exposures, which in turn reduces inventory efficiency. Risk management always entails additional costs. Unlike past studies that emphasize diversification in supply and demand, this study highlights transportation modal flexibility, particularly the value of air transport in mitigating global supply chain risks and disruptions. Our findings indicate that industries with a higher proportion of exports and imports via air transportation achieve significantly better inventory efficiency than those relying primarily on sea or land transportation. Furthermore, during disruptions like the COVID-19 pandemic, increased use of air transportation enabled industries to enhance inventory efficiency, sustain production flow, and meet customer demand more rapidly. For example, during the COVID-19 pandemic, Apple encountered considerable supply chain disruptions affecting both air and ocean freight. To address these challenges, the company chartered around 200 private planes to accelerate the delivery of high-demand products, such as the iPhone 12 and AirPods, to retail locations. This proactive strategy enabled Apple to sustain inventory levels and fulfill customer demand despite global transportation constraints (The Information, 2020).

For practitioners, the capability to switch from ocean to air transport when needed can be a decisive competitive advantage during periods of uncertainty. Firms that regularly utilize both air and ocean freight modes experience lower switching costs when transitioning to air transport, as their freight forwarders already maintain contracts and reserved space with airlines. Unlike ocean freight, where firms may directly manage operations through an internal shipping department, access to air transportation capacity is largely mediated by freight forwarders in practice. This circumstance underscores the importance of building robust partnerships with freight forwarders who possess established networks with both ocean and air carriers. Freight forwarders can provide strategic guidance, ensuring firms have flexible shipping options and capacity reserved across different transportation modes. Besides, freight forwarders serve as critical intermediaries for managing complex logistics requirements, such as consolidating shipments, negotiating rates, and ensuring compliance with air freight regulations. Their expertise becomes particularly valuable during supply chain disruptions, enabling firms to secure capacity at short notice and reduce lead times. By leveraging their freight forwarders' established networks and expertise, firms can respond faster to surges in demand and supply shortages, gaining a competitive edge and capturing market share from less agile competitors.

Moreover, the transportation challenges associated with reshoring emphasize the need for robust contingency planning. Many U.S. manufacturers face rising labor costs in outsourced countries, logistical bottlenecks, tariff risks, and geopolitical conflicts. Legislation such as the Infrastructure Investment and Jobs Act (2021), CHIPS and Science Act (2022), and Inflation Reduction Act (2022) provides strong incentives for domestic sourcing and production. Consequently, the construction of manufacturing facilities in the U.S. is accelerating, particularly in high-tech sectors like electronics and electrical manufacturing (U.S. Department of the Treasury, 2023). This trend reflects a shift from "low-cost" to "best-cost" strategies, prioritizing supply chain resilience over cost savings (McLaughlin and Peterson 2023). Reshoring manufacturing bases to home or nearby countries presents both opportunities and challenges for transportation strategies. As manufacturing returns to domestic soil, firms must address the growing complexity of balancing imports and exports with evolving logistics requirements. The effectiveness of reshoring may be limited if international shipping volumes remain high during or after the reshoring trend. This is because U.S. manufacturers possibly continue to depend on imported raw materials and export finished goods to global markets. Consequently, if flexibility in transportation modes is restricted—a factor not extensively addressed in practice—the anticipated risk mitigation benefits of reshoring may be less significant than projected.

8. Conclusion

This study investigates two primary research questions: (1) What are the impacts of global supply chain risks and disruptions on firms' inventory performance? and (2) How does transportation modal flexibility, specifically the strategic use of air versus ocean freight, influence inventory performance amid these disruptions? Using industry-level data from the U.S. manufacturing sector from 2003 to 2021, including the COVID-19 pandemic period, this study examines the effects of export and import ratios, the influence of global supply chain disruptions, and the moderating role of air transportation on inventory efficiency.

Findings reveal that industries with higher exposure to global markets—through sales and raw material sourcing—face increased supply chain risks, leading to reduced inventory efficiency. However, strategic use of air transportation effectively mitigates these negative impacts, supporting inventory efficiency and resilience in the face of disruptions.

These findings have a significant contribution to the global supply chain risk management literature by highlighting the critical role of transportation modal flexibility. While global supply chain risk management and resilience have been widely studied, gaps remain in understanding how transportation flexibility—particularly switching to air from ocean freight for international shipping—affects inventory performance during disruptions. Prior research has predominantly focused on strategies such as supplier diversification and operational flexibility (Manuj and Mentzer, 2008a; Tang, 2006b), with limited empirical support for transportation mode flexibility for international shipping. This study addresses this gap by demonstrating the value of air transportation in the global supply chain, particularly under varying conditions such as the COVID-19 pandemic (Ke et al., 2015; Jain et al., 2018; Manhart et al.; 2020; Kulpa et al., 2024). Lastly, this study supplements the growing body of literature on reshoring manufacturing operations, another measure of risk mitigation, (Cheng et al., 2024; McLaughlin & Peterson, 2023; Pedroletti & Ciabuschi, 2023). Our study suggests incorporating transportation flexibility for future reshoring research is necessary as the transportation challenges will continue.

Practically, this study offers actionable insights for strengthening global supply chain resilience. Transportation modal flexibility enables firms to adapt to unexpected disruptions, such as natural disasters, labor strikes, or infrastructure failures, by pivoting between transportation modes to maintain continuity and avoid costly delays. The findings encourage practitioners to adopt a balanced and responsive transportation strategy, incorporating a flexible portfolio that leverages both air and ocean freight. By doing so, firms can effectively manage the costs and benefits of transportation flexibility, especially during periods of uncertain demand.

Several limitations should be acknowledged. First, this study primarily examines air transportation as a strategic tool for managing supply chain risks. Future studies could broaden this approach by exploring other strategies to achieve transportation flexibility, such as investigating both the decision of global logistics network geography and the locations of suppliers and customers on transportation flexibility simultaneously because these decisions may be interrelated.

Second, this study focuses on inventory efficiency as measured by inventory turnover, a metric widely adopted in prior research (Ke et al., 2022; Gaur et al., 2005; Eroglu and Hofer, 2011). While inventory turnover provides valuable insights into operational efficiency, the scope of this study is constrained by data availability. As a result, other relevant operational efficiency indicators, such as return on assets (ROA), employee productivity, and manufacturing cycle time, are not included. The exclusion of these measures may limit the comprehensiveness of the findings, as these alternative metrics could provide a more holistic view of operational performance. Future research could address this limitation by incorporating a broader range of efficiency measures to validate and extend the findings of this study.

Additionally, future research could conduct longitudinal studies to assess how transportation modal flexibility contributes to supply chain resilience over time. Such studies could track the long-term impacts of flexible transportation strategies on inventory efficiency and financial performance. Further, given the variability in supply chain structures across industries, sector-specific research could provide deeper insights. For example, studying transportation flexibility in sectors like automotive, pharmaceuticals, or electronics may reveal unique challenges and opportunities not evident in more general analyses.

Finally, while this study highlights the benefits of air transportation as a strategy for mitigating supply chain risks, it is important to consider its environmental impact (Bartle et al., 2021). Air transportation is associated with significantly higher carbon emissions compared to other modes, such as ocean or rail transport. The increased reliance on air freight to manage disruptions and improve inventory efficiency may contribute to greater environmental degradation. Future research could explore strategies to balance operational benefits with sustainability goals, such as incorporating green logistics practices, carbon offset programs, or multimodal solutions to minimize the ecological footprint of transportation flexibility. Addressing these concerns would enhance the practical applicability of transportation strategies in achieving both efficiency and sustainability.

CRediT authorship contribution statement

Jian-yu Fisher Ke: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Woohyun Cho:** Writing – review & editing, Writing – original draft, Methodology, Formal analysis, Conceptualization. **Hao Su:** Writing – review & editing, Writing – original draft, Visualization, Methodology.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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