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Systemic risks in supply chains: a need for system-level governance

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Abstract

Purpose – Global and interconnected supply chains are increasingly exposed to systemic risks, whereby individual failures propagate across firms, sectors and borders. Systemic risks have emerged from the decisions of individual firms, e.g., outsourcing and buffer reduction, and are now beyond their control. This paper aims to identify appropriate approaches to mitigating those risks.

Design/methodology/approach – Systemic risks require analyzing supply chains beyond a dyadic perspective. We approach the problem through the lenses of complex systems and network theories. Drawing on the lessons learned from other systemic-risk-prone systems, e.g., energy and financial networks, both in research and practice, we analyze the adequate level of governance to monitor and manage systemic risks in supply chains.

Findings – The authors argue that governance institutions should be mandated to overview and reduce systemic risks in supply chains from the top down, as central bankers do for the financial system. Using firm-level data and tools from network analysis and system dynamics, they could quantify systemic risks, identify risk-prone interconnections in supply chains and design mitigating measures. This top-down approach would complement the bottom-up supply chain management approach and could help insurers design policies for contingent business interruptions.

Originality/value – Instead of looking at supply chains purely from the firms' angle, the perspective of insurers and governments is brought in to reflect on the governance of risks.

1. Introduction

Systemic risk can be seen as the flip side of highly complex and interdependent systems, as our societies, operating in a globalized world, have become (Goldin and Mariathasan, 2014; Centeno et al., 2015). A systemic failure can be defined as the sudden dysfunction of a system sparked by the disruption of some of its parts. It is characterized by cascading processes that turn localized, component-level, or agent-level perturbations into a general dysfunction or collapse (Kaufmann & Scott, 2003; Haldane & May, 2011). Recent striking examples include the disruption of drinkable water supply in Texas caused by cold-induced interruptions of several gas power stations and wind turbines (CNN, 2021), the paralysis of 3.5 billion USD-worth of goods triggered by the silting up of the Ever Given cargo ship in the Suez Canal (The Economist, 2021), or the coronavirus pandemic which has caused unprecedented social and economic impacts around the world.

In supply chains, systemic disruptions originate when one chain member cannot deliver its products to the next one in time. Such situations are common and often harmless because safety stocks, alternative sourcing, or redesign measures are available somewhere else in the chain. But, sometimes, a particular combination of disruptions in space and time triggers a propagation wave along the supply chain, leading to shortages and unexpectedly large economic losses. After a disaster, many businesses get disrupted even though they are not directly affected (Tierney, 1997; Sheffi, 2005; Fujimoto; 2011; Todo et al., 2013). Such indirect consequences can be magnified by the social, economic, or geopolitical context in which they occur. The 2021-2022 chip shortage, triggered by pandemic-control measures affecting production and transportation and by extreme weather events, has been, for instance, greatly amplified by the uneven post-lockdown economic rebound (Attinasi et al., 2021; Fyfe, 2021).

The magnitude of these events (LaBelle, J., & Santacreu, 2022) and the shortage of basic sanitary products during the Covid-19 outbreak in many countries have incentivized policymakers to take actions to stabilize supply chains and secure the supply of critical components. Such ambitions join pre-existing debates on strengthening economic resilience in a more turbulent climate (e.g., Reichstein et al., 2021). Amid rising political debates on manufacturing reshoring, relocation, and reindustrialization (Barbieri et al., 2020), what can firms and governments do to tackle systemic risks in supply chains? Why should they manage such risks differently than more common supply risks? What are the appropriate levels of governance and types of measures?

A study published by the World Economic Forum defines a supply chain risk as systemic when it has the three following properties (World Economic Forum, 2012): it is triggered by an unexpected event, it propagates and induces ripple effects, and it gets amplified because of the inability of the network structure to absorb it. This definition emphasizes the role of network structures in limiting or amplifying risks and implies that some patterns are more prone to risk than others. Similar approaches to systemic risks can be found in the energy (e.g., electricity networks), finance, and banking sectors (Acemoglu et al., 2015; Haldane & May, 2009) as well as in ecosystems (e.g., McCann, 2000). We underline that the network structure of supply chains is not an exogenous attribute of the world economy but the result of individual firms' choices over time. In other words, it is shaped by individual behavior rather than by any random processes, leading to the conclusion that systemic risk in supply chains can be, at least potentially, managed.

Before systemic risk can be managed, it must be measured, which is itself challenging (Pflug & Römisch, 2007). First, systemic risks range among the low-probability, high-impact types of risks, or tail risks, for which nontrivial risk metrics need to be applied (Frank et al., 2014). Next, advanced network modeling is often required to capture the cascading dynamics, whose output is often marked by large uncertainties due to inherent complexities and the lack of data to characterize the system (Thurner et al., 2018; Colon et al., 2021). Last, human behavior is often crucial in unfolding systemic events but is generally difficult, or even impossible, to quantify (Hochrainer-Stigler et al., 2020).

A traditional dyadic approach to supply chains is not appropriate to tackle systemic risks. We propose to take the lenses of complex system and network theories, whereby a supply chain is seen as a network of productive units connected in space and time through transport and communication processes, operating in a larger socioeconomic, geopolitical, and ecological environment, in the vein of Caddy and Helou (2007) using general system theory and Surana et al. (2005) and Pathak et al. (2007) using complex adaptive system theory. By considering supply chains as a whole, we can conceptualize and study emerging properties such as resilience, stability, or viability (Christopher & Peck, 2004; Ivanov, 2020). This approach underlines the role of interconnections within and across supply chains and their dynamics (Forrester, 1961; Sterman, 2000).

Our standpoint differs from more general system-thinking or holistic approaches to supply chain risk management, presented for instance by Ghadge et al. (2013), which comprehensively incorporate many dimensions of risks but focus on management options at the level of firms. Instead, our primary focus is on the ensemble of firms connected through the supply chains and the network-related risks rather than the firms themselves. In an analogy with finance, which will be elaborated on later, we take the standpoint of central bankers overviewing the financial system rather than that of banks. This distinction is crucial because, as pointed out by Churchman (1971, 1979), the way to conceptualize the system is a design choice in itself with profound consequences on the goal of a system, how it ought to be, how to measure improvements, and therefore on potential interventions. Here, we acknowledge that supply chains are mental constructs that we use to analyze the phenomenon of risk propagation which we call systemic risks, and which ought to be reduced. Their boundaries are constrained by our ability to identify all the organizations involved in producing and delivering a product.

With this standpoint, we analyze the root causes of systemic risk in supply chains, namely the business practices of individual firms and how competitive pressures have shaped a highly global, interconnected, yet fragmented production system. Due to the bounded scope of individual firms, how large they may be, they are not aiming to mitigate global turbulences directly. They would rather adapt to them by increasing their agility, often referred to as organizational or business resilience. This firm-centric resilience has, however, ambiguous impacts on system-level resilience and could, in fact, fuel systemic risks.

We argue that risk-mitigation frameworks applied by individual firms are not appropriate to mitigate systemic risks in a globalized world. Additional layers of governance are needed. First, business organizations can help identify sectoral threats and work with other stakeholders to alleviate them, for instance through lobbying, but they have limited means and bounded scope. Next, insurers are becoming central players in tackling systemic risks. Through the development of business interruption insurance, or supply chain insurance, they inherit the complexity of the supply chains and need to assess the pattern of interconnections within their portfolio. Governments are already playing a role, for instance by providing infrastructure or rescue packages, but without monitoring or directly tackling systemic risks. We argue that there is a need for an additional system-level layer of governance with the overarching mandate to reduce systemic risks in supply chains, as central banks for the financial system. Such an institution would overview supply chains from the top down, monitor the level of systemic risks, and act to reduce systemic-risk-prone structures of supply chains. The toolbox of complex system and network analysis could be used, provided adequate data collection procedures and transparency regulations are in place.

The paper is organized as follows. Section 2 highlights the mechanisms that have intensified systemic risks in global supply chains. Section 3 briefly reviews firms' practices and strategies to deal with supply chain risks and their consequences on systemic risks. Next, section 4 contrasts how systemic risks are tackled in other sectors, namely power grids and financial networks, and pinpoints the current gaps in managing systemic risks in supply chains. Finally, section 5 presents a framework for managing systemic risks, highlighting the role of different layers of governance and their practical implications.

2. Increase of systemic risk in global supply chains

Globalization has made economies more interconnected. Between 1980 and 2019, international trade has grown 35% faster than the world gross domestic product (World Bank, 2021; World Trade Organization, 2021). This growth has been increasingly driven by the trade of production inputs and intermediaries, called vertical trade (Hummels et al., 1998, 2001; Jones et al., 2005). These larger transnational flows result from the disintegration of production processes, which have been split into multiple stages that are run by different geographically scattered companies (Ferrarini, 2013). Consequently, supply chains have become longer and more complex, which gave rise to the field of supply chain management (Oliver & Webber, 1982; Christopher; 1992). This trend is particularly marked for technological products such as cars or electronic goods, which are made of an increasing number of components—modern cars are made of about 30,000 pieces. A mobile electronic device may be designed in the USA but assembled in China, with components from South Korea, the USA, and Japan; those parts are themselves made of subcomponents from China, the Philippines, etc. (Timmer, 2010). According to Sheffi (2005), some electronic products travel half a dozen times the Pacific Ocean before being sold. Global value chains now account for almost 50% of global trade (World Bank, 2020).

The global fragmentation of production results from outsourcing and offshoring strategies (Jones et al., 2005). Some companies have opened subsidiaries in other countries to offshore, i.e., relocate some of their activities. They seek to benefit from lighter production costs and significantly lower wages. Other companies have chosen to focus on a small segment of their activities, where they are the most competitive and will concentrate their research and development, marketing, and logistic efforts. They outsource the other segments to specialized suppliers and benefit from their higher flexibility and reduced costs. These practices have been facilitated by the gradual removal of tariffs starting 1960s (Hummels et al., 2001; Yi, 2003; Kaminski & Ng, 2005) and boomed in the 1980s when Japanese and US companies offshored and outsourced activities in Southeast Asia and China (Baldwin & Lopez-Gonzalez, 2015). The development, at affordable costs, of transportation and communication technologies, financial intermediation, and insurance services has enabled the management of remote production units and suppliers, also for small companies (Jones et al., 2005).

Such practices have generated complex patterns of interdependencies, which have facilitated the propagation of shocks. In global and fragmented supply chains, distant processes are interdependent, and unexpected issues may quickly propagate. The `Albuquerque accident' involving Swedish company Ericsson is prototypical (Norrman & Jansson, 2004; Sheffi, 2005). In 2000, a lightning bolt hits an electric line in Albuquerque, New Mexico's largest city, and induces a short power outage in a factory owned by the Dutch company Philipps. In the absence of an alternative power generator, fire sparks; it is extinguished ten minutes later but has affected some critical equipment. Two production lines are stopped for three weeks and stay insufficiently productive for months. The disrupted process was extremely specific, and Ericsson failed to find an alternative supplier promptly. In a booming market, the production of cell phones was disrupted. The losses incurred by Ericsson were about 50 times higher than the material damages (Sheffi, 2005). Following this accident, Ericsson sold its cellphone production activity to the joint venture Sony Ericsson and profoundly renewed the management of supply chain risks (Norrman & Jansson, 2004).

The nature of trigger events can be very different—e.g., a geopolitical crisis, a social movement, or, as in the `Albuquerque' accident, a weather event—and they may disrupt production through a variety of mechanisms: damages to productive equipment, workforce or transporters unable to access production sites, disruptions of essential utilities such as gas, electricity, water, communication. Some large natural disasters have cast light on the role of supply chains in propagating risks globally. The 2011 Tohoku earthquake and the tsunami that followed generated the most enormous human and material damages in Japan since World War II. It also disrupted the production of many critical components, leading to significant production losses worldwide (World Economic Forum, 2012). In Japan only, Todo et al. (2013) reported that about 90% of economic output losses were due to supply chain disruptions. The same year, central Thailand was hit by floods, the highest in 70 years, which heavily disrupted the global supply chains of cars and electronic components (Chongvilaivan, 2012). Importantly, natural events need not be destructive to destabilize supply chains, as illustrated by the eruption of the Eyjafjallajökull volcano in 2010 and its impact on global businesses through the disruption of air transportation.

Supply chains are nowadays more exposed because they are longer and more specialized. Events that are rare for each firm become more likely when the whole chain is considered. Barrot & Sauvagnat (2016) showed that vertical specialization—the fact that inputs are more specific and sourced from distant suppliers—largely increases the propagation of risks. Disruptions not only cascade from suppliers to customers but may also affect supply chains horizontally: if a firm is affected by the disruption of one specialized supplier, its other suppliers tend to suffer from losses due to demand reduction. These supply chain intricacies are one of the drivers behind the rising economic impact of natural disasters (Stecke & Kumar, 2009; Swiss Re, 2014, 2016). In surveys run by the Business Continuity Institute (BCI), a private consultancy that surveys about 500 firms each year on supply chain disruptions, adverse weather and climate extreme events almost always rank among the three primary sources of supply disruption (BCI, 2015). These threats are not likely to fade out with climate change, which induces a shift in the frequency, intensity, and spatial distribution of weather-related extreme events (Ghil et al., 2011). These phenomena are of serious concern for businesses, insurers, and, in general, organizations operating through a multi-tiered, complex web of intermediaries, such as humanitarian aid.

3. Limits to firm-level risk management

Mitigating supply chain risks is very challenging for firms, and the need for competitiveness strongly shapes their efforts. Supply chain disruptions are rather frequent—at least once per year for most BCI survey respondents (2018). Their negative impact on the financial performance of companies has been empirically confirmed (Hendricks & Singhal, 2003, 2005). Mitigating the risk of supply-chain disruptions widely differs from the management of other operational risks. Supply chains may indeed bring to one's door the risks taken by another firm far away, both its operational risks—e.g., an accident on a production line—and its environmental risks—e.g., a climate or geopolitical event.

Managers, therefore, need to increase their monitoring capacity. However, they often lack visibility over their supply chain, such that 30% of the respondents of the BCI survey do not attempt to identify the source of supply chain disruptions. While firms usually know their direct suppliers, they often struggle to keep track of their sub-suppliers, also called tier-2 suppliers, and entities further away in the chain (BCI, 2018; Wang et al., 2015). Over half of the disruptions seem, however, to originate from this deeper segment (BCI, 2018). In addition, supply chains are fluctuating systems—e.g., suppliers change their contractors, firms go bankrupt, others enter the market—and are therefore hard to map in real-time.

Inherent difficulties of inter-organizational communication may also accentuate the propagation of supply disruptions. Jüttner et al. (2003) identify such network-related risks: unclear responsibility, lack of responsiveness or overreaction, distorted information, and mistrust. A slight fluctuation in demand at one point of the chain may be magnified as orders cascade up, leading to excess inventory, production downtime, and transportation peaks. This phenomenon, known as the bullwhip effect (Lee et al., 1997), is well known by supply chain managers, empirical documented (e.g., Thun & Hoenig, 2011) and has been experimentally tested for decades through the so-called beer game (Sterman, 1989).

Therefore, managing the risk of supply disruptions has become a prominent topic of supply chain management, which focuses on ways to coordinate operational and strategic capabilities within and across firms' boundaries to enhance the value created for the end customer (Mentzer et al., 2001). This field was initially concerned with inventory reduction and the involvement of suppliers to speed up product development (Cooper et al., 1997). Management scientists have published frameworks to identify supply chain risks and mitigation strategies derived from interviews, focus groups, and case studies—the `Albuquerque accident' for instance (Chopra & Sodhi, 2004; Blackhurst et al., 2005; Manuj & Mentzer, 2008). Resilience is often set as the target for supply chain risk management (Christopher & Peck, 2004; Blackhurst et al., 2005; Abe & Ye, 2013). They implicitly refer to the engineering definition of resilience, i.e., shortening the return to normal operation, rather than the ecological or psychological definition of the concept (Pimm, 1984; Holling, 1996).

Two types of measures are typically put forward. A first set aims to increase the in-built robustness of the supply, e.g., hold safety stocks and multiple production facilities, enlarge the supplier base, standardize inputs. Such measures can be calibrated to deal with high-probability low-impact risks using operation research models (Snyder et al., 2016). However, preparing for rare events that may generate great damages is far more challenging (Norrman & Lindroth, 2004). In the absence of meaningful metrics to handle such uncertainties, managers may use stress tests, in the form of `what if' scenarios, to identify bottlenecks and particularly vulnerable points (Chopra & Sodhi, 2004; Christopher & Peck, 2004). Another set of measures aims to improve organizational agility to handle unexpected disruptions, e.g., collaboratively developing rescue plans with suppliers, decentralizing decision-making, and increasing communication between services. A pillar of such an approach is the design of business continuity plans, which identify solutions to enable the pursuit of operations during a disaster and speed up recovery. Such measures often go with developing a more responsive corporate culture (Sheffi, 2005).

Most of the time, competition favors firm agility rather than supply-chain robustness. Staying competitive is a matter of survival for firms, and balancing risks and returns is their very nature. Supply chain managers permanently deal with contradicting objectives (Cooper et al., 1997): reduce inventories while ensuring product availability, source standardized inputs for customized products, maintain a diverse supplier base but reduce sourcing costs. Measures strengthening the robustness of supply chains, such as safety stocks and multiple sourcing, are costly, and the benefits they generate may be hard to evaluate.

With heightened competitive pressure globally, companies have tended to streamline their supply chains to cut costs. Some of the principles of the so-called Toyota model (Enkawa & Schvaneveldt, 2001), such as just-in-time or lean management, have had a substantial impact on supply chain practices. Following them, firms develop stronger relationships with fewer suppliers, enabling them to rely on fewer inventories and shorter delivery times. They can also better manage product quality and design more customized products, thereby gaining competitive advantages. These practices may even be implemented in conjunction with global outsourcing (Das & Handfield, 1997).

These optimization processes have made supply chains more sensitive to disruptions (Stecke & Kumar, 2009; World Economic Forum, 2012). For instance, Fujimoto (2011) underlines that the high rate of customer-specific or buyer-specific processes in Japanese industries has contributed to lengthening economic recovery after the 2011 Tohoku earthquake. Similarly, Todo et al. (2013) have established the positive effect on the post-earthquake recovery of having geographically diverse suppliers and customers but have stressed that this diversification strategy might erode competitiveness. Fujimoto (2011) argues that some Japanese sectors are globally competitive precisely because of highly concentrated technology providers. He identified the `diamond structure' of many Japanese supply chains of manufactured goods: few final producers, many tier-1 and tier-2 suppliers, and few tier-3 suppliers for essential components. This concentration at the base of the chain, driven by cost-effective technologies, came with significant economies of scale that boosted the competitiveness of many sectors. At the same time, the chain has become less resilient since a disruption affecting these few suppliers may generate enormous consequences.

Measures that strengthen the structural robustness of supply chains seem too costly in the struggle for competitiveness. Outsourcing has been pursued at the expense of network brittleness. Some companies have managed to compensate for this loss of structural robustness by enhanced agility. They have developed the internal organizational capability to proactively identify and manage unexpected events (Chopra & Sodhi, 2004). Incidentally, Toyota is one of the top performers in this regard; it has often managed to resume production much earlier than expected after disasters (Nishiguchi & Beaudet, 1998; Fujimoto, 2011).

For some supply chain managers, a low-probability hazard will inevitably occur, unexpectedly propagate, and generate losses even with mitigating efforts. Their role is to foster adaptability and responsiveness, which are sources of competitiveness (Sheffi, 2005). For Ponis & Koronis (2012), who reassess the ecological foundations of resilience (Holling, 1973; Walker et al., 2004), resilience is not only about restarting the production line but how firms may learn from disruptions and reorganize. This view joins the broader business strategy literature, in which, as proposed by Hamel & Välikangas (2003), resilience is the capacity for continuous reconstruction in a fast-changing environment.

This approach to resilience recognizes the possibility of sudden and abrupt changes and that firms alone cannot fully control their supply chains. Firms are embedded into a complex web of interactions; it creates systemic risks that are escaping their control and to which they need to adapt. From an economic theory standpoint, Lorenz et al. (2009, p441) define systemic risk "as an undesired externality arising from the strategic interaction of the agents." We argue that this approach and definition elude the role of agents in shaping the network of such strategic interactions. Firms are embedded into the complex web of interactions they have collectively created. In other words, systemic risks are not external to the modern economic system but one of its by-products.

It is worth noting that supply-chain stability can be interpreted as a public-good problem (Hardin, 1968). Firms benefit from a stable supply chain but have few incentives to contribute to this stability. In a stylized, game-theoretic supply-chain model, Colon et al. (2020) found that the fragmentation of production into many distinct entities disincentivizes firms from providing safety stocks. Systemic risks are, as a result, increased. In other words, firms benefit from a low level of turbulence, but their need for competitiveness, in the regulatory and economic context of the past decades, has led them to create risk-wave-prone supply chains. Like climate change, mitigating those new, systemic risks requires collective actions with few short-term benefits. Firms are more incentivized to adapt to this new environment individually and boost their internal resilience. Adapting to systemic risks allows them to stay competitive, but it is not considered whether this individual adaptation increases even more systemic risks. To escape this trap, we argue that a top-down approach needs to be combined with these bottom-up initiatives.

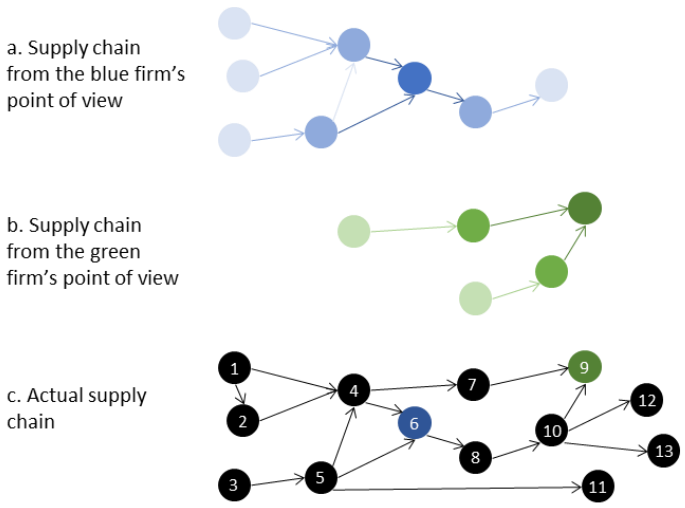
4. Governing systemic risks in networked systems

Figure 1 illustrates the intrinsic limitations of bottom-up, firm-centric approaches to supply-chain risk. Panels (a) and (b) present the perspective of two firms, colored in blue in (a) and in green in (b), on their supply chains. The whole supply chain is represented in panel (c). The blue firm, numbered 6, has a good overview of the firms located upstream; however, it has limited information on two interdependencies between suppliers that would play an essential role in the spreading of a disruption. Its two tier-one suppliers, firms 4 and 5, are not independent because firm 5 also supplies firm 4. Firm 6 may be aware of this relationship but is likely to have little information about it. Two tier-two suppliers, firms 1 and 2, are also connected, but the blue firm is not likely to know about it. The green firm, a final producer, has a simpler supply network. Its two tier-two suppliers, firms 4 and 8, are indirectly connected through firm 6, a connection which the green firm does not know. The failure of firm 4 would have higher consequences than it would expect.

Each firm in panel (c) manages its supply-chain risks, but their risk evaluation is inaccurate because they have a limited view of the actual network of interdependencies. In addition, firms have the incentive to boost their profit but not reduce supply-chain instabilities. Consequently, the sum of all firm-level risk-mitigating measures is not likely to adequately manage the propagation of risks, as illustrated by Colon et al. (2020). A similar phenomenon is observed in financial systems: the profit-maximizing behavior of agents did not prevent and even contributed to the 2008 crisis (Haldane & May, 2011).

No agent is formally entitled to monitor these supply chain intricacies nor to manage systemic risks in supply chains, unlike two other systems that are also confronted with systemic risks: power grids and financial systems; see Table 1. They serve as points of comparison to further analyze how systemic risks in supply chains may be governed from a top-down perspective. In power grids, systemic risk is the potential occurrence of a sizeable and unexpected blackout resulting from a small perturbation or a minor grid reconfiguration (Hines et al., 2008). Power grids are managed by transmission system operators, which are either public or heavily regulated and thrive on reducing the risks of such systemic failure. In finance,

Figure 1 Gap between bounded perceptions of the supply chain and the overview needed to manage systemic risks.



Notes: Schematic diagram of a supply chains perceived by two firms (a-b) and how it actually is (c). Each bubble represents a firm, and each arrow represents a supplier–buyer relationship. The blue (a) and green (b) firms share the same supply chain, but they see it differently. One can assume that firms know their tier-two suppliers and clients. The lighter the color of the supplier, the clients, and the linkages, the less information the firm has on them. In panel (c), the entire supply chain is represented, and firms are identified by a number used in the main text.

as experienced in many crises, strong interlinkages between banks and other players make the financial system prone to domino effects and bankruptcy chains.

Contagion risks are illustrated by the 2007 subprime mortgage crisis, which paved the way to the largest financial crisis since the 1930s. The goal of central banks is to reduce systemic risks, even though they only manage parts of the global system (National Research Council of the National Academies, 2007; Goldin & Vogel, 2010). After the 2008 financial crisis, new tools were developed to overview the system-wide impact of the interconnections between financial institutions. These methods, which came from network and complex system theories, consider the financial markets as a dynamic network of heterogeneous and interlinked nodes, each of them having an adaptative behavior. On these premises, indicators were designed to measure systemic risk and to estimate the criticality of specific banks, such as the DebtRank algorithm (Battiston et al., 2012; Bardoscia et al., 2015; Caccioli et al., 2017). They are becoming important tools to measure and manage financial systemic risks (Caceres-Santos et al., 2020; Poledna et al., 2021)

Tackling systemic risks requires escaping from a firm-centric view and overviewing these intricacies. Viewing the supply chain as a whole and analyzing it through the lenses of system thinking has already been proposed (Surana et al., 2005; Pathak et al., 2007; Ivanov, 2020), yet their implications for risk management are focused on firms. We argue that another approach is needed, which we illustrate with examples from power grids and financial networks. Supply chains differ because no organization is formally entitled to tackle systemic risks.

Insurers and reinsurers may de facto take this role because firms increasingly ask them to cover economic losses generated by supply chain disruptions (Allianz Global Corporate & Specialty, 2012: Mizgier et al., 2018). On top of business interruption (BI) insurance products, which cover loss of income caused by damages to the insured properties, contingent business interruption (CBI) insurance covers losses resulting from property damages of suppliers or customers. The market for CBI insurance has grown over the past decade (Voelker; 2016). Risks are thereby transferred to insurers and reinsurers, which may become the organizations that could also deal with systemic risks in the global production system.

However, this transfer of risk is highly challenging to insurers. The distribution of BI and CBI claims has a much heavier tail than traditional property damage insurance, showing that such losses can be disproportionately higher and harder to predict (Mizgier et al., 2018). BI and CBI insurance are complex and tied to multiple characteristics of the insured firm—e.g., locations of the production sites, production and supplier redundancy, inventory, business continuity plans, supplier and client network—and to the reaction of the firm during a disruption as due diligence measures—e.g., rescheduling, inputs or supplier substitution (Rose & Huyck, 2016; Mizgier et al., 2018). With fragmentation and high connectivity of the production system, double counts and misevaluation of potential damages triggered by one event are likely. For instance, the disruption of a non-insured supplier could spark CBIs for multiple insured firms. Insurers, like central bankers and transmission operators, are in high demand to better understand the role of the network structure on systemic risks and assess the contribution of specific firms to supply chain risks (Munsch, 2013).

The contagion dynamics in supply chains is highly multidimensional, combining financial, operational, and strategic aspects. Complex systems and network theories provide methods to model such phenomena. Such modeling is particularly challenging because firm-to-firm data are tough to access. On the financial aspect, suppliers and customers are interdependent through their payments, leading to potential chains of bankruptcies. This financial domino effect in supply chains has been investigated in theoretical settings (Battiston et al., 2007; Delli Gatti et al., 2009) and actual data (Fujiwara, 2008).

Firms within a supply chain are primarily interdependent on their operations. Dynamic input-output models can then be applied to track cascading disruptions (e.g., Hallegatte, 2013). Because of data availability, those models have, in general, a sector-to-sector granularity. Recent works have modeled supply chains at a thinner level using firm-level data, enabling the study of systemic risks in supply chains (e.g., Inoue & Todo, 2019). For instance, by introducing a logistic dynamic into an economic input-output model, Colon et al. (2021) found a trade-off between localized and globalized supply chains. When they are too global, supply chains are exposed to multiple disruptions but can restart quickly because all parts of the chains are unlikely to be disrupted simultaneously. When they are too local, supply chains are isolated from most disruptions, but if a problem occurs, it is likely to affect multiple interdependent firms simultaneously, which considerably lengthens the recovery. This finding is consistent with Todo's analysis of the Tohoku earthquake (2013). Firms whose supply chains were entirely affected suffered much more than those with geographically diverse supplier networks.

Insurers can use such studies and models to set guidelines and requirements for their customers who want their supply chain insured and help them adjust the premium prices (Dong & Tomlin, 2012; Zhen et al.; 2016). As more and more firms get insurance for their supply chains, insurers and reinsurers need

Table 1 Main features of systemic risks in power grids, financial systems and supply chains

Domain	Power grids	Financial systems	Supply chains
Nodes of the network	Power plants, lines and substations	Banks, funds, investors, and firms	Non-financial firms
Agent managing systemic risk	Transmission network operators	Central banks	Insurers, governments
Examples of trigger events	Disconnection of a line	Misevaluation of an asset	Accident in a facility
Propagation mechanisms	Load redistribution	Financial interdependence	Supply disruption
Amplification mechanisms	—	Herding behavior	Bullwhip effect
Consequences	Blackout	Bankruptcy chain	Economic loss

to identify the interdependence between the supply-chain-risk profile of different firms. They need to overview supply chains from the top to gauge the level of systemic risks and protect their assets. To that end, analyzing firms as the nodes of a complex network and applying such network models are crucial. But not all firms would want to get insured, either because of costs or because they assume they are not at risk. Therefore, insurers' view would only be partial, and cooperation with other stakeholders and institutions may be needed, such as business organizations.

The provision of stable supply chains is also of public interest. The 2021-2022 global chip shortages have strongly affected multiple industries, leading to sizeable economic impacts (Attinasi et al., 2021; LaBelle & Santacreu, 2022). Governments and global institutions have a role to play in managing systemic risks in supply chains from the top. Given the global footprint of supply chains, no government alone can entirely grasp systemic risks. Instead, regional or global governance arrangements on systemic risks in supply chains need to be established, as for the financial system (Goldin & Vogel, 2010) and climate change (Field et al., 2012). In the wake of the COVID-19 pandemic, the Organization of Economic Cooperation and Development (OECD) has issued guidelines for increasing the resilience of global supply chains, highlighting the importance of regulations and intergovernmental cooperation, i.e., top-down measures on top of bottom-up, private-sector efforts (OECD, 2020; 2021). Even though global institutions still exhibit structural shortcomings for appropriately tackling systemic threats (Goldin & Vogel, 2010), significant steps could be taken to reduce systemic risks in supply chains.

5. Steps to reduce systemic risks in supply chains

Table 2 summarizes the different risk layers in terms of the severity of cascading impacts through the systems, starting from the low-risk layer, focused on the individual firms, up to the systemic-risk layer, which includes severe disruption of the whole supply chain. We suggest governance options, examples of measures, and analytical frameworks and tools for each layer.

We start with the bottom row, which focuses on individual firms. They are the risk bearers and need to manage their risk. The first, straightforward approach is to develop their own capacities to manage disruptions—e.g., hold safety stocks, find alternative suppliers, develop continuity plans. Such measures are appropriate to a so-called low-risk layer (Mechler et al., 2014), which includes rather frequent supply chain risks and for which well-identified mitigating measures exist. Uncertainties are quantifiable, such that cost-benefit analysis can be implemented, and optimal levels of stocks can be informed by operation research models (Snyder et al., 2016).

For less frequent but more damaging realizations of supply chain risks, which we can call a middle-risk layer, firms can engage with the other firms in their supply chains. They can collaboratively design continuity plans with suppliers, adjust the technical design of the products to reduce dependency on critical components, agree on proactive stock management processes, etc. The strategy of certain multinational "flagship firms" may be particularly in moving the practice of a whole industry and connecting firms within a business network (Rugman & D'Cruz, 2003). These two layers, which correspond to the bottom rows of Table 2, entirely lie within the framework of SCM and correspond to what Azadegan & Dooley (2021) identified as micro and meso-level resilience strategies.

Some risks are common to a whole sector, e.g., when many car manufacturers depend on a few chip factories. Business organizations can collect concerns and experiences from the bottom up to identify those risks, for instance, by surveying and interviewing their members. They can, in turn, produce guidelines, communicate good practices, or try to align the interests of their members on some supply chain goals. This level of governance is grounded in the decisions of firms, i.e., from the bottom up, but a certain degree of autonomy can be established such that supply chain risks may be overviewed from the

Table 2 Different layers of supply chain risks and their associated governance options, examples of measures and relevant analytical frameworks and tools.

Approach	Risk layers	Governance	Measures	Frameworks and tools
Top-down ⬇	Systemic	Government, coalition of governments, intergovernmental institutions	Transparency, data regulation, global monitoring, strategic stocks	Complex system models, network analysis, stress testing, what-if scenarios, etc.
	Middle/ Systemic	Insurers, reinsurers	Portfolio balancing, premium pricing, risk-mitigating measures and due diligence requirements	Risk quantifications, copula models, etc.
	Middle/ Systemic	Business organizations	Strategic or tactical alignments, lobbying, guidelines, experience sharing	Surveys, interviews, policy reviews, data sharing, sectoral analysis, etc.
	Middle	Supplier-buyer arrangements	Pre-booked stock, refilling processes, design adaptation, etc.	Supply chain management, contract management
⬆ *Bottom-up*	Low	Risk management of individual firms	Safety stock, dual sourcing, business continuity plans, etc.	Supply chain management, operation research models, cost-benefit-analysis, expert knowledge

Notes: On the top row, a top-down governance approach is more appropriate for the systemic risk (top row). A bottom-up approach is preferred for the low layer of risk with little propagation impact (last row). In between, the governance approach can be mixed.

top down. Business organizations may integrate objectives of supply chain stability in their lobbying practices, for instance, by asking public authorities to fund infrastructure projects.

Firms may ask insurers to cover their supply chain risks. Such contracts transfer the risk to insurers from the bottom up. But the growing amount of supply chain liabilities is such that the supply chain complexities and their associated propagating risks are also transferred to the insurance market. Large insurers and reinsurers need to "connect the dot" by estimating risks of cascading disruptions between seemingly disconnected insured companies, thereby adopting a top-down approach to managing systemic risks. They may adjust the premiums not only according to measures taken by the firm, such as safety stocks, but also to network-dependent choices, i.e., the position of the firm within the supply chain and how it is connected to it, which can be in part decided by the firm.

At the highest level, systemic risks are also a concern for governments. Macro-level measures are already taking place in specific sectors through guidelines or relief measures (Azadegan & Doodley, 2021). Governments can also organize strategic stocks of critical inputs or issue policies to increase transparency. Policies that extend accountability of multinational firms, such as the French Loi de Vigilance or the forthcoming European Directive on Corporate Sustainability Due Diligence, can powerfully stimulate firms' oversights of their supply chains and contribute to more transparent value chains (Clerc, 2021).

But to adequately address systemic risks in supply chains, a governance body needs to be set up and given a formal mandate by one or several governments to ensure supply chain stability, like power grid operators who prevent blackouts or central banks that aim at financial stability. Such a body, agency, or committee would be detached from the firm-centric view and could focus on overviewing the system of all firms and their interactions. It could be first established by a single government, then extended to a group of states with already formal governance institutions and shared interests, such as the European Union or the OECD.

By viewing supply chains as complex and dynamic networks, such institutions could perform stress tests and identify bottlenecks, as promoted by the OECD (2021). To that end, the system-level quantification of risks through complex systems and network modeling is crucial. Such analytics could then lead to measures to define country-level strategic stocks and contingency plans and reshape supply-chain networks. Measures could be, for instance, taken to restrict the connection between the firms to decrease systemic risk, in the vein of anti-trust policies, or to ensure that critical public procurement includes redundant production pathways. By simulating a 'systemic-risk tax' in interbank networks, Poledna & Thurner (2016) show that most systemic risks could, in theory, be eliminated. This tax was inducing a reorganization of the network to avoid risk-inducing interdependencies, as if, in Figure 1, firms would be incentivized to modify their supplier network.

This top-down approach is, of course, not a panacea that could solve all systemic risks but corresponds to the adequate playing field to tackle this issue. Regulations have limitations, and their implementations can cause side effects, particularly when it increases the level of uncertainty in the business environment (Darby et al., 2020). A top-down approach cannot replace the management of supply risks done by each company. Firms have a more profound knowledge of their current operations and relationships with suppliers and clients, making their bottom-up approaches effective and appropriate. A top-down network overview will be shallower in understanding each node of the system but more comprehensive for capturing the intricacies of supply chains and therefore systemic risks.

In practice, the top-down approach would require setting up databases fed by robust data collection procedures, whereby firms would declare their suppliers and clients and quantify their level of dependency. In the USA, regulation No. 131 of Statement of Financial Accounting Standards obliges publicly listed companies to declare any customers representing more than 10% of sales. This regulation has enabled researchers to draw significant findings on the propagation of supply chain disruptions; see Barrot & Sauvagnat (2016). It needs to be developed and strengthened because, as such, it has a very limited scope of application and lacks standardization of the responses (see the example of the steel industry in Klimek et al., 2019). Setting up such data collection requirements is likely to start in a single country, enabling institutions from that country to engage in the top-down approach to systemic risk reduction. Given the global footprint of supply chains, analyzing the import and export of different sectors from one country to another would quickly appear to be crucial, making international cooperation necessary to align standards and systematize data reporting. The OECD (2021) has identified practical measures to improve supply-chain transparency and data circulation, with the example of the Agricultural Market Information System created after the 2007 food crises.

A challenge is defining the proper scope of data that needs to be captured because it is not feasible, and arguably not desirable, to centralize all firms' data in one place. This question directly connects to the models that will use those data and their optimal complexity level. Recent findings from systemic risk research provide some elements to guide the analysis. Three kinds of systemic-risk patterns should at least be captured: the "too big to fail" pattern, e.g., a firm that produces 10% of the world's steel, the "too interconnected to fail" pattern, i.e., firms whose disruption would cause major domino effects (Battiston et al., 2012), and the "too specialized to fail," e.g., the sole provider of a crucial technical component to a whole sector. These patterns come from the study of financial and ecological networks and have meaningful applications for supply chains.

Last, a tremendous challenge is the exposure of supply chains to multiple threats: extreme weather events, industrial accidents, geopolitical unrest, pandemics. For the same pattern of interdependencies between firms, the actual level of systemic risks can sharply increase when several threats materialize simultaneously, for instance, flooding amid pandemic restrictions. Such unfolding of events, often called "perfect storms," partly explains the 2021-2022 global chip shortage (Fyfe, 2021). In another field, similar unfortunate intricacies accounted for the 2019-2020 Australian wildfire (Handmer et al., 2020). For supply chains, such events unveil pre-existing weaknesses (Kent & Haralambides, 2022), such that similar scenarios are valuable inputs to supply chain stress testing and should be integrated into the governance of systemic risks.

6. Conclusion

A by-product of the globalization and fragmentation of supply chains is the rise of systemic risks. Competitiveness-led outsourcing and offshoring strategies have generated complex interdependencies between firms, which they now find hard to handle. The field of supply chain management provides a valuable framework to tackle low (frequent but small-impact supply-chain disruptions) and middle layers (less frequent but higher-impact disruptions) of risks from the bottom up. Firms mobilize their resources to create buffers, engage with suppliers, and set up business continuity plans. But many measures that sustain the robustness of the supply chain seem incompatible with competitiveness objectives. All firms benefit from the stability of supply chains, but few have any incentive to support this stability. As a result, firms individually adapt through enhanced agility, which has an unclear effect on systemic risks. As experienced in financial systems, firm-level mitigation measures do not necessarily reduce systemic risks. Such potential contradictions remain to be researched within the supply chain literature.

We argued that a top-down approach is needed to tackle systemic risks in supply chains. Governance institutions should be mandated to promote supply chain stability, as central bankers aim to stabilize the financial system. Such institutions could be existing or new and should be as independent as possible from the large firms. The extent and geographical coverage of supply chains to overview would need to be discussed and defined in the mandate. To manage stability of supply chains, this regulating body would rely on analytical tools that compile firm-level data and supplier–buyer relationships. Methods from network analysis and system dynamics can be applied to quantify systemic risks, identify risk-prone patterns of interconnection, and design potential measures.

Such methods, which are at the edge of complex system modeling, can enrich the analytical toolbox of supply chain management beyond the dyadic perspective, both in theory and practice. They offer ways to disentangle the multiple pathways of interdependencies within and across supply chains, which is crucial for institutions managing systemic risks, for insurers when issuing contingent business interruption insurances of interconnected companies, and for supply managers trying to identify vulnerabilities generated by a complex supply network. These methods still require improvements and inputs from supply chain management research to appropriately tackle the multidimensionality of supply chains.

Collecting supply-chain data from individual firms is a crucial prerequisite. In the USA, a minor regulation, limited in scope, has already greatly helped understand risk propagation in supply chains. A systematic, standardized, and ideally international data collection process would help tackle system risks immensely. It could be fostered by regulations on supply chain transparency and due diligence (OECD, 2021). The example of the 2008 financial crisis is insightful for supply chains in that regard. Data requirements and network modeling have significantly helped better characterize systemic risks. Treating and integrating those data, which are often heterogeneous and incomplete, still face important implementation challenges. Such a monitoring process would need to be iteratively updated to keep up with the dynamic nature of supply chains.

The Covid-19 pandemic has highlighted the fragility of several supply chains, such that governments have flagged their intention to take state-led actions to secure critical supply chains and avoid knock-out effects. This top-down approach could be used for this purpose. Insurers could also be involved in such governance institutions because they are increasingly asked to ensure supply chain losses via contingent business interruption insurances. Covering their clients' risks, which are unlikely to be independent, exposes them to systemic risks, such that they have a clear interest in reducing them. In practice, implementing stability-enhancing measures from the top is expected to meet resistance because it may erode the profitability of some firms, even though most firms would benefit from more stable supply chains. In this context, the choice of governance settings and instruments will be crucial to reducing systemic risks successfully, representing an important topic for further research.

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