Enhancing resilience: model-based simulations

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d'Artis Kancs
European Commission Joint Research Centre, Brussels, Belgium and Science Research Innovation Implementation Centre, National Armed Forces of Latvia, Zpiic, Latvia

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Abstract

Purpose – In light of the recently experienced systemic shocks (the COVID-19 pandemic and the war in Ukraine), we investigate supply chain robustness. We aim to understand the potential consequences of uncertain events or adversary's action on critical supplies in the Alliance.

Design/methodology/approach – We leverage a parsimonious supply chain model and investigate the relationship between upstream supplier concentration/diversification and the supply chain's robustness (survival probability) in the presence of uncertain systemic shocks. In several scenarios of shock events, we simulate alternative input sourcing strategies in the presence of uncertainty.

Findings – A firm-level cost-focused optimisation may lead all upstream suppliers to concentrate in one location, which – when subsequently hit by a shock – would result in a disruption of the entire supply chain. A chain-level forward-looking optimisation diversifies the upstream supplier location and sourcing decisions. As a result, the supply chain's survival probability is maximised, and critical supplies will continue even under the most demanding circumstances.

Research limitations/implications – Our findings encourage political and military decision makers to enhance upstream supply chain robustness in critical and strategic sectors, such as the diversification of nitrocellulose supplies currently sourced almost exclusively from China by European gunpowder manufacturers.

Practical implications – Our findings have direct recommendations to supply chain downstream decision makers and to the government's policy choices. Since global supply chain (GSC) disruptions in critical sectors may have catastrophic impacts on social welfare and the probability of shocks such as COVID-19 and Russia's war may not be known even approximately, robust decision rules seem to be the appropriate tools for policymaking in critical and strategic sectors such as energy supplies, food and water, communication and defence. A robust supply chain is one in which the survival probability is maximised, which we show in a central planner strategy's simulations.

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Originality/value – The paper shows formally why a market-based global input sourcing strategy may be efficient from an individual firm's perspective but may be suboptimal from a societal resilience perspective.

Keywords Resilience, Robustness, Defence supply chains, Modelling, Simulations, Uncertainty

Paper type Research paper

1. Introduction

Recent decades have been characterised by an increasing fragmentation and interdependency of global production networks both across upstream tiers as well as across different supply chains. In the age of globalisation of cross-border production networks, lower cost is often associated with economies of scale in input sourcing, whereas higher-quality inputs tend to be found in markets with niche expertise. Both factors drive company participation in global supply chains (GSCs). The cost and specialisation advantages for international companies that motivate involvement in GSCs are unavoidably associated with a greater uncertainty in the face of shocks, such as global pandemics, the climate crisis and adversarial attacks (Preston *et al.*, 2022). The widespread modern emphasis on globalisation has been acknowledged as a fundamental cause of vulnerability and weakened resilience (NATO, 2022).

The Alliance, the 32 North Atlantic Treaty Organisation (NATO) member countries plus Individually Tailored Partnership Programme (ITPP) countries (currently, Australia, Japan, New Zealand and South Korea), is under increasing threat from adversaries. The landscape of these threats is expanding, including the weaponisation of GSCs. Russia's weaponisation of energy supply to Europe and holding food supplies hostage as part of its Ukraine war strategy were visible hybrid war elements extending to GSCs. In the defence sector, nitrocellulose – the main ingredient of gunpowder – is supplied largely by China (the largest exporter globally) to European defence manufacturers. As a result, the scaling up of European production of explosives – in response to the war in Ukraine – depends not only on China but also on uncertain future supplies of nitrocellulose to European defence companies. The weaponisation of GSCs is often accompanied by less visible hybrid threat elements to (1) undermine and harm the integrity and functioning of economies by targeting vulnerabilities of interlinked networks, creating new vulnerabilities through interference activity, exploiting potential weaknesses, creating ambiguity and undermining the trust of civil society; (2) manipulate established decision-making processes by blurring situational awareness, exploiting gaps in information flows, intimidating individuals and creating fear factors in Alliance societies and (3) maximise impact by creating cascading effects, notably by tailoring attacks, and combining elements from specific domains to overload even the best prepared systems, with unpredictable, negative consequences (Hybrid CoE, 2023).

The widespread fragmentation of global input sourcing and new forms of hybrid warfare jointly reinforce vulnerabilities in supply chains. These vulnerabilities can magnify and accelerate the impacts of system-wide threats to critical supplies in the Alliance. Two major sources of vulnerabilities in the defence sector have been identified in the literature: (1) geographic location-related uncertainties: raw material or input suppliers located in systemic challenge or adversary countries and (2) upstream supplier concentration: a single (or few) company supplying downstream customers whose disruption or disappearance due to an adversary's action or shock event would ripple across the entire supply chain network. Less acknowledged sources of vulnerability are related to growing supply network complexity and opaqueness to downstream customers. It becomes increasingly difficult to answer the question, "Where are goods made?" In order to gain an overview of input dependencies, trace, map and optimise the upstream sourcing channels, downstream company decision-makers contract specialised companies for collecting, processing and visualising information about the upstream supplier networks (Kong *et al.*, 2017). Due to lower labour costs, many of these supply-chain tracing and mapping companies have their roots in systemic challenge countries, constituting an additional – less acknowledged – vulnerability to the Alliance.

The currently unpredictable global security environment has led the Alliance to increase its focus on preparedness and resilience. Defence through resilience should ensure that the socio-politico-economic fabric can function in the face of adversity under a wide range of contingencies, which could severely impact societies and economies (NATO-EU, 2023). In order to avoid trading long-term security needs for short-term economic interests and achieve the desired resilience and robustness, it requires a holistic, integrated and dynamically coordinated approach. The present study contributes by leveraging data exploitation and advanced analytics to provide support to Alliance political and military leaders in data-driven decision-making.

It is challenging to achieve long-term security goals and support resilient and diversified supply chains while allowing for a continued flow of essential goods and avoiding shortages in the short-, medium- and long-run without neglecting the economic needs of business and society (NATO, 2022). Our analysis addresses this challenge by leveraging a parsimonious supply chain model. We use this model to simulate alternative strategies for upstream supplier concentration and/or diversification in the presence of information incompleteness and uncertain shocks. Specifically, we study the relationship between the upstream supplier concentration (which in upper tiers is not visible to the downstream manufacturer) and the supply chain robustness (survival probability).

Using hypothetical shock scenarios, we simulate alternative supplier optimisation strategies in the presence of uncertainty. The shock realisation is unknown to firms when they make their operational decisions. First, we study the supply chain robustness when upstream supplier decisions are made individually by profit maximising firms without mutually coordinating. We show that an individual cost-focused optimisation may lead all upstream suppliers to concentrate in one location, which – when subsequently hit by a shock – would result in all upstream (and downstream) firms perishing. This leads to a disruption of the entire supply chain, as at least one input supplier is required for the downstream manufacturer to produce the final good and/or service. Second, we investigate the role that a government (central planner) can play to mitigate the supply chain's vulnerability to shock events and/or adversary actions and enhance resilience. We show that by coordinating the upstream supplier concentration and/or dispersion decisions, the supply chain's survival probability can be significantly improved.

2. Previous literature

Most empirical studies that have analysed supply chain vulnerabilities in the defence sector have focused on the USA. Two major sources of vulnerabilities in defence supply chains have been identified: (1) geographic location-related uncertainties: input supplier companies being located in systemic challenge or adversary countries (Xu *et al.*, 2020) and (2) upstream supplier concentration: a single company (or few firms) supplying downstream customer(s) whose disappearance would ripple across the entire supply chain network (Kidd, 2019; Govini, 2020; Gowat, 2020). A third – less acknowledged – vulnerability source is related to the GSC complexity, information opaqueness and outsourcing. The supply chain literature exploring complexity and opaqueness-driven vulnerabilities is relatively recent, e.g. Lund *et al.* (2020) and MacCarthy *et al.* (2022).

Kidd (2019) investigated the first through fourth tiers of suppliers to two major contractors of the U.S. Department of Defense (DoD) – 3M and Rockwell – identifying 1,253 upstream suppliers. To gain insight into supply chain networks, Kidd (2019) uses the Mergent Online database, allowing to identify upstream suppliers of a downstream company from open-source data. Although, the approach does not allow one to track the exact supply chain of a specific end-product, it does provide a valuable insight into network relationships between upstream suppliers and downstream customers. The findings of Kidd (2019) reveal that (1) many upstream suppliers share relationships at multiple levels within the network and across tiers. These supply networks can be described as complex supplier matrices where the direct supplier of one primary company also supplies companies up and down the supply chains of other primary companies in various tiers. (2) Supplier diversity diminishes further upstream in the GSC (and thus as the number of tiers increases). At the 4th – the last analysed – tier, the networks of the two rather different major DoD suppliers are hard to distinguish. (3) The number of identified supplier-suppliers grows exponentially with each additional upstream tier in the GSC. Starting from tier 5, the network becomes so large and interconnected that it reaches a singularity – one global supplier ecosystem. (4) The further upstream in the GSC, the larger the fraction of supplier-suppliers from Russia, China or the Korean Peninsula. Products sold by many well-established USA firms have their origins in nations whose relations with the USA are uncertain at best (Kidd, 2019).

Govini (2020) examined the supply networks of 1,000 U.S. DoD suppliers from over 100 countries. Qualitatively, the findings of Govini (2020) are along the same lines: (1) Moving upstream along the GSC, a larger share of supplier-suppliers is located abroad. While 84% of tier 1 suppliers are USA companies, 70% of suppliers in tiers 2–5 are foreign owned. (2) The share of upstream suppliers located in systemic challenge/adversary countries is increasing over time. For example, the number of Chinese suppliers in the upstream network rose 356% to 2,235 between 2013 and 2019. These findings are in line with Kancs (2023) at the macro level. (3) Foreign upstream companies have a large presence in critical industries. International companies, including from systemic challenge countries, have the largest presence among 18 critical industries: major chemicals, 85%; electronic components, 84%; and speciality chemicals, 83%. (4) The share of critical industries' suppliers located in systemic challenge countries is increasing over time. In the semiconductor industry, for example, the number of Chinese companies has grown by 364% between 2010 and 2019, bringing China's share of the supply base in critical industries to 13%. The share held by USA companies fell from 56 to 28%, 144 companies in 2019, as foreign firms have surged in the semiconductor industry.

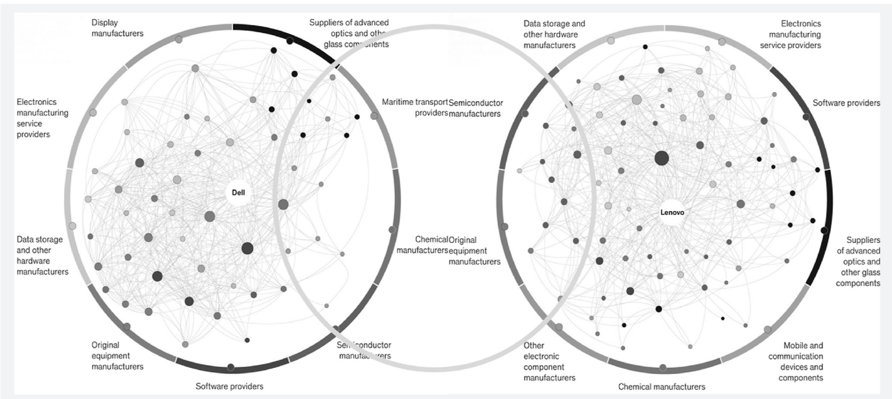
Gowat (2020) maps the networks of U.S. Defence Logistics Agency suppliers and analyses their risks. The study focuses on risk stemming from obtaining and employing potentially counterfeit, non-conforming or otherwise malicious components. This was achieved with (1) supplier risk analysis (i.e. credit risks, fraud risks, etc.); (2) supply chain mapping (supply chain network data relating one company to upstream or downstream companies) and (3) supplier performance issue analysis (i.e. failed testing, late delivery, potential fraud, etc.). The study finds that USA defence logistics lacks an understanding of a primary supplier's upstream partners in tiers 2 and 3. This understanding is particularly important in cases where the primary (tier 1) suppliers for at-risk electronic components are wholesalers or distributors instead of trusted original equipment manufacturers (OEMs). The fact that so many GSC customers are not OEMs is leading to an increased risk that components may have been unknowingly compromised by a "bad" actor further up the supply chain (tier 2, tier 3, etc.). These potentially "bad" actors may consist of hostile nation states, counterfeiters or negligent suppliers, to name a few examples. Gowat (2020) concludes that potentially defective or malicious components pose a significant risk to the defence sector and to reliable operation of critical weapon systems.

Overall, this defence supply chain literature suggests that the number of foreign suppliers involved in the production of goods delivered to the USA military is far higher than originally thought. The fraction of inputs supplied from companies located in systemic challenge countries is rising, including critical industries. The concentration of input suppliers in lower tiers of defence supply chains implies unknown vulnerabilities. The same supplier-suppliers often serve multiple upstream customers, thus increasing their individual impact on the supply chain. If one such input supplier becomes unavailable, it has the potential to trigger a major rupture once it ripples through the various levels of a GSC. In addition, hostile nation states or fraudulent businesses can use such influential suppliers to introduce counterfeit parts into a supply chain that may find their way quickly through multiple sourcing channels into the hands of defence actors.

Another strand of the literature focuses on the continuously growing size and complexity of GSCs both vertically (the number of tiers in the supply chain) and horizontally (the number of intertwined upstream suppliers and downstream customers connected in each node) (e.g. Lund *et al.*, 2020). According to Stanton *et al.* (2022), many GSCs form multiple-tier networks (rather than chains). While optimising input production locations, transportation costs and international tax structures, the upstream supplier structures across tiers are becoming increasingly complex and transnational in nature. As a result, the global production process of one final demand product often relies on thousands of upstream suppliers of input components that are intertwined in huge upstream networks. For example, Airbus sources inputs from 1,676 directly visible tier-one suppliers while working with over 12,000 tier-two suppliers and below worldwide. Thus, Airbus sources inputs from more than 8 times as many total upstream suppliers as those visible from tier 1 (Lund *et al.*, 2020).

Antras and Chor (2018) note that downstream manufacturing companies in such complex networks (such as the one supporting Airbus Defence and Space) have incomplete information about their position in the GSC, including distance from final demand and distance from raw materials. Similarly, the degree of the intermediate input market concentration at upper tiers is not visible to downstream customers producing the final goods (Preston *et al.*, 2022). An example of highly complex GSC interdependencies in the semiconductor industry is illustrated in Figure 1, where tier-one and tier-two input suppliers of Dell (Military and Defence) (left) and Lenovo (right) are depicted. According to Bloomberg Global Supply Chain Data (2023), Dell has nearly 5,000 worldwide tier-one and tier-two input suppliers (second-level input interdependencies), whereas Lenovo sources from around 4,000 tier-one and tier-two input suppliers globally. More importantly, there are 2,272 shared input suppliers between these two USA and Chinese companies.

Overall, our supply chain mapping efforts confirm: (1) extremely high GSC interdependencies between USA and Chinese companies in critical sectors, such as the semiconductor industry; (2) a large number of intermediate inputs with a high input supplier



Source(s): Computed by authors based on Bloomberg Global Supply Chain Data (2023)

Figure 1.
GSC interdependencies in the semiconductor industry: USA company (left) and Chinese company (right)

concentration (low degree of diversification) due to highly specialised inputs and/or cost advantages; (3) vulnerability of semiconductor sector firms to common GSC shocks due to a large fraction of shared input suppliers and (4) the total number of global input suppliers is not exactly known even to these large public companies. (The total number of global input suppliers is determined by considering the entire recursive sequence of all the input suppliers through all tiers. Typically, this is known only for the first and second-tier input suppliers at any level.)

Given the GSC complexity, interdependencies and upstream information gaps, specialised companies (external to the supply chain) are tasked with collecting, tracking and mapping GSCs and providing a visualisation of these data to the responsible supply chain decision makers (Burant and Schneider, 2024). Due to an increasing demand for a clearer understanding of a company's upstream supplier networks, many commercial solutions for supply chain mapping and end-to-end traceability have emerged and are being offered over the past decade, e.g. Blue Yonder, SupplyOn, Elementum, Coupa, E2open and others (MacCarthy *et al.*, 2022).

An example of a map from a simple supply chain with only six tiers and fewer than one hundred upstream suppliers is provided in Figure 2. Note that even in this simple supply chain, not all the upstream suppliers could be identified and traced (they are captured in boxes labelled "undisclosed" in Figure 2). This simple supply chain map is illustrative for considerably larger, highly complex, multi-tier, non-linear, intertwined supply networks, which dominate the intermediate goods trade in the 21st century. Although the depicted supply chain is relatively small and shallow, it contains 77 upstream supplier firms (compared to 12,000 for Airbus Defence and Space), with a highly heterogeneous and non-linear supplier distribution across tiers: 6th tier: 12 suppliers; 5th tier: 27 suppliers; 4th tier: 33 suppliers (plus an unknown number of undisclosed suppliers); 3rd tier: 2 suppliers; 2nd tier: 2 suppliers and 1st tier: 1 supplier. In addition, the intertwined character of the supply chain (Lavassani *et al.*, 2023) is visible from the reciprocal relationships between different suppliers: intermediate inputs flow both within and across tiers in both directions (see arrows in Figure 2).

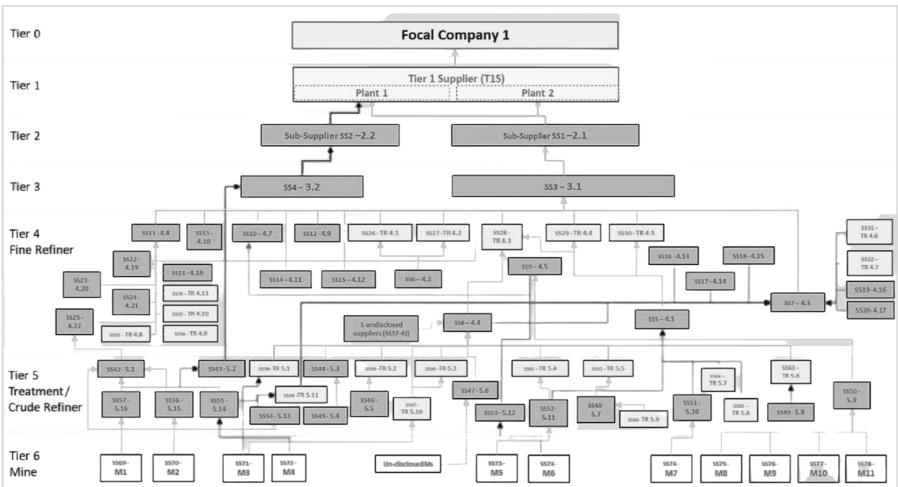


Figure 2.
Example of a simple supply chain map in the mining industry

Source(s): MacCarthy *et al.* (2022)

This simple supply chain map also illustrates the sources for differences between the *expected* and *realised* vulnerability. Indeed, in the absence of full information about all upstream supplier tiers, the experienced vulnerability in the face of a shock event may be very different from the expected vulnerability based on a shallower view of suppliers. For example, consider the case between two firms at Tier 3: (1) Firm 3.1 (SS3) sources from 33 (plus undisclosed) Tier 4 suppliers, which further source from 26 tier 5 suppliers, which in turn source from 12 Tier 6 suppliers; (2) Firm 3.2 (SS4) sources from only 1 Tier 5 supplier, which in turn sources from only 1 tier 6 supplier (no Tier 4 suppliers). The exposure to upstream ruptures is considerably higher for firm SS4 compared to SS3. Further, the availability of information is highly asymmetric across suppliers at different tiers: whereas SS4 has partial information (up to tier 5) about its vulnerability to upstream ruptures, firm 2.2 (SS2) at tier 2 does not have this knowledge. In contrast, when SS1 and SS2 individually consider their exposure to potential upstream shocks with a shallow view, the observable information (using direct inputs) suggests an equal vulnerability for SS1 and SS2 – they both source their direct inputs from one supplier each (SS3 and SS4, respectively). However, using a deeper view, the true vulnerability is very different for firms SS1 and SS2. This simple real-world GSC example illustrates that (1) the perceived GSC resilience and robustness may be very different from the experienced resilience and robustness and (2) the number of suppliers and input sourcing diversification matters not only at the first upstream tier (which is visible to the upstream manufacturer) but at all levels throughout the entire supply chain. Upstream input supplier concentration is the main focus of the simulation-based analysis in Section 3.

The upstream information unavailability and outsourcing of data collection by manufacturers of final goods implies a further GSC vulnerability. From the viewpoint of the Alliance, the key concern with external companies mapping GSCs is that due to lower labour costs, many commercial supply chain mapping solutions have their origins in systemic challenge countries, e.g. offshoring the most labour-intensive tasks. Strategic Alliance decisions which rely on information sourced and distributed by companies from systemic challenge countries are an invisible and less known source of GSC vulnerabilities. On the one hand, an asymmetric access to detailed information about supply chain flows, bottlenecks and vulnerabilities may be misused by an adversary. On the other hand, the information delivered to the Alliance may be manipulated by an adversary, for example, to create a false perception of resilience. As noted by Hybrid-CoE (2023), foreign information manipulation and interference (FIMI) presents a growing political and security challenge.

In summary, these findings from the extant literature have important implications for political and military decision-makers as well as for scientific inquiries. First, GSCs consist of highly complex networks of input flows that are partially invisible to final good manufacturers and to lower-tier downstream input suppliers. The information asymmetry between upstream suppliers and downstream customers together with information incompleteness drives a gap between the perceived and actual vulnerability. Investigating how firms form their supply chain decisions in a partial information environment is the first contribution of our study to the literature. Second, the effect of uncertain aggregate shocks can be amplified by this information gap. For some shocks, e.g. exchange rate volatility, firms can learn from past experience, form beliefs and adapt supply chain decisions to offset risks. Other shocks such as the COVID-19 pandemic and the full-scale Russian war do not have recent historic imprints during the lifetime of most decision-makers from which to learn and form expectations. We investigate how firms' supply chain efficiency and robustness decisions and outcomes change in the presence of these system-wide shocks. Finally, whereas most studies in the literature focus on an ex-post documentation of supply chain vulnerabilities, we undertake *ex ante* model-based simulations to explore how government can enhance supply chain resilience via coordinated policy actions. Such evidence is very limited in the extant supply chain literature in spite of its potential importance for the defence and other critical sectors.

3. Simulation-based evidence

To study the link between the upstream supplier diversification (which is not visible to the downstream manufacturer) and the supply chain's robustness (survival probability), we leverage a parsimonious supply chain model and simulate alternative strategies of upstream supplier concentration and/or diversification in the presence of information incompleteness and uncertain aggregate shocks. First, the most important characteristics and channels of adjustment relevant to the analysis along with the main intuition of the modelling framework are detailed. For a complete formal description of the underlying supply chain model, see Kancs (2023, 2024a). Applying the model, we simulate alternative incomplete information scenarios, each of which is investigated under different shock realisation possibilities. The main interest of this effort is to establish to what extent a targeted government action can improve the robustness of a critical supply chain.

3.1 Modelling framework

We assume that time is discrete and extends out to an infinite horizon. At the start of every period t, there are two types of firms: upstream input suppliers and one downstream manufacturer. The production process is organised in two vertical tiers: at Tier 2, upstream firms produce intermediate inputs, which they supply to the final good manufacturer in Tier 1. Each Tier 2 firm produces a single intermediate good that is different from other intermediate good producers (horizontal differentiation).

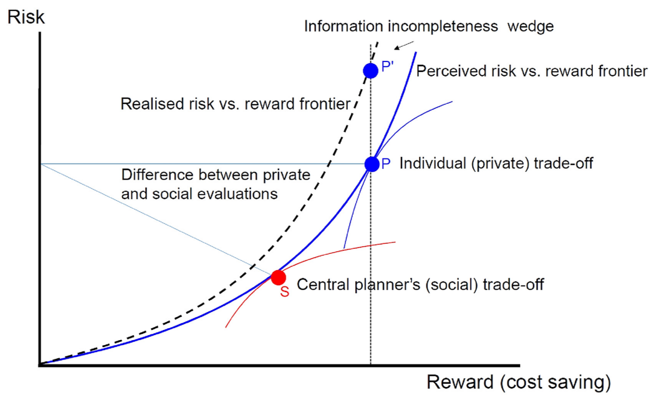
The model includes two locations (regions): east and south. This allows us to study supplier concentration and/or dispersion decisions and their impact on supply chain robustness. Note that mathematically this is equivalent to introducing a third tier with Tier 2 suppliers deciding on their upstream sourcing diversification/concentration. At the beginning of every period, each intermediate good firm denoted by j faces a location decision to choose one of the two locations where it sets up production. Except for the probability that an aggregate shock hits, the locations are otherwise identical in the baseline model. Firm j chooses a location r_j to minimise cost c, with the objective of choosing the least-cost path of production. The intermediate input firms are myopic, and their optimisation horizon is the current period. Hence, they choose region $r_j = 1$ or $r_j = 2$ to minimise cost $c(r_j)$. The global downstream manufacturer does not require a physical location to produce the output.

The production process for intermediate goods is uncertain, as the firm's location may be hit by a shock. Specifically, in every period t, an aggregate shock occurs with probability ε; hence, there is no aggregate shock with probability $1-\varepsilon$. Conditional on such a shock occurrence, and before the production takes place, all intermediate good firms in exactly one region of east or south perish with probability ζ or $1-\zeta$, respectively. We presume that $\zeta \gg 1/2$, implying that east is riskier than south. In the following period $t+1$, the choice of regions and intermediate input production takes place only by the surviving firms. Importantly, the information about the spatial realisation of a shock event is incomplete to firms: firms do not know *ex ante* if there will be a shock in the next period and which region the shock will affect. In contrast, the length of shocks (one period) and intensity parameters (ε, ζ) are constant and known to all firms.

In the baseline model, we assume that the price per produced intermediate input is constant and independent of production and the state of the world; the small and numerous intermediate input producers are price takers. Given that prices are fixed, there is no way of adjusting prices to compensate the intermediate supplier for locating in a specific region. Note that upstream intermediate input prices are fixed during the investment horizon, which is one period. At the end of a period, the upstream suppliers can relocate between regions without cost, as there are no adjustment and/or switching costs in the baseline model.

The downstream manufacturer aggregates intermediate goods from all upstream suppliers and produces a final demand good. The sophistication and value of the final demand good depends on the number of intermediate parts used in its production: it is desirable to use more inputs in production. Thus, final good quality increases with the number of components used. The revenue from selling the final demand good is linear in the number of intermediate inputs it contains; hence, the globally sourcing downstream producer wants to successfully source from as many suppliers as possible to maximise revenue. The long-term benefit of the downstream firm is the expected value v, defined as the difference between the total revenue, which depends on the number of surviving firms, and the total production cost. At least one intermediate input supplier is needed to produce the final demand good. The downstream firm has zero profits, and all its revenue is transferred to intermediate input firms, which is equally shared among surviving firms to pay the cost before starting production in the next period.

The trade-off between efficiency (costs) and robustness (surviving suppliers) of the downstream firm is illustrated in Figure 3. In the model, there is both a marginal benefit and cost of diversification. The forward-looking profit-maximising downstream firm aims to ensure a certain resilience of the production process while keeping cost low. A key factor in a firm's choice of suppliers involves diversification of risk. This is incorporated in the trade-off of lower cost versus a higher-quality product. The trade-off between the uncertainty (in the form of risk) that comes with GSCs (vertical axis) and the rewards (horizontal axis) is illustrated in Figure 3. The solid line represents the uncertainty-reward frontier; everywhere on this line, firms' willingness to substitute one unit of uncertainty for a cost saving is constant. Starting from the origin, movement along this line represents optimal sourcing solutions with fewer upstream suppliers, leading to less diversification, higher risk and lower cost. Risk due to shocks is assumed to increase when prioritising costs and sourcing from a more concentrated and/or specialised collection of upstream suppliers. Diversification of input sources reduces risk but at a diminishing rate (the curve is not linear). In an underlying model, the equilibrium solution is found at the tangency of the indifference curves and the uncertainty-reward frontier, which is represented by tangency P in Figure 3.



Source(s): Authors' illustration based on Lettau and Ludvigson (2003)

Figure 3. Firm efficiency-robustness trade-off with externalities and incomplete information

Note that there may be differences in risk and/or reward outcomes between a centrally optimised efficiency-robustness supply chain and individually optimising firms. This gap will be larger in the presence of externalities and market inefficiencies (See, e.g. Turvey (1963) for the underlying concept). First, centrally planned (social) evaluation of the risk-reward trade-off may put a greater stress on risk than individual (private) evaluation. Myopic individual upstream suppliers are willing to accept more risk for any given level of reward compared to a socially optimising central planner, which more strongly values lowering risk. The indifference curve shapes (and position in Figure 3) reflect that individual upstream suppliers would prefer more risk for any given level of reward (curve "individual (private) trade-off"), but the central planner is relatively more focused on lowering risk (curve "central planner's (social) trade-off"). In equilibrium, the central planner is desiring a lower level of risk, point *S*, than individual input suppliers, point *P* in Figure 3. This difference between the private and social evaluation of risk is an externality that is not internalised by individual suppliers in their optimisation decisions, leading to market inefficiency.

The equilibrium outcome in this space is likely to be suboptimal when information availability forces companies to act without full information (see discussion in Section 2). GSCs are characterised by complexity and non-transparency, with firms at lower tiers invisible to downstream firms. In fact, most manufacturers do not know their suppliers beyond one tier. The general lack of understanding of where inputs originate – supply chain opaqueness – causes downstream firms to make suboptimal decisions with respect to the risk-reward trade-off. This leads to misaligned input sourcing strategies. In Figure 3, the supply chain opaqueness-caused market imperfections are shown on curve "realised risk vs reward frontier", which is above the "perceived risk vs reward frontier". We refer to the gap between the two curves as the "information incompleteness wedge" in Figure 3.

3.2 Simulation scenarios

The modelling framework introduced in the previous sections contains trade-off channels of adjustment according to which, in the pursuit of efficiency, a supply chain could become vulnerable to aggregate shocks. On the other hand, a supply chain with a greater robustness to shocks has to sacrifice efficiency during normal times (in the absence of shocks). How exactly is a supply chain's robustness (survival) related to the supplier concentration and/or diversification? How can a central planner (i.e. government) enhance resilience and ensure a continued flow of essential goods under a systemic shock? We attempt to answer these questions in this section by formulating and simulating three different shock realisation scenarios. The three possible shock realisations and the associated supply chain rupture outcomes are as follows: (1) there is no aggregate shock; (2) the aggregate shock hits east in period 10, and all firms in the east perish; (3) the aggregate shock hits south in period 10, and all firms in the south perish. Note that the period of the shock does not change the qualitative outcomes of results. The three possible shock realisations are summarised in the rows of Table 1. The alternative location decisions of upstream supplier firms allow us to investigate supplier concentration and/or dispersion impact on the supply chain's robustness.

Table 1. Simulation scenarios: key assumptions about shock realisations

	Risky environment
No aggregate shock	Known shock distribution, no aggregate shock
Aggregate shock in east	Known shock distribution, shock realisation in East
Aggregate shock in south	Known shock distribution, shock realisation in South

Source(s): Table by authors

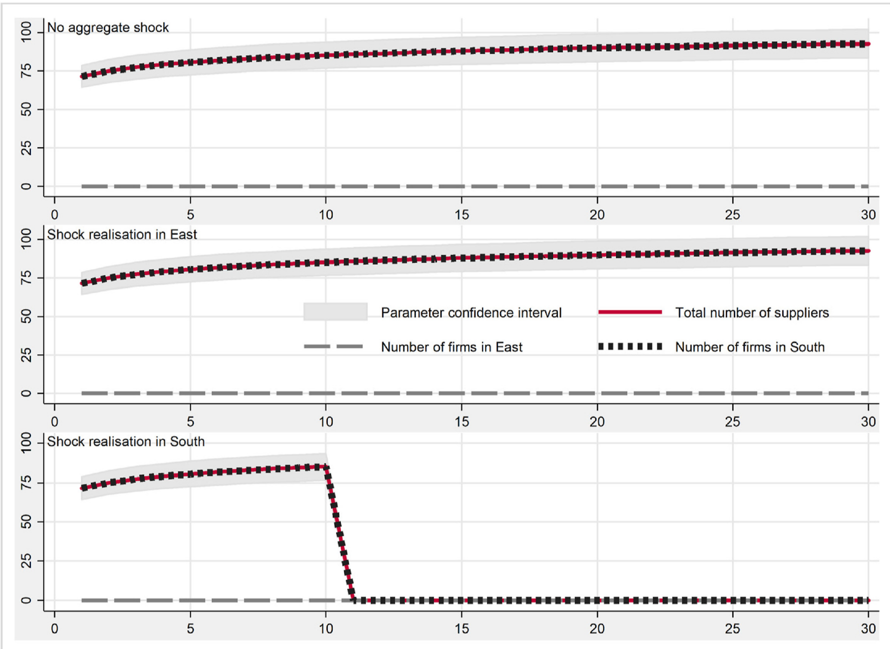
The information about the spatial realisation of an aggregate shock is incomplete to firms: firms do not know *ex ante* which region (and if any) will be hit by a shock. In the simulations presented below, we study how the incompleteness of information about the shock realisation affects supplier decisions and the supply chain's robustness. We will see that the information incompleteness and asymmetry pose a serious challenge to selecting an optimal (both efficient and robust) supplier allocation.

In a second set of simulations, we investigate the role that a government (central planner) can play to mitigate the supply chain's vulnerability to shock events and enhance resilience, e.g. by coordinating the upstream supplier concentration and/or dispersion decisions. To analyse the optimal upstream supplier diversification pattern that accounts for both the supply chain's efficiency but also robustness, we simulate the above-described information incompleteness environment under three shock realisation scenarios in a central planner's optimisation problem. Key modelling assumptions under each simulation scenario remain the same as above and are summarised in Table 1.

As regards the role of uncertainty and information precision on supplier diversification, we show that uncertainty drives a wedge between the expected realisations and the experienced realisations of shock events. Information imprecision creates a bias in the individually optimal suppliers' diversification strategy.

3.3 Simulation results

Simulation results when small individual suppliers optimise without mutually coordinating their supply decisions are reported in Figure 4. The number of upstream suppliers in each



Note(s): *Y*-axis measures the number of intermediate input suppliers; *X*-axis time periods
Source(s): Figure by authors

Figure 4. Simulation results: supply chain's survival under various shock realisation scenarios, individual supplier optimisation

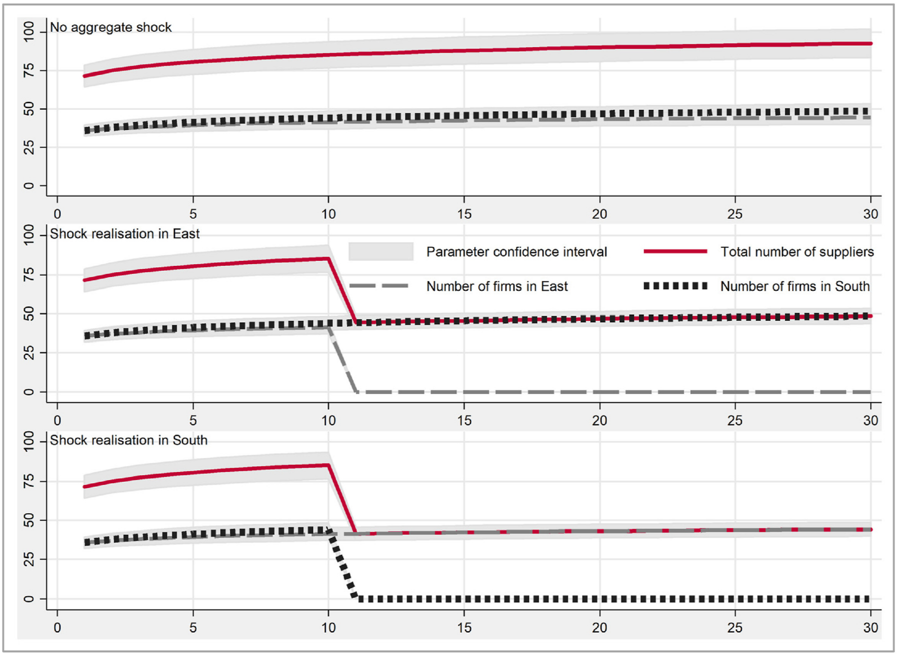
location is presented as a dashed grey line for east and a squared black line for south, respectively, with the total number of intermediate input firms as a solid red line. The latter carries the most importance to the downstream manufacturer. Note that the number of supplier firms is growing between periods – at a decreasing rate– due to positive profits in the industry. Upstream firm growth reaches zero in a steady state – the qualitative results are the same.

First, note that given our assumption of lower shock probability in the south, the expected value for each input supplier when locating in south is always larger than the expected value when locating in the east. Note that assuming lower costs in the south would yield qualitatively equal results. Thus, all intermediate input firms choose to locate in the south. With this choice, every upstream supplier maximises its own current period efficiency. Collectively, however, they expose the downstream manufacturer and, in our example, the entire supply chain to an aggregate shock in South. Indeed, this can be seen in the two bottom panels, where after an aggregate shock in period 10, the number of upstream suppliers in the south drops to zero (squared black line). Given that no supplier is located in east, no input producers survive the shock, and the intermediate input supply (Tier 2) of the downstream manufacturer (Tier 1) drops to zero (solid red line). Because no final good manufacturing can take place without intermediate inputs, the entire supply chain is disrupted. Hence, this supply chain is not robust to aggregate shocks in a pure market-driven environment where small individual suppliers do not internalise the entire supply chain's upstream diversification decisions. Examples of such supply chains include European energy extracting companies concentrating in Russia until 2022 and nitrocellulose supplier concentration in China. As a result, scaling up of European production of explosives entirely depends on China, and future supplies of nitrocellulose to European defence companies are also uncertain due to geopolitical uncertainties.

Such outcomes leading to a supply chain's vulnerability are efficient in "normal times" but are not robust under aggregate shocks. Ensuring robust supply chains in place may be particularly crucial in critical and strategic sectors, such as defence. Can a central planner (government) take action to increase the supply chain's robustness with respect to aggregate shocks? For example, can a coordinated upstream supplier diversification strategy mitigate the supply chain's vulnerability to systemic shock events, such as when China stops supplying nitrocellulose – the main ingredient of gunpowder – to European defence manufacturers? To answer these questions, we simulated the same three-shock realisation scenarios in a central planner's optimisation problem. The efficiency-robustness trade-off remains to be solved under a central planner's optimisation; however, the perspective is different. Whereas individual suppliers (explained above) maximise their current period's profits, a centrally coordinating agent maximises the entire supply chain's expected value; hence, it internalises the survival externality. Simulation results for the supplier allocation under a central planner's optimisation are reported in Figure 5.

In contrast to individual upstream suppliers, the central planner also considers the entire GSC's resilience in its optimisation. The central planner is willing to locate some intermediate input supply facilities in the east to insure the downstream production's robustness against an aggregate shock in the south. It internalises the survival and diversifies the input sourcing. This can be seen in Figure 5, where the dashed grey lines (number of firms in the east) are above zero in all scenarios – a share of intermediate input firms larger than zero in the east. In contrast to individual optimisation solutions reported in Figure 4, where the optimal individual supplier strategy leads to a corner solution, the results shown in Figure 5 report an internal solution (the number of surviving suppliers is greater than zero) in all scenarios.

In Figure 5, a risk-averse central planner exhibits an allocation behaviour that takes into account all the sources of risk, resulting in a desire for supplier diversification. The diversification is achieved as in a traditional expected utility maximisation problem. The



Note(s): *Y*-axis measures the number of intermediate input suppliers; *X*-axis time periods
Source(s): Figure by authors

Figure 5.
Simulation results: supply chain's survival under various shock realisation scenarios, central planner's optimisation

central planner faces a trade-off between instantaneous profits (what the individual intermediate good suppliers maximise) and survival (robustness). Figure 5 also suggests that the optimal location of intermediate suppliers and hence the supply chain's diversification depends on the number of active (survived) upstream suppliers. Note that this is not the case under individual supplier optimisation, where each supplier acts independently and does not consider location decisions of other suppliers.

A robust allocation is the firm's strategy, and when the decision-maker is not confident enough to assign probabilities to events about which they have little information, the supply chain's survival is crucial. The optimising agent chooses to be prepared for the worst. The simulation results presented in Figure 5 summarise strategies that reduce the differences in expected value over all possible states of shock realisations. The central planner's robustly effective strategy guaranteeing the survival of the critical supplies is comparable to insights from behavioural theories, where in many cases agents tend to choose the robust survival-maximising strategy (Ilut and Schneider, 2023).

Comparing Figures 4 and 5, we may conclude that under individual supplier optimisation, the optimal firm choices are independent of the information precision. Individual upstream suppliers choose a solution that is not robust from the overall supply chain's perspective, i.e. they all locate in one region (south in our example). The downstream firm and hence the entire supply chain is vulnerable to an aggregate shock to the south (bottom panels in Figure 4). The optimal supplier allocation is rather different under a central planner's optimisation (Figure 5), which tends to result in internal solutions – a proportion larger than zero of intermediate input suppliers are located both in south and east in all scenarios. Because the south is assumed to face less uncertainty than the east, a larger fraction of upstream suppliers is located in the south (Figure 5). These results are consistent with Figure 3 above, where the indifference curve shapes suggest that individual upstream suppliers accept more risk for any given level of reward (curve "private (individual) trade-off"), compared to the central planner, who incorporates uncertainty explicitly in their decision (curve "social (centralised) trade-off").

4. Conclusions

The landscape of global hybrid threats is expanding, now including forms such as the weaponisation of supply chains. Production processes are increasingly scattered globally across borders. Because of outsourcing, offshoring and an insufficient investment in resilience, supply chains across the globe have become increasingly complex and fragile. Motivated by increasing GSC dependencies and the recently experienced aggregate shocks, this paper explored the impact of incomplete information about future shocks on supply chain robustness. Specifically, we have investigated the relationship between upstream supplier concentration and/or diversification, its visibility to downstream partners and the overall supply chain robustness (survival probability) in the presence of uncertainty.

In these situations, under imperfect information and uncertainty, a wedge can exist between individual firms' profit-maximisation strategy and a robust strategy that diversifies risk across the supply sources. A broader societal view often values resilience more highly than private sector firms, which may prefer more risk for any given level of reward. The main insight from the simulated examples is that suppliers locating evenly across the locations diversifies the systemic risks due to a shock and maximises the number of surviving locations. We demonstrate in simulations that a coordinated government action can qualitatively improve the robustness of supply chain outcomes. Achieving a socio-politico-economic resilience that meets the NATO baseline requirements – which must be maintained under the most demanding circumstances – will require a mobilisation of resources. For example, efforts to restructure supply chains by enhancing resilience and robustness may need to be accompanied by financial incentives to compensate the company costs associated with such a reorientation, which is a promising area for future research.

These findings have direct application to supply chain downstream manufacturers and to political and military leaders in data-driven decision-making. Since GSC disruptions may have catastrophic impacts on both civil and military resilience, and the probability and impacts of shocks such as COVID-19 and Russia's war of aggression against Ukraine may not be known even approximately *a priori*, decision rules supporting supply chain robustness seem to be appropriate. This is particularly applicable for critical and strategic sectors such as energy supplies, food and water, communication and defence. For example, diversification of nitrocellulose supplies currently sourced almost exclusively from China by European gunpowder manufacturers should be strongly encouraged by political and military decision-makers to enhance upstream supply chain robustness. A robust gunpowder supply chain would be one in which the survival probability is maximised in the event of an adversary's hostile action. Our model demonstrates this impact via simulation of a central planner's strategy. Robust decision rules support input supplier survival and continuation of final good manufacture in the presence of an aggregate shock. In the best case, a substantial fraction of both suppliers and final good manufacture continues no matter the location of the shock realisation.

Among limitations, the presented analysis has not addressed the fundamental trade-off of shorter supply chains, which feature lower marginal cost but may also have fewer suppliers. This can reduce competition, product availability and consumer access to products. Further, under extreme parameter settings, there may be a plethora of rational expectation equilibria trajectories, without any smooth convergence properties, neither converging to a steady state nor even to a limit cycle. These are promising avenues for future research.

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Corresponding author
d'Artis Kancs can be contacted at: d'artis.kancs@ec.europa.eu