Enhancing Resilience: Model-based Simulations[1]

d'Artis Kancs, PhD
Science Research Innovation Implementation Centre,
Latvian National Armed Forces

d'artis.kancs@ec.europa.eu

ABSTRACT

Since several years, the fragility of global supply chains (GSCs) is at historically high levels. In the same time, the landscape of hybrid threats is expanding. This paper aims to assess the economies' foreign input reliance and foreign market reliance, identify possible vulnerabilities by simulating shocks to GSCs in presence of uncertainty. We stress test supply chains by simulating most demanding circumstances and crystallise relevant, effective and efficient policy solutions. Conceptually, we employ a newly developed modelling framework, which is specially designed to account for the increasingly inter-dependent GSCs and study resilience and robustness in presence of hybrid shocks. The scalable data model is parameterised by combining World-Input Output Tables with those from the Inter-Country Input-Output. We study how the decision of a GSC input sourcing diversification changes in the presence of uncertainty and what are the implications for supply chain robustness and resilience. Model-based simulations facilitate decision making by providing interoperable and directly comparable quantifications of counterfactual resilience and robustness strategic choices and allow to identify policy solutions towards baseline resilience requirements.

1.0 INTRODUCTION

Two developments with a global character and dynamically interrelated across industries and countries have accelerated in recent years. One is an increasing vulnerability of global production networks. In the same time, the landscape of hybrid threats is expanding and intensifying (European Commission 2021). More than ever since the end of the Cold War, the last authoritarian regimes and strategic competitors test the Alliance's resilience and seek to exploit the openness, interconnectedness and digitalisation of free and open societies, interfere in democratic processes and institutions, and target the security of citizens through hybrid tactics, such as, the recent attempts of energy weaponisation by Russia. In the age of globalisation and cross-border production networks, global production fragmentation increases foreign exposure of domestic industries, which participate extensively in global supply chains (GSCs). The specialisation and cost advantages for international companies that arise from involvement in GSCs are unavoidably associated with greater risks and ambiguity in the face of shocks, such as global pandemics, the climate crisis and hybrid attacks. These uncertainties are acknowledged by the Secretary General Stoltenberg: "over-reliance on the import of key commodities, like energy [on the sourcing-side, and] exporting advanced technologies, like Artificial Intelligence [on the selling-side] can create vulnerabilities and weakened resilience".

The first line of the Alliance's defence is resilience – ensuring that the socio-politico-economic fabric can function in the face of adversity.[2] Leveraging the strong commitment to action and achieving the desired

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[2] www.nato.int/docu/review/articles/2019/02/27/resilience-the-first-line-of-defence/

resilience and robustness requires a holistic, integrated and dynamically coordinated approach. On the policy side, political leaders need to take responsibility for being fully open with citizens about the changing character of hybrid threats. Achieving an enhanced socio-politico-economic resilience that meets the seven baseline requirements – which must be maintained under the most demanding circumstances – will require a mobilisation of resources. A full transparency is therefore important regarding the costs and sacrifices that will be needed, for example, to defend security in the face of Russia's war on Democracy and possible future warfare. As noted by Secretary General Stoltenberg at the World Economic Forum 2022: "we should not trade long-term security needs for short-term economic interests",[3] which implies costs and sacrifices.

How to 'achieve the required resilience' while doing as little damage as possible to the society's socio-politico-economic fabric'? Indeed, the challenge is to achieve long-term security goals without neglecting the short- and medium-term economic needs of economy and society. In the context of GSCs, the challenge is to ensure resilient and diversified supply chains in place to allow for a continued flow of essential goods and avoid shortages in the short-, medium- and long-run. Our analysis investigates this trade-off formally by framing it as a constrained optimisation problem with two constraints – a resilience/robustness constraint on the desirability side and a resource mobilisation constraint on the feasibility side. We simulate the optimal strategy of private sector firms in presence of GSC shocks under uncertainty. By integrating predictive analytics, model-based simulations provide interoperable and directly comparable quantifications of positive and normative effects of counterfactual resilience and robustness policy choices in critical and non-critical sectors. The scalable data model allows to identify strategies for addressing Alliance's vulnerabilities arising from societies' openness and economies' interconnectedness in international trade and global production networks, and the embedded information awareness tool facilitates strategic decision making.

The present paper builds on and complements the existing Science & Technology Organisation (STO) strategic analytical support, including the Multi-Dimensional Data Farming, Causal Reasoning, and resilience tools. The Resilience Data Analytics Tool can be used, among others, to assess the levels of resilience by leveraging open-source data, big data analytics, machine learning, and data visualisation and allows the identification of potential shocks to the Alliance's resilience. The Resilience Model provides a holistic framework for simulating a wide range of Political, Military, Economic, Social, Information, and Infrastructure (PMESII) shocks (e.g. electricity blackout, cyber attack, martial law enforcement, big human movement, state of war, armed conflict), and allows assessing both resilience domains (civil support to the military, continuity of government, and continuity of essential services) as well as risk (command and control, protection, movement/ manoeuvre, and sustain) (Hodicky et al. 2020). The Joint Warfare Centre (JWC) leverages the Joint Theatre Level Simulation (JTLS). Our scalable data model - which is based on Antras and de Gortari (2020) and Jiang et al. (2022) - is complementary to the existing resilience modelling and simulation tools, as it is specifically designed to account for the asymmetric exposure of specific sectors, and to study the allies' resilience and robustness in the presence of exogenous shocks under uncertainty causing, for example, supply ruptures, demand ruptures/surges or transportation ruptures.

2.0 GLOBAL SUPPLY CHAINS: CURRENT SITUATION

We begin by taking stocks of the Alliance's foreign input dependence. Knowing economies' international exposure on intermediates input and output markets is crucial to identify potential vulnerabilities and allow for policy actions where needs arise before major GSC-disruptions occur. We approach this question by querying recent statistical data through different micro-macro lenses. First, we look at the firm-level perspective by using firm-level data to understand firms' input sourcing and output market decisions, how import and export participations are linked, and how globally operating firms organise their production networks. Second a value-added (macro) approach is employed to assess how the industrial production is allocated internationally and how each stage of production contributes to the final product. This aggregated approach provides an alternative to the micro view by concentrating on countries and industries as the unit of

[3] www.nato.int/cps/en/natohq/opinions_195755.htm

analysis. The macro-approach to measuring GSCs connects national Input Output (IO) tables across borders using bilateral trade data to construct a World Input-Output Tables. These data are applied to measure trade in value added, as well as the length and location of producers in GSCs. Both in the firm-level analysis and value-added approach an understanding of the domestic economy's foreign exposure via the GSC channel requires a knowledge of where are goods made? This core question is approached from different sides (location of output, inputs) and by viewing through different lenses (micro, macro).

2.1 Micro perspective: Firm-level foreign reliance

We start with the micro approach, where the firms are the unit of analysis; they are the ones that decide whether and to what extent to participate in GSCs. Firms upstream and downstream face contracting problems – moral hazard or incomplete contracts. Integrating internationally and vertically helps to solve the informational problem and reduce supply chain uncertainty. Firm-level forward participation in GSCs is evidenced through exporting of intermediate inputs whereas backward participation in GSCs through importing of intermediate inputs. The observed world trade flows in international trade statistics are best understood as the aggregation of individual firm-level decisions related to the destinations to which firms export their intermediate goods, but also the origin countries from which they source intermediate inputs, or the 'platform' countries from which they assemble goods for distant destination countries.

How exposed are Alliance's companies to foreign input supplies and output markets? This question can be answered at several levels. Taking the airspace industry as an example, we can say it was made in Stevenage when a product rolls off the Airbus Defence and Space assembly line in Stevenage, UK. This is the first-level truth, but it is not the whole truth. The second level recognises that the Stevenage plant buys inputs from other sectors located at home and abroad. Tracing the first-level production location of inputs gives us the second-level answer; this provides a directly observable dependence on foreign inputs. The intermediate import measure is directly observable in standard trade databases, and it has a number of advantages. However, this measure of intermediate imports is not the whole truth either because purchased foreign inputs also use inputs. The third-level answer - the whole truth of foreign input reliance - takes account of the entire recursive sequence of all the inputs into all the inputs. According to Lund et al. (2020), Airbus has 1,676 publicly disclosed tier-one suppliers. In the same time, Airbus works with over 12,000 tier-two suppliers and below worldwide. This implies that Airbus has more than 8 times as many total suppliers as in tier one.

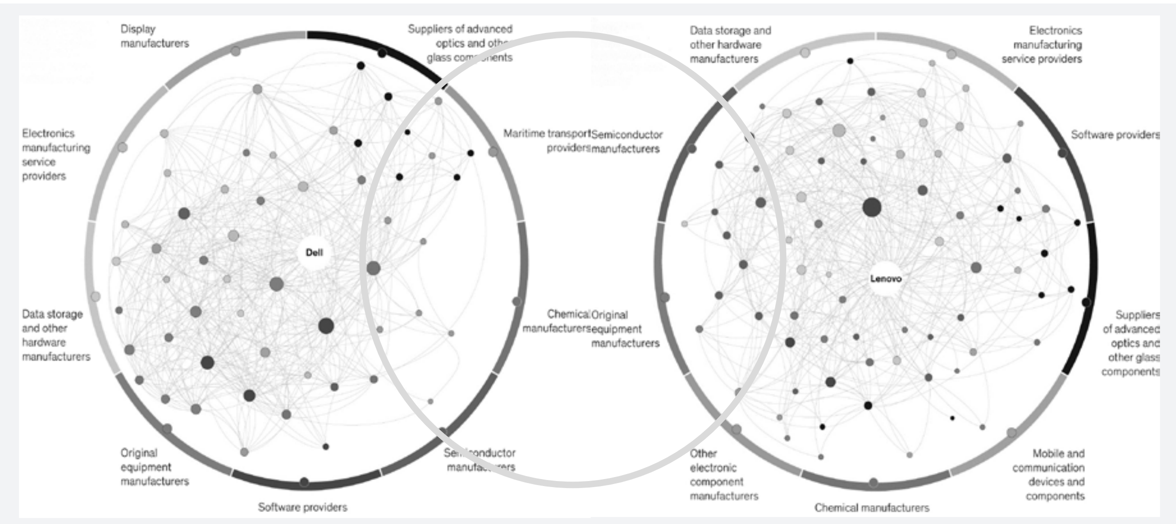

Figure 1: GSC interdependencies: a US company and a Chinese company in IT industry
Source: Computed based on www.dell.com/en-us/dt/oem/military.htm; Bloomberg Global Supply Chain Data; and www.dell.com/en-ca/dt/oem/defence.htm data.

An example of GSC interdependencies in the IT industry are 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 the Bloomberg Global Supply Chain Data, Dell has nearly 5,000 worldwide tier-one and tier-two input suppliers (second-level input interdependencies), whereas Lenovo draws on around 4,000 tier-one and tier-two input suppliers globally. More importantly, there are 2,272 shared input suppliers between the US company and the Chinese company. These examples illuminate: (i) extremely high GSC interdependencies between US and Chinese companies in IT industry; (ii) large number of intermediate inputs with a high input supplier concentration (low degree of diversification) due to highly specialised inputs and/or cost advantages; (iii) vulnerability to systemic exposure of IT sector firms to common GSC shocks due to a large fraction of shared input suppliers; and (iv) the total number of actual global input suppliers by accounting for the entire recursive sequence of all the inputs into all the inputs is not exactly known even to these large public companies (known are only the first and second tier input suppliers).

Why is the domestic company supply chain foreign exposure important for policy makers? GSCs are characterised by externalities and market failures, which implies that the firm-level equilibrium efficiency-robustness allocation may be inefficient socially (see section 3). Typically, the efficiency-robustness allocation of private sector firms is skewed toward efficiency more than it would be socially optimal, and due to GSC complexity and opaqueness private misjudgements as to how uncertain GSCs actually are may lead to a misperception of the actual vulnerability. An even more important argument for a policy maker attention is given by the increasing deployment of foreign supply dependence as a hybrid threat by adversaries (European Commission 2021). A recent example is Russia's attempt to weaponise energy supplies against Europe.

2.2 Macro perspective: Foreign exposure of economies

Continuing with the value-added (macro) approach – where the unit of analysis are industries & countries – we look at how production is allocated internationally and how each stage of production contributes to the final product. Combining international trade data with national Input-Output tables yields cross-country or World Input-Output Tables (WIOT). Information contained in these tables allow us to shed light on value-added trade flows across countries and the implied degree to which production processes have become globalised. To measure the international fragmentation of production processes, we rely on insights from the theoretical “macro” literature, which mostly focuses on the development of structural interpretations of the WIOT, with the ultimate goal of constructing reliable tools for counterfactual analysis by acknowledging the relevance of GSCs in the world trade (Antras and Chor 2022).

A variety of metrics has been developed to assess the foreign exposure of a sector or economy as a whole (see e.g. Johnson 2018). For example, the content of value added in final goods, value added in gross exports, positioning in GSCs. Foreign Input Reliance (FIR) measures the sourcing-side exposure of a sector or the entire economy. We use the Inter-Country Input-Output (ICIO) data from the OECD to compute FIR for G7 economies and China in 2019 (the most recent available data). The computed bilateral FIR corresponds to the share of foreign sources used as intermediate inputs into domestic production. Table 1, panel (a) reports row nations' reliance on inputs from column nation for manufacturing production. Cell shades are indexed to share sizes; darker shades indicate higher FIR (more import-dependent).[4] For example, 11.8 in the row for Canada (CAN) and the column for China (CHN) indicates that 11.8% of Canadian manufacturing production was made using inputs sourced directly and indirectly from China. The global dominance of China in intermediate input trade can be seen by the fact that CHN column is shaded primarily in dark. The fact that the CHN column is relatively dark indicates that China is an important supplier of inputs to manufacturing industries of all analysed G7 economies. It is also worth noting the asymmetry

[4] The matrix diagonal elements are suppressed, as we are interested in foreign inputs and foreign exposure. The diagonal elements would show a nation's input reliance on itself - both in terms of direct domestic sourcing and indirect sourcing through the re-import of previously exported inputs.

between the USA manufacturing production's reliance on Chinese inputs, 9.9%, and China's manufacturing production's reliance on US inputs, 3.7%.

(a)	USA	CAN	GER	GBR	FRA	ITA	JPN	CHN	ROW
USA		5.4	1.8	1.0	0.7	0.8	2.1	9.9	13.0
CAN	32.5		2.1	1.5	0.9	0.9	2.0	11.8	21.1
GER	4.6	0.5		3.2	4.7	3.8	1.6	6.9	42.0
GBR	6.2	1.4	6.9		4.1	2.6	1.3	7.7	29.5
FRA	5.6	0.7	10.1	3.8		4.7	1.2	6.4	35.3
ITA	3.5	0.5	8.9	2.6	5.8		0.9	7.6	39.6
JPN	4.1	0.7	1.3	0.7	0.6	0.4		10.7	26.0
CHN	3.7	0.8	1.7	0.6	0.7	0.6	3.2		24.6

(c)	USA	CAN	GER	GBR	FRA	ITA	JPN	CHN	ROW
USA		3.2	1.0	0.8	0.7	0.4	1.3	5.6	9.6
CAN	31.9		0.8	1.3	0.6	0.3	1.7	10.8	9.3
GER	7.1	0.8		3.8	5.1	4.2	1.6	10.0	41.0
GBR	7.0	0.9	4.7		2.9	2.1	1.2	5.5	25.8
FRA	5.2	0.7	8.4	3.9		5.1	1.4	8.0	33.1
ITA	5.9	0.7	6.7	2.6	4.6		1.3	5.4	31.9
JPN	5.7	0.6	1.1	0.6	0.5	0.4		14.4	16.8
CHN	8.0	0.8	1.3	0.9	0.7	0.7	2.8		15.7

(b)	USA	CAN	GER	GBR	FRA	ITA	JPN	CHN	ROW
USA		-1.4	-0.6	-0.5	-0.2	-0.2	-1.8	6.0	-3.9
CAN	-1.1		-0.2	-0.8	-0.2	-0.1	-1.6	6.1	2.0
GER	0.7	-0.2		-0.5	-0.3	-0.1	-0.3	4.9	5.0
GBR	1.0	0.1	0.4		-0.7	-0.4	-0.7	4.9	0.1
FRA	1.4	0.1	1.1	-0.2		-1.1	-0.5	4.0	0.2
ITA	0.4	-0.1	0.1	-0.4	-0.8		-0.3	5.0	3.9
JPN	0.4	0.1	0.1	0.1	0.1	0.1		5.6	5.7
CHN	-1.3	-0.1	-0.7	-0.2	-0.4	-0.4	-6.1		-8.2

(d)	USA	CAN	GER	GBR	FRA	ITA	JPN	CHN	ROW
USA		-0.5	0.1	0.1	0.1	-0.1	-0.3	3.8	1.4
CAN	-17.6		-0.1	0.1	-0.1	-0.2	-1.1	8.3	-0.2
GER	-1.5	0.1		0.3	0.1	-0.8	0.1	6.5	6.0
GBR	-0.8	0.1	0.1		-0.4	-0.8	-0.1	3.9	2.1
FRA	-0.1	0.1	1.2	-0.2		-0.9	-0.1	5.7	4.0
ITA	0.3	0.1	1.8	0.1	-0.1		0.1	3.9	6.6
JPN	-2.3	-0.2	0.1	-0.1	-0.1	-0.1		7.5	3.3
CHN	-3.9	-0.8	-0.4	-0.5	-0.5	-0.6	-3.2		-0.8

Table 1: Panel (a): Foreign Input Reliance in 2019 (FIR, %); Panel (b): Change in Foreign Input Reliance between 2000 and 2019 (ppt); Panel (c): Foreign Market Reliance in 2019 (FMR, %); Panel (d): Change in Foreign Market Reliance between 2000 and 2019 (ppt). Source: Authors' computations based on Inter-Country Input-Output (ICIO) Tables http://oe.cd/icio. Notes: ROW denotes the Rest of the World.

Next, we investigate how Foreign Input Reliance has changed during the last two decades by comparing FIR in 2019 with FIR in 2000. Table 1, panel (b) reports change in row nations' reliance on inputs from column nation for manufacturing production between 2000 and 2019. Darker-shaded cells indicate larger changes in FIR. For most countries the bilateral FIR matrix with respect to China was considerably larger in 2019 than it was in 2000. In panel (b), the figures in the China column are all positive and all significantly different from zero, indicating that the G7 industries' input dependence on China has increased. In contrast, the figures in the USA column are small, mostly, under 1ppt, and some figures are even negative (e.g. China). Most of the panel (b) entries for other countries are negative. Overall, the reliance of G7 economies on Chinese inputs has increased substantially between 2000 and 2019, whereas the opposite is observed for Chinas reliance on inputs from G7 (last row in Table 1, panel (b)).

Industries participating in GSCs are exposed also to sales-side shocks. Therefore, it is not less important to understand domestic industries' foreign dependence on the output side. Conceptually similar to the FIR index - which measures countries' total reliance on foreign production on the sourcing side - the Foreign Market Reliance (FMR) index measures countries' reliance on foreign markets on the sales side. Table 1, panel (c) reports row nations' total input sales to column nations' manufacturing industries for G7 economies and China in 2019, again based on the Inter-Country Input-Output (ICIO) data from the OECD. As before, cell shades are indexed to share sizes; darker shades indicate higher bilateral FMR (more foreign market-dependent). Overall, the G7 economies’ foreign market exposure with respect to China is high (higher than the bilateral foreign exposure between most G7 country pairs). Second, the global importance of the USA and China stand out from the rest, as the respective columns are primarily shaded dark. However, the bilateral US-China asymmetry is less marked and reversed since China's sales-side reliance on the US is 8.0% while that of the US on China's market is only 5.6%.

Finally, as for the input sourcing side, we also compute the change in Foreign Market Reliance between 2000 and 2019. Table 1, panel (d) reports change in row nations' total input sales to column nations' manufacturing industries, 2019 vs. 2000. Dark-shaded cells indicate large FMR decreases or increases. Overall, panel (c) suggests that the G7 economies’ FMR has been further increasing with respect to China during the last two decades. These findings apply both to the input sourcing side as well to the sales side. Given that the foreign exposure is an inverse measure of the domestic industries' resilience and robustness (see trade-off in Figure 1) with respect to GSC shocks, our results imply that the increasing dependence on intermediate inputs from China and market sales in China may contribute negatively to the G7 economies' vulnerability.

2.3 Increasing Global Supply Chain vulnerabilities

Because of a widespread production outsourcing, off-shoring and often insufficient investment in resilience in absence of robustness-promoting policies, many global production networks have become excessively complex and fragile (Baldwin and Freeman 2022). The GSCs of 2020s are efficient but brittle – vulnerable to breaking down in the face of a pandemic, a war or a natural disaster. These developments are important to understand, as the increasing fragility of GSCs may have implications for the vulnerability of critical sectors and essential services as well as implications for the entire Alliance's security and defence.

In absence of systemic shocks to GSCs, the foreign input and output dependence may not be crucial. In reality, however, all production structures entail uncertainty, and sourcing inputs from abroad exposes domestic activity additionally to foreign shocks, making globally fragmented production structures more vulnerable than locally organised production processes. There are at least three key channels exposing the domestic activity to GSC shocks: the costs and effects of delinking; the propagation of micro shocks into macro shocks; and GSCs amplify the trade impact of macro shocks (Antras and Chor 2022).

Different metrics and indices have been developed to monitor and track the state of GSCs. The Global Supply Chain Pressure Index (GSCPI) is one of most robust indices; it is being deployed by the Federal Reserve Bank of New York. GSCPI measures a common factor of several cross-country and global indicators of supply chain pressures (e.g., delays in shipments and delivery times and shipping costs after purging these from demand measured by new orders). As illustrated in Figure 2, the GSC pressure is at historically high levels since 2020, which is signalling an escalating probability of GSC ruptures.

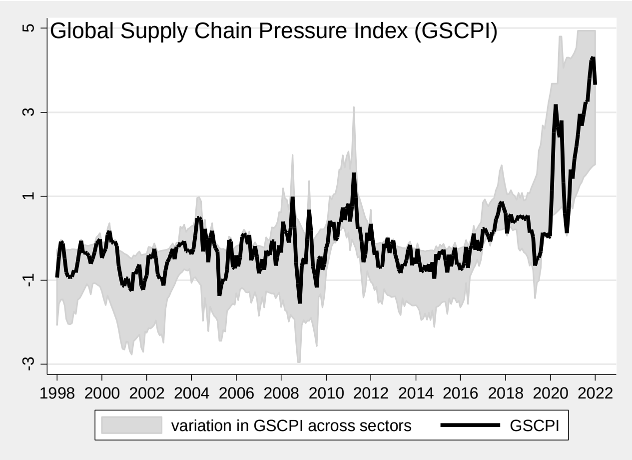

Figure 2: Global Supply Chain Pressure Index (GSCPI) 1998-2022
Source: Computed based on www.newyorkfed.org/research/policy/gscpi

The GSC-disruption-caused losses are escalating and the frequency and intensity of hybrid threats is increasing, particularly during the recent years (European Commission 2021). Similarly, the World Economic Forum (2021) is explicit about the increasing vulnerability of GSCs to shocks: "The increasing frequency of supply-driven disruptions – ranging from global pandemics and the climate crisis to cyber threats and geopolitical tensions – combined with an ever intensifying set of demand-driven disruptions – including the rise of new consumer channels, pent-up demand and a fragmented reopening of the global economy – will continue to destabilise global value chains."

2.4 Accelerating evidence-based decision processes

Both the firm-level and aggregate stock-taking exercises of where we are in terms of the GSC-foreign reliance provide valuable insights to decision makers about the true supply chain pressures and vulnerabilities via foreign input and output exposure. However, the collection of these data takes time, which typically lasts several years and hence implies delays in the evidence base to respond to shocks. In the case of firm-level evidence, the necessary data are collected via numerous sequential company surveys following the entire recursive upstream and downstream sequence of all the input providers of all input inputs. In the case of macro-level aggregate evidence, the time lags are even larger, as national account data, international trade statistics and input-output tables are usually published with a backlog of around three to four years. For these reasons, the retrospective evidence does not allow to react pro-actively to dynamically changing external threats.

New technologies and advances in big data offer new opportunities to monitor and trace GSCs and locate arising bottlenecks in real time. For example, blockchains allow to record and access real-time data, avoiding unnecessary delays in decision maker response to dynamically changing and intensifying hybrid threats, such as the recent attempts by Russia to weaponise energy supplies against Europe. The content stored on the blocks – and the management of the stored data performed by the various participants – can be securely controlled depending on how the blockchain is configured (Ciaian et al. 2021). There are several types of distributed ledgers that can provide safe real-time solutions for recording, tracking and securing of sensitive data. For example, public blockchains allow anyone to access them; private blockchains are only open to selected users; whereas permissioned blockchains are a hybrid of public and private blockchains where anyone can access them as long as they have permission from the administrators to do so. In the context of GSCs in critical sectors, blockchains can be designed with limited access to designated actors along the Alliance's defence chain.

A private blockchain is the most restrictive distributed ledger that operates as a closed database secured with cryptographic concepts and the organisation's needs. Only those with permission can run a full node, make transactions, or validate/authenticate the blockchain changes. For example, in a private blockchain of a critical defence sector the participation at the network would be only through an invitation where their identity or other required information is authentic and verified. The validation would be done by the network operator(s) or by a clearly defined set protocol implemented by the network through smart contracts or other automated approval methods. Hyperledger is one such private blockchain frameworks – already used by many enterprises and medium-sized companies within the Alliance – that could be deployed within a relatively short period of implementation for the management and secure sharing of sensitive GSC data in critical sectors (Ravi et al. 2022).[5] It was initiated as an open-source distributed ledger by the Linux Foundation in 2016. The current Hyperledger release offers a modular, scalable and secure framework for real-time transactions, compatible with smart contract technology and secure sharing of sensitive data. The key advantage of deploying a private blockchain for the management and security of sensitive GSC data in critical sectors would be that by reducing the focus on protecting user identities and promoting security of data, efficiency and immutability (the state of not being able to be changed by adversaries) is prioritised (Ravi et al. 2022). A second important advantage would be a continuous access to real-time data, allowing to avoid unnecessary delays in decision maker response to GSC shocks and potential Alliance's vulnerabilities.

3.0 SIMULATION-BASED DECISION SUPPORT: A VIEW FORWARD

In the previous section, we have taken a retrospective snapshot of foreign input reliance. In this section, we look forward - what can decision makers undertake to enhance the robustness/resilience of supply chains? In particular, we aim to understand the potential consequences of extreme events - like natural disasters,

[5] www.hyperledger.org/

pandemics, hybrid and/or military aggression - on GSCs and the participating upstream industry resilience and robustness under alternative strategies. Model-based simulations will help us answer this question. We undertake GSC stress tests by simulating counterfactual shock scenarios under alternative uncertainty setups. According to our simulation results, the optimal input sourcing diversification depends on the GSC integration and the nature of shock uncertainty.

3.1 Modelling framework

Inspired by the theoretical GSC literature (for an overview, see Antras and Chor 2022), which is largely concerned with developing tools to solve the complex problems that firms face when designing their optimal global production decisions - forward GSC participation, backward GSC participation, centralised versus lead-firm approaches - the underlying conceptual framework is a parsimonious partial equilibrium model based on Jiang et al. (2022). For the sake of brevity, we abstract from many important GSC-related decision of firms highlighted in recent literature, such as staggered GSC participation, buyer-supplier matching, or relational nature within GSCs.[6] In our stylised model of a supply chain, we focus on the key input sourcing decisions of a firm to study shocks to GSCs. The framework allows to investigate how the decision of a GSC diversification changes in the presence of uncertainty.

The modelled GSC consists of two types of firms: small intermediate good producers and one globally sourcing downstream firm producing a final demand good. There are two locations: the East and the South which they differ in the probability that an aggregate shock hits. More generally, the locations may differ in terms of unit production costs, c, prices, p, trade costs and face other asymmetries. Nevertheless, to introduce the framework and gain the intuition of the main mechanics, we start with symmetric prices and costs across the two locations. Time occurs in discrete steps, the discount rate is beta. The discrete time version of the model is sufficient to characterise and compare the alternative solutions.

Presume there are Nt intermediate input firms at the start of period t. Each input firm produces a single and unique intermediate good that is different from other intermediate input producers. At the beginning of every period, each intermediate input firm faces a location decision to choose one of the two locations where it sets up production, whereby locations may be subject to aggregate shocks. The location decision of an intermediate input producer maximises short-term profit, p; the intermediate input firms do not care about their survival. The production of the intermediate good is uncertain. In each period t, one of two locations may suffer an aggregate shock with arrival probability gamma; hence, there is no aggregate shock with a probability 1 - gamma. Conditional on such a shock, and before the production occurs, all intermediate good firms in the East or South perish with probability theta or 1 - theta, respectively. In counterfactual simulations, we presume that theta >> 1/2, implying that the East is riskier than the South. Intermediate input firms are risk-neutral. In the following period, t+1, the intermediate input production takes place by the surviving firms. Between periods, the number of intermediate input producers can grow with a growth rate A. The growth of intermediate input firms depends on the total number of surviving input producers in the world, the new entering intermediate input producers are being distributed across locations according to the existing shares of surviving input firms in each location. The evolution of intermediate input firms depends on the aggregate shock realisations.

The downstream producer aggregates intermediate goods from all the input suppliers and manufactures a final demand good. The sophistication of the final demand good depends on the number of intermediate inputs used in its production. The final demand good is more desirable, the more inputs are used in its production - the quality increases with the number of inputs. 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 use as many parts as possible to produce and sell the final demand good internationally. Hence, the downstream firm cares about intermediate input supplier survival. The long-term benefit of the downstream firm is the continuation value, v. The expected value of continuation is the differences between the revenue -

[6] For more complete theoretical foundations of these channels of GSC adjustment, we refer to Antras and Chor (2022).

which depends on the number of surviving firms - minus the cost. At least one intermediate input is needed to produce the final demand good. All the revenue from the downstream firm is transferred to the intermediate input firms, which is equally shared among all input producers (surviving firms and new entrants) to pay the cost before starting production in the next period (the downstream firm has zero profits).

The price per produced intermediate input, p, is constant and in this version of the model and we assume that it is independent of production and the state of the world; the small intermediate input producers are price takers. Given that prices are fixed, they cannot adjust after a shock and there is no way of compensating the intermediate input producers that locate themselves in a region. Note that the prices are fixed is as long as the investment horizon. Given that the investment horizon is one period, at the end of the period the input producers can relocate between regions without cost (there are no adjustment/switching costs in the model).

The model incorporates the well-known trade-off between efficiency and robustness already mentioned in section 1. In the pursuit of efficiency, a supply chain could become vulnerable to aggregate shocks. On the other hand, a supply chain with a greater resilience to shocks has to sacrifice efficiency during normal times (in absence of shocks). In the model, there is both a marginal benefit and cost of diversification. Profit maximising firms (integrating in GSCs or not) aim to ensure a certain resilience/robustness of the production process while keeping the cost optimisation and customer satisfaction in mind. Lettau and Ludvigson (2003) refer to the risk-reward trade-off as a decision process of firms, which typically care about both uncertainty (i.e. they value resilience/robustness), as well as the reward from cost savings. In the context of firm's input sourcing decisions, a key trade-off in both resilience and robustness decisions at the firm level involves diversification of uncertainty versus lower cost and higher quality inputs. Lower cost is usually associated with economies of scale in input sourcing, whereas higher quality inputs tend to be found in markets with niche expertise – both implying a higher participation in GSCs. The trade-off between the uncertainty (in form of risk and ambiguity) 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 the firms' willingness to substitute one unit of uncertainty for reward is constant. Moving on this line starting from the origin we can think as sourcing from fewer more specialised GSC suppliers. Uncertainty is assumed to increase as manufacturers concentrate production of a particular input in the single cheapest location. Diversification of sources reduces risk and ambiguity but at a diminishing rate. Solving the underlying mathematical model, the equilibrium solution is found at the tangency of the indifference curves and the uncertainty-reward frontier, represented by point P in Figure 3.

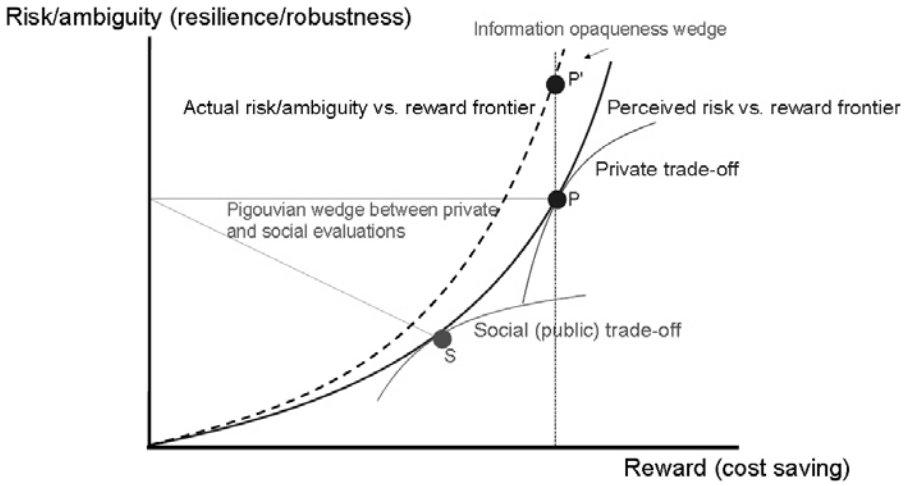

Figure 3: Firms' efficiency-robustness trade-off, externalities and market failures
Source: Based on Lettau and Ludvigson (2003) and Baldwin and Freeman (2022)

Although optimal from the perspective of a single firm, the equilibrium efficiency-robustness outcomes may be inefficient socially in the presence of externalities and market failures (Baldwin and Freeman 2022). First, social evaluation of the uncertainty-reward trade-off may put a greater stress on uncertainty than private evaluation. Private companies may accept more risk/ambiguity (resilience/robustness) for any given level of reward compared to the society, which usually cares relatively more about risk/ambiguity (resilience/robustness). The indifference curve shapes (and position in Figure 3) reflect that private sector firms would agree with more risk/ambiguity for any given level of reward (curve 'Private trade-off'), but the public cares relatively more about risk/ambiguity (curve 'Social (public) trade-off'). In equilibrium, the public is desiring a lower level of uncertainty, point S, than the private sector, point P in Figure 3. This wedge between the public and private evaluation for risk ('Pigouvian wedge') is an externality that is not internalised by economic actors in their optimisation decisions leading to a market failure.[7] As became evident during the recent GSC ruptures, markets for medical supplies share features of the public-private wedge, as do other 'strategic' inputs such as semiconductors.

The equilibrium efficiency-robustness outcome is likely to be socially suboptimal also in markets where a collective action problem creates information asymmetries that force companies to act without a full information. In 2020s, GSCs are characterised by complexity and non-transparency. Even large, sophisticated companies do not know all their suppliers and the suppliers of their suppliers, and even seemingly 'purely domestic companies' might not appreciate being part of a global network. The general lack of firms' understanding of where they sit in their own supply chains - supply chain opaqueness - implies that companies may be sub-optimally making decision with respect to the risk-reward trade-off and misaligning their input sourcing and output supplies. Russia's war on Ukraine and the implications on global food and energy supplies visibly demonstrate how this lack of information about where domestic company inputs and input-inputs are sourced from can result in private misjudgements about the actual vulnerability of GSCs. In Figure 3, the supply chain opaqueness-caused market imperfections are shown on curve 'Actual risk vs. reward frontier', which is above the 'Perceived risk vs. reward frontier' curve. We refer to the gap between the two curves as the 'Information opaqueness wedge' in Figure 3. Since GSCs are highly interwoven and generally not fully contained within the boundaries of a single firm, information about them has public good features. This information is costly to collect, cheap to share, and provides value to many.

3.2 Simulation scenarios

In order to study how a GSC's decision of input sourcing diversification changes in the presence of uncertainty and what are the implications for supply chain robustness and resilience, we set up a number of counterfactual scenarios. We study three shock realisation possibilities, three setups of shock expectations and two arrangements of the GSC integration. The key modelling assumptions in the counterfactual scenario construction are summarised in Table 2.

The first dimension allows to study how the evolution of intermediate input firms depends on the aggregate shock realisations: (i) there is no aggregate shock (with probability 1 - gamma); (ii) the aggregate shock hits the East in period 10 and all firms in the East perish (with probability gamma*theta); (iii) the aggregate shock hits the South in period 10 and all intermediate input producers in the South perish (with probability gamma*(1-theta)). These three shock possibilities are summarised in the columns of Table 2.

Second, we study alternative aggregate shock scenarios with respect to the conditional probability that the shock hits the particular location. We recognise that there are two categories of imperfectly predictable events between which choices must be made: risky events and ambiguous events (Knightian uncertainty). (i) In the risk-free scenario, the value of the conditional probability that the aggregate shock affects the location is known. (ii) In the GSC risk scenario, the distribution of the conditional probability that the aggregate shock affects the location is known (the shock is distributed according to some a priori known distribution; in our simulations we assume that the distribution is uniform). (iii) In the GSC ambiguity scenario, the shock has bounded uncertainty and the distribution of the conditional probability that the aggregate shock affects

[7] See, e.g. Turvey (1963) for the underlying concept.

the location is unknown; all firms know that a shock can occur in one of the regions but they do not know the underlying distribution. These differences in the conditional probability that the shock hits the particular location are summarised in rows of Table 2.

	No aggregate shock	Aggregate shock in East	Aggregate shock South
Fragmented risk-free scenario	Externality, known probability, no shock realised	Externality, known probability, shock realised in East	Externality, known probability, shock realised in South
Fragmented GSC risk scenario	Externality, known shock distribution no shock realised	Externality, known shock distribution shock realised in East	Externality, known shock distribution shock realised in South
Fragmented GSC ambiguity scenario	Externality, unknown distribution, no shock realised	Externality, unknown distribution, shock realised in East	Externality, unknown distribution, shock realised in South
Integrated risk-free scenario	Internalised externality, known probability, no shock realised	Internalised externality, known probability, shock realised in East	Internalised externality, known probability, shock realised in South
Integrated GSC risk scenario	Internalised externality, known shock distribution no shock realised	Internalised externality, known shock distribution shock realised in East	Internalised externality, known shock distribution shock realised in South
Integrated GSC ambiguity scenario	Internalised externality, unknown distribution, no shock realised	Internalised externality, unknown distribution, shock realised in East	Internalised externality, unknown distribution, shock realised in South

Table 2: Simulation scenario construction, key assumptions

Finally, we investigate two different vertical integration arrangements of the GSC: a fragmented GSC and an integrated GSC. In the fragmented GSC, the small input producers individually decide their location and the downstream firm purchases the surviving suppliers' products. The intermediate input producers are small; they do not take into account the impact their decision has on the decision of the location of others. Due to the externality explained in Figure 3, individual supplier's location decisions may not be socially optimal (when the probability of global survival is taken into account). This wedge between private and social allocations comes from the pricing system's inability to compensate input suppliers properly for moving into the South. Given that there is no cost of switching between locations, the intermediate input firms are solving a static problem - the continuation value is the same for all firms. Input producing firms are maximising the expected value of East versus South. In the integrated GSC, the globally sourcing downstream firm is vertically integrated with intermediate input firms and hence can determine their location. The downstream firm can choose all its suppliers’ locations, thereby internalising the location decision (i.e., when input suppliers are subsidiaries of the downstream firm). In the input supplier allocation decision, the downstream firm takes into account the overall distribution of intermediate input firms, and the expected value of continuation in all states of the world. By internalising the externality, the globally sourcing downstream firm aims to ensure all its input suppliers survive. These differences in the integration arrangements of the GSC are visible when comparing in rows of 2-4 with rows 5-7 in Table 2.

3.3 Simulation results

We study how the input supply diversification changes in the presence of uncertainty. Among others, our parsimonious model allows to analyse the survival probability of a GSC, and complex linkages between vertical integration and uncertainty expectations. Simulation results are summarised in Figures 4-6. The black dotted line describes the intermediate input firm location decisions and their survival In the South, the grey dashed line in the East, whereas the solid red line reports the total number of operating intermediate input firms in each specific GSC setup.

In the fragmented GSC setup (left panels in Figure 4), given our assumption of lower shock probability in the South, it is the preferred location for all intermediate input firms. The value of locating in the South is always larger than the value of locating in the East, because the continuation value for each input producer, conditional on having survived the aggregate shock, is independent of location. Simulation results presented in the left panels in Figure 4 suggest that the fragmented GSC results in a corner solution (all firms locate themselves in the South). Individual intermediate input producers maximise their own efficiency (productivity) - exposing the downstream firm to an aggregate shock to the South.

In the integrated GSC setup (right panels in Figure 4), the downstream firm is willing to allocate intermediate input production facilities also in the East to insure itself against an aggregate shock in the South - it internalises the survival probability and diversifies the supply chain. In the right panels of Figure 4, the dashed grey lines (number of firms in the East) are above zero in all scenarios. The integrated GSC results in an internal solution - a share of intermediate input firms larger than zero in the East. The downstream firm maximises survival, hence it internalises the survival externality.

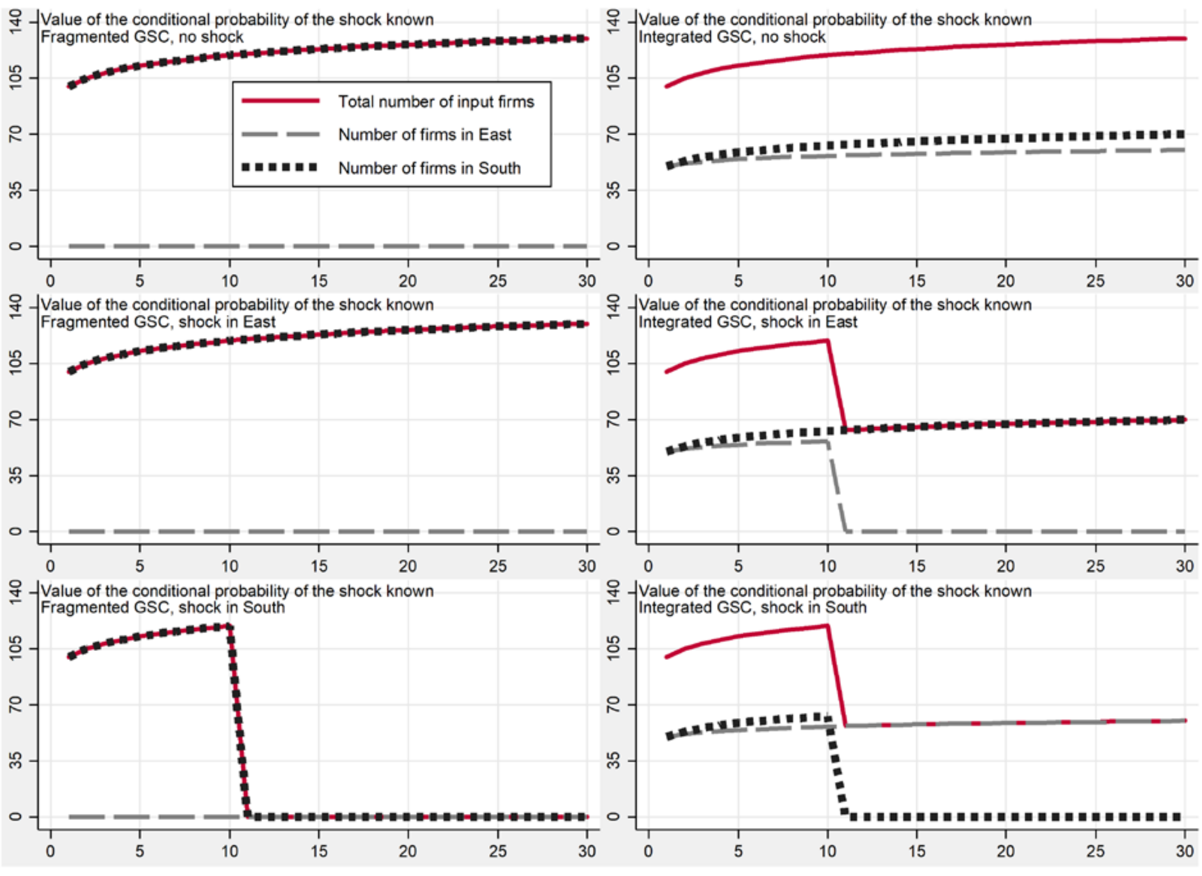

Figure 4: Simulation results with known value of the conditional shock probability. Notes: Y-axis measures the number of surviving intermediate input producers; X-axis refers to time periods. Fragmented GSC is shown in left panels; integrated GSC is shown in right panels

Next, consider the GSC risk scenario in Figure 5, where the distribution of the conditional probability that the aggregate shock affects the location is known. Specifically, without loss of generality, in our simulations we assume that the distribution is uniform.

In the fragmented GSC setup (left panels in Figure 5), the risk-neutral intermediate input firms are maximising the expected value of East versus South and given our assumptions South dominates for all intermediate input producers. Given that the East is riskier in our setup, the worst case for each individual input-producing firm still implies that the worst case in the South is better than the worst case in the East. In a fragmented GSC, intermediate input firms do not take into account the survival probability of the downstream firm.

The risk-averse downstream firm exhibits an allocation behaviour that takes into account all the sources of risk - a desire for diversification. The diversification is obtained as in a traditional expected utility maximisation problem by either increasing the variance or the risk aversion to infinity. The downstream firm faces a trade-off between instantaneous profits (what the individual intermediate good producers maximise) and the probability of survival. The downstream firm's optimal allocation of intermediate input suppliers to the particular location depends on the number of suppliers that have survived.

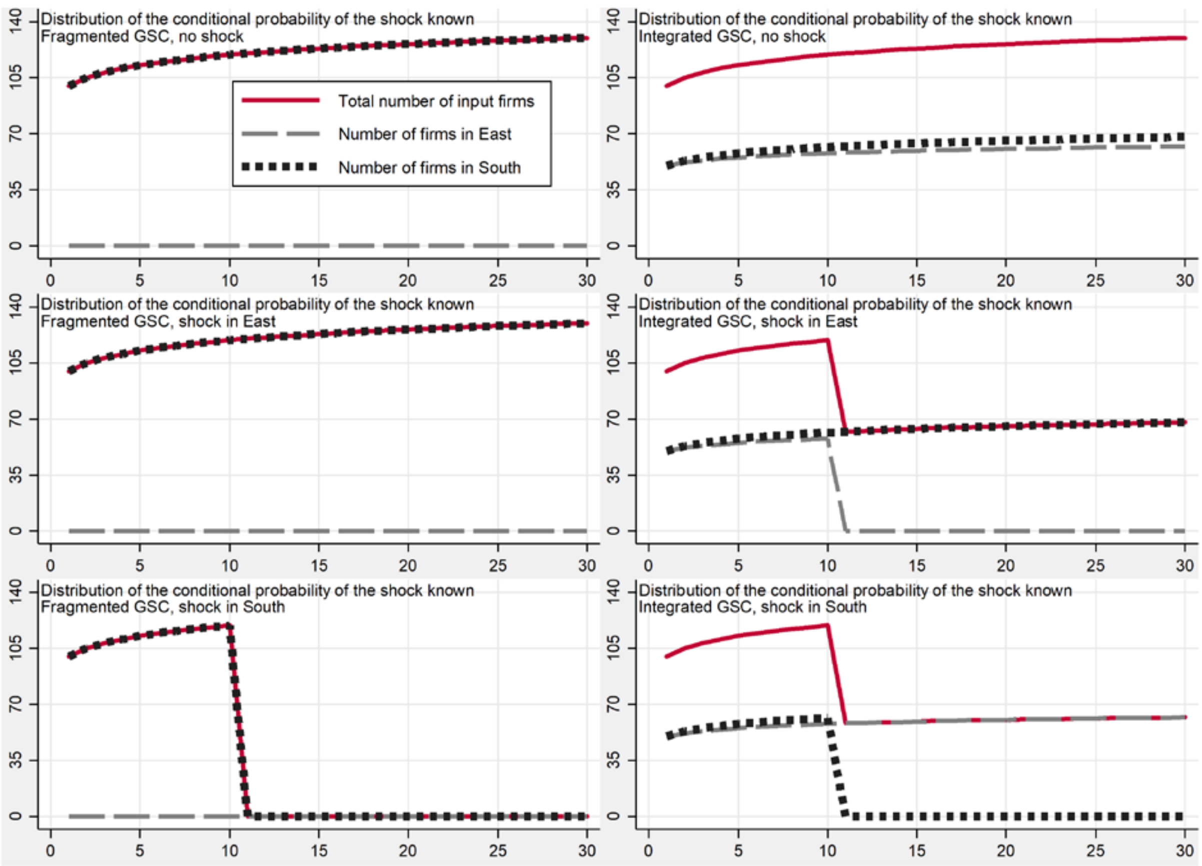

Figure 5: Simulation results with known distribution of the conditional shock probability. Notes: Y-axis measures the number of surviving intermediate input producers; X-axis refers to time periods. Fragmented GSC is shown in left panels; integrated GSC is shown in right panels

Being averse to ambiguity, the intermediate input producers and the downstream firm maximise the expected profit assuming the worst-case value of the conditional probability that the aggregate shock affects the region of firm's location. Ambiguity-averse downstream firm's optimal allocation of intermediate input suppliers to the South is independent of the number of surviving intermediate input producers. It does not matter how bad the East is relative to the South, there is a level of ambiguity for which the downstream firm allocates half the firms in the East. According to the simulation results reported in the right panels of Figure 6, a robust supply chain is one in which the survival probability is maximised, and where there will be production even in the worst of circumstances.

In terms of robustness, an optimal allocation of intermediate input producers is a uniform allocation across locations; in our example, allocating half of the intermediate input producers in the East and half in the South. This implies that in the presence of an aggregate shock - independently where it occurs - half of the input producers disappear, half survive. The flows and costs are identical, therefore, the expected value is independent of the true shock realisation. Robustness is needed when the intermediate input supplier survival is important, the agents do not know the distribution of the shock they are facing, and therefore need to prepare for the worst. The simulation results presented in the right panels of Figure 6 present a strategy that reduces the differences over all possible states of nature. These results of a downstream firm's strategy guaranteeing the survival of the downstream firm are comparable to insights from the behavioural finance literature, where in many cases individuals will tend to chose the robust survival maximising strategy.

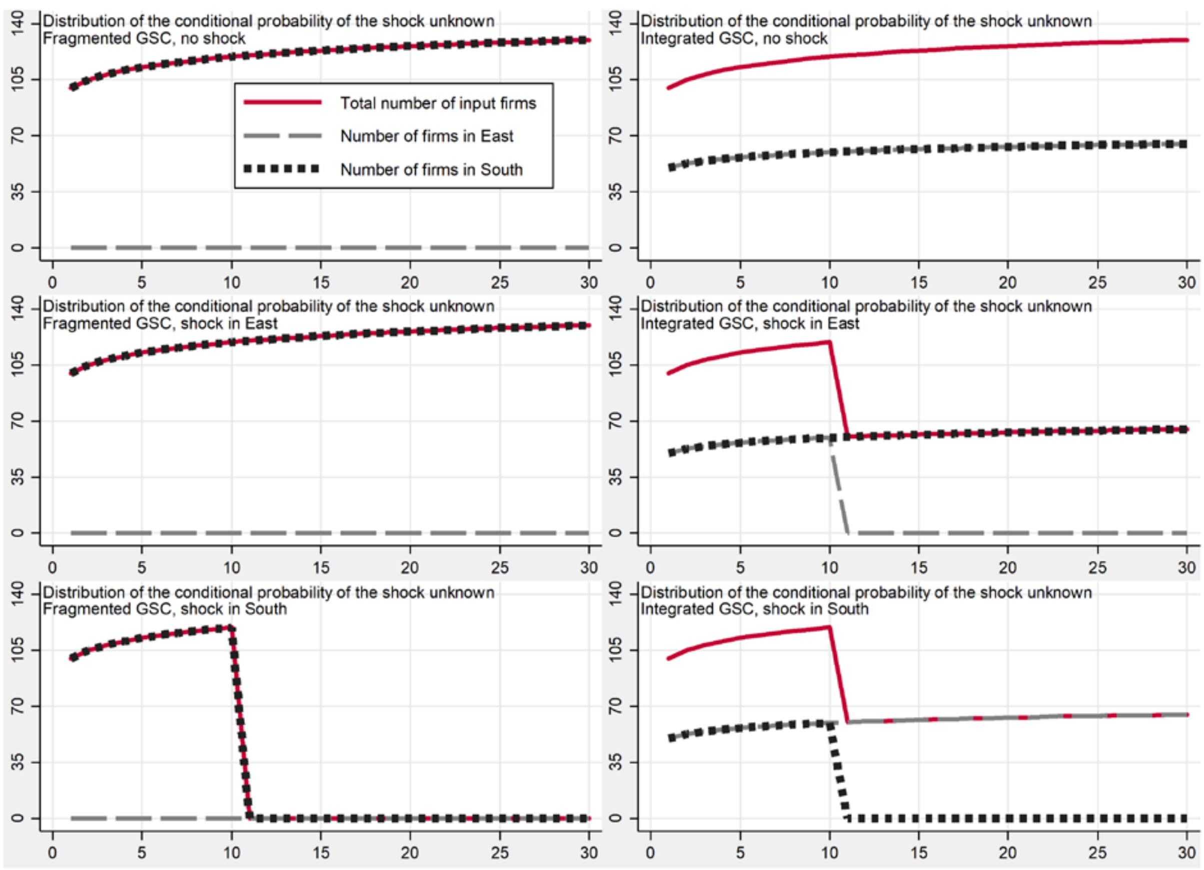

Figure 6: Simulation results with unknown distribution of the conditional shock probability. Notes: Y-axis measures the number of surviving intermediate input producers; X-axis refers to time periods. Fragmented GSC is shown in left panels; integrated GSC is shown in right panels

Comparing the left panels in Figures 4-6, we may conclude that in fragmented GSCs, the optimal firm choices are independent of the nature of the shock. Individual input producers will choose a corner solution (e.g., locating exclusively in the South) irrespectively of whether they are facing risk or ambiguity - exposing the downstream firm to an aggregate shock to the South. Individual intermediate input firms maximise efficiency (or productivity), while the downstream firm maximises survival. The optimal behaviour of the downstream firm is rather different in a vertically integrated GSC (right panels in Figures 4-6). In an integrated GSC, the downstream firm's optimisation tends to result in internal solutions - a proportion larger than zero of intermediate input firms in the East). When the downstream firm faces risk, the optimal allocation of firms is an increasing function of the number of intermediate input firms (right panels in Figure 5). When ambiguity is present, the optimal firm allocation solution is an internal and fixed ratio (right panels in Figure 6). Since GSC disruptions in critical sectors may have catastrophic impacts on social welfare, and the probability of such disruptions is not known even approximately, uncertainty and robust decision rules are the appropriate tools for analysis and policy recommendations.

3.4 Policy maker choices and constraints

Next, we investigate the role of government policies on GSC diversification. As discussed in section 2, the sourcing of specialised inputs and cost advantages are among the main drivers of the raise in the intermediate goods trade resulting in highly complex globally fragmented production and trade networks. Given intermediate input price differences across world-wide locations, we simulate a government policy stimulating a decentralised economy with globally fragmented GSCs to achieve a diversified input sourcing outcome – similar to integrated GSCs in section 3.3.

In order to study the challenge of "not trading long-term security needs for short-term economic interests" formally, we frame it as a constrained optimisation with two policy constraints: a robustness/resilience constraint and a resource mobilisation constraint. We aim to introduce the trade-offs into simulations by achieving the baseline resilience while doing as little damage as possible to the society's socio-politico-economic fabric. The robustness constraint ensures that the baseline resilience requirements with respect to foreign input sourcing and output sales are fulfilled – the supply chain's capacity is subject to a minimum reduction (floor) constraint. The resource mobilisation constraint implies that governments do not ask the impossible of domestic economy and society – the supply chain's capacity is subject to maximum mobilisation (floor) constraint. While private sector firms may be willing to temporarily forgo possible gains or even accept losses, especially when it is in the name of a good cause, profit maximising firms' tolerance of forgoing profits is not infinite and this should be accounted for.

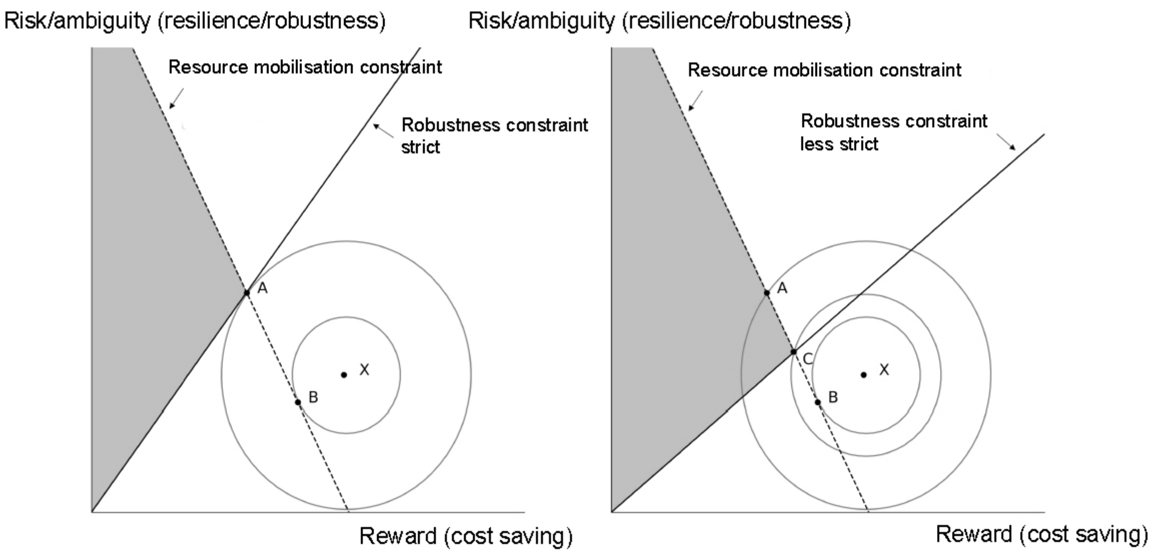

Figure 7: Welfare maximisation and constrained policy optimisation
Source: Based on Lettau and Ludvigson (2003) and Baldwin and Freeman (2022)

Figure 7 shows the key intuition of the constrained policy optimisation problem in a static setup graphically.[8] The aggregate welfare is represented by indifference curves (circles), with each circle representing a

[8] The solution of the full simulation model is more complex, with heterogeneous firms choosing optimal strategy in a dynamic general equilibrium (for details, see Antras and de Gortari 2020 and Jiang et al. 2022).

different level of welfare. The optimal welfare in absence of shocks and policies (and abstracting from other factors such as externalities and market imperfections) is represented by point X. The solid line represents the uncertainty-reward frontier (as in Figure 3); everywhere on this frontier the domestic industries' robustness/resilience to GSC shocks is constant. Solving the underlying mathematical model, the equilibrium solution after the implementation of the robustness/resilience constraint is found at the tangency of the indifference curves and the uncertainty-reward frontier, represented by point A in the left panel of Figure 4. The other boundary condition is represented by the resource mobilisation constraint - the dashed line in Figure 7. Under these two constraints, the new equilibrium state of the economy would be represented by the solution to the welfare maximisation problem subject to both constraints, which would occur at point A in the left panel. Note that the grey shaded area represents the feasibility region of all possible combinations.

Figure 7 also illustrates a scenario with less binding resilience requirements (right panel). The robustness/resilience constraint is less steep, implying that the new equilibrium is now at point C. The level of welfare resulting from these minimum resilience standards (represented by the circle going through point C) is not as high as under the optimal resilience strategy (the circle going through point B) but it is closer to the optimal than the welfare achieved under the alternative strategy (the circle going through point A). The right panel of Figure 4 demonstrates that this strategy represents a more efficient outcome (higher welfare).

We set up and simulate a baseline scenario and two adverse scenarios. Our benchmark is a supply chain in absence of any policy which in the pursuit of efficiency could become vulnerable to extreme events/shocks. In line with the Alliance's resilience strategy,[9] we have constructed three simulation scenarios: risk-free baseline (S0) where the value of the conditional probability that the aggregate shock affects the location is known, and two adverse scenarios with alternative GSC shock expectations. In Scenario (S1) 'Demanding circumstances', the expected GSC shocks are frequent, idiosyncratic (shocks to the firm) with a priori known distribution. S1 corresponds to the standard approach in the GSC literature. In scenario (S2) 'Most demanding circumstances', we study an environment in which the expected GSC shocks are infrequent, aggregate with an unknown distribution. Scenario S2 is designed to challenge the baseline robustness requirements regarding the core functions of continuity of government, essential services to the population and civil support to the military – which must be maintained under the most demanding circumstances. The government policy that we simulate aims to compensate the downstream firms' input sourcing disadvantage from specific locations due to global differences in prices. The policy can be interpreted as an ex-ante subsidy to the allocation of an intermediate input production facility in a disadvantaged (from the efficiency point of view) location.

3.5 Simulation results

The simulation results are summarised in Figure 8. A key distinguishing feature in the optimal firm strategy under different shock scenarios is the absence/presence and type of uncertainty in firm optimisation. The optimal firm strategy in the risk-free baseline (S0) implies a solution to the efficiency-robustness trade-off that is highly skewed towards effectiveness (just-in-time). Firms do not internalise the probability of the GSC survival in their optimisation. In the presence of extreme shocks to GSCs, such a firm strategy makes firms highly vulnerable and the survival probability is low (top left panel in Figure 8). Under the 'Most demanding circumstances' scenario (S2), the optimal firm strategy implies resilience through diversification and redundancies. Internalising shock ambiguity in firm strategy, under robust decision rules firms seek to maximise the payoff in the worst-case scenario of a set of potential strategies (bottom left panel). Compared to S0, a robust supply chain with a diversified input sourcing strategy and excess capacity may seem excessively costly in normal times (without shocks), because that excess capacity exists to be used when extreme shocks occur. However, in the presence of extreme shocks to GSC, such a firm strategy makes firms highly robust and the survival probability is high. The optimal firm strategy reconciles both efficiency and robustness in the S1 scenario (top right panel in Figure 8). The GSC-related costs are higher than under S0, but lower than under S2. On the other hand, the supply chain capacity (black solid line) will not be able to

[9] www.nato.int/docu/review/articles/2019/02/27/resilience-the-first-line-of-defence/

achieve the level of scenario S2 though it still will be higher than under the baseline S0. The shaded areas in Figure 8 provide confidence intervals at 90%, 95% and 99% levels.

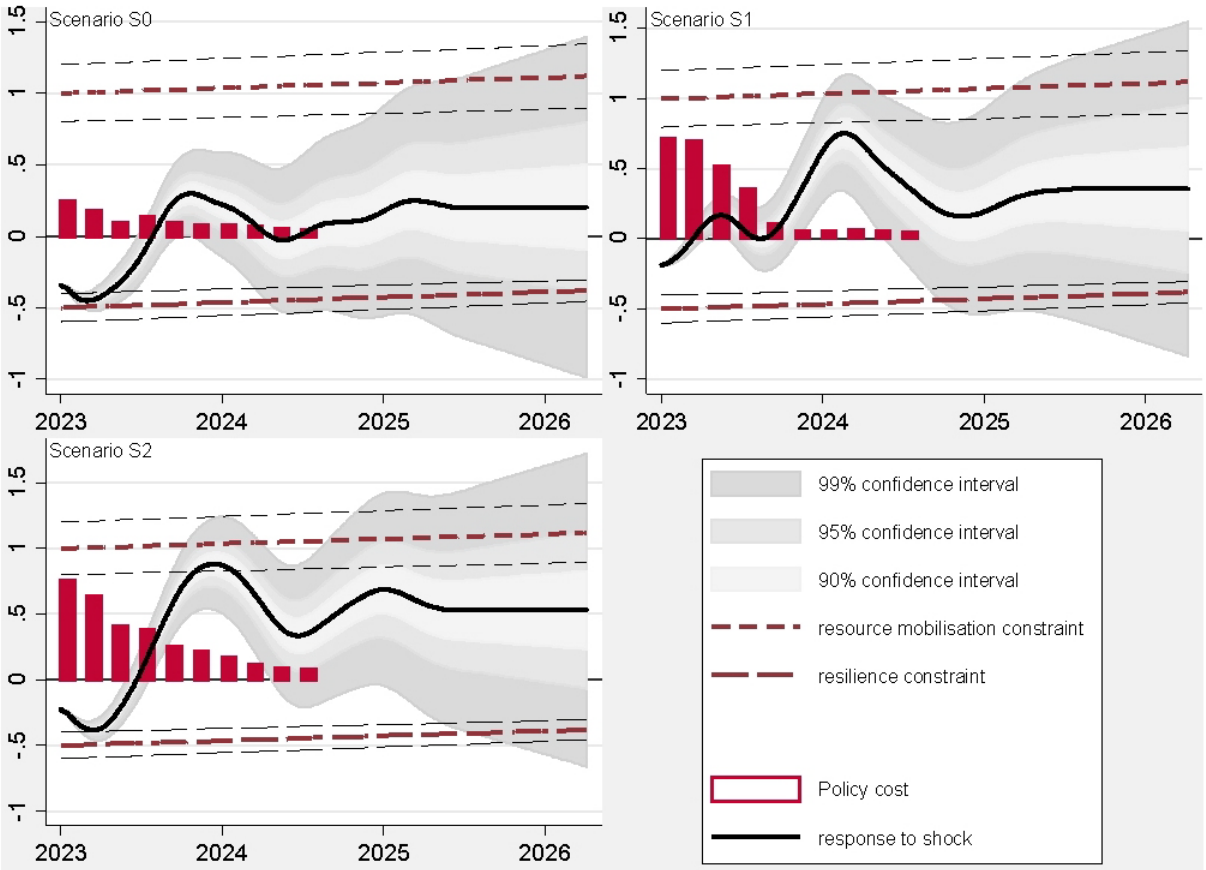

Figure 8: Simulation results: optimal efficiency-robustness strategy under three shock scenarios with resilience constraint and resource mobilisation constraint.
Notes: Y-axis measures percentage deviations in GSC; X-axis refers to response periods in time

The optimal firm response strategy illustrated in the top right panel in Figure 8 corresponds to a resilient supply chain which can optimally deal with risk and function under demanding circumstances in the medium- to long-run. Policies facilitating reasonable minimum resilience/robustness standards to non-critical sectors may provide resilience from a security perspective and sustainability from an economic perspective in the medium- and long-run. The situation illustrated in the bottom left panel in Figure 8 corresponds to a robust supply chain, which can optimally deal with ambiguity, and function under most demanding circumstances in the medium- to long-run. From a policy perspective, implementing such a policy with the highest minimum resilience/robustness standards to critical sectors of the economy may be the most GSC-shock- proof and robust strategy. Given differences and the societal sacrifices and resource mobilisation costs across scenarios, a distinction between 'critical sectors' and 'non-critical sectors' is important to manage the load on domestic producers and possible adverse effects on the tolerability constraint. Resilience baseline requirements determine the critical sectors and essential services, which must be maintained under the most demanding circumstances.

Differences in the optimal firm strategies under the three simulated scenarios depend on the nature of expected shocks and the policy framework (subsidies/taxes, maximum resource mobilisation and minimum capacity (floor/cap) constraints. Under scenario S1, a robust approach implies greater risk aversion, which leads to higher firm incentives for diversification. That is not the case in scenario S2, as resilience/robustness cannot be achieved with an infinite risk aversion by firms. According to our modelling framework and simulation results, the diversification implied by robust decision rules under scenario S2 is both quantitatively and qualitatively different from the diversification that is obtained in the S1 risk-averse firm strategy by either increasing the variance or the risk aversion to infinity (scenario S1). Under the 'Most demanding circumstances' scenario (S2), the optimal firm strategy implies that resilience/robustness can be achieved with ambiguity aversion by firms.

Summing up, the optimal resilience strategy will depend on political priorities - not trading long-term security needs for short-term economic – and political feasibility (robustness/resilience constraint and resource mobilisation constraint). Since GSC disruptions may have catastrophic impacts on the socio-politico-economic fabric, and the probability of such disruptions is not accurately known, uncertainty and robust decision rules are the proper tools for analysis and resilience-enhancing policy recommendations. The difference between the public and private evaluation for risk and ambiguity ('Pigouvian wedge') implies that governments and the private sector might experience risk differently; whereas a social evaluation of the risk-reward trade-off will likely put a greater stress on the risk than a private evaluation. Given that in most cases governments are the residual claimants in case of natural disasters, global financial crisis or other system-wide shocks, governments are more likely to prefer a more 'robust approach' than the private sector would. For instance, if the cost of a natural disaster is very asymmetric, the government is more likely to pay attention to the worst-case than the private sector. Our simulations show that the government can align private incentives by imposing minimum resilience/robustness standards or by providing a subsidy to relocation from riskier locations in the GSCs. For example, Japan did so as a response to COVID-19. In August of 2020, Japan set up a fund to compensate firms that diversify out of China (Jiang et al. 2022).

4.0 CONCLUSION

The landscape of hybrid threats is expanding and production processes are increasingly fragmented across borders. Because of outsourcing, off-shoring and insufficient investment in resilience, many supply chains across the globe have become highly complex and fragile. GSC vulnerabilities are important to understand, address and monitor, as the escalating fragility of GSCs may have severe implications for the functioning of critical sectors and essential services, such as energy supplies, food and water, communication networks and transport systems under the most demanding circumstances, as well as implications for the entire Alliance's security and defence.

The presented model-based simulations provide an interoperable and directly comparable conceptualisation of positive and normative effects of counterfactual resilience and robustness policy choices in GSCs. The current work adds value and contributes along a number of dimensions to the existing modelling and simulation exercises at the Alliance's and Member State levels. First, it integrates several horizontal cross-cutting PMESII elements in one global modelling framework. Indeed, many supply chains are essential to everyday life for the functioning of the entire socio-politico-economic fabric. Second, a particular attention is paid to critical sectors, potential vulnerabilities are assessed based on the severity and likelihood of their disruption against a range of stress test scenarios. Data from Inter-Country Input-Output and World Input-Output Tables reveal that in a number of highly specialised industry-country pairs on the sourcing/selling side even a small shock to supply/demand can have major ramifications on the entire socio-politico-economic fabric. Third, model-based simulations enable a better understanding of the complexities underlying GSCs and provide a scientific evidence base to a resilience-enhancing decision support. To answer the simple question 'where are things made?' comprehensively – as increasingly needed by defence decision makers – one needs to look at foreign input reliance by taking into account the entire recursive sequence of all inputs and all inputs of inputs, not just the first-tier inputs.

Results of such simulations allow the vulnerability source identification and assessment of possible mitigation strategies that could strengthen supply chains in an effective and efficient manner. The decision maker choice of the most suitable strategy in each particular domain and sector should depend on the nature of the shocks, source of vulnerability, strategic priorities and resource mobilisation possibilities in the short-, medium- and long-run. Our results have also practical implications and suggestions for decision makers. First, we urge for an Alliance-wide assessment of the key capability areas and economy sub-sectors that the Alliance's security relies upon, including the mapping of critical sectors' vulnerabilities in GSCs. Model-based simulations can provide the necessary evidence base. Second, a stock taking exercise is needed to identify what is directly available within the Alliance (including its strategic partners) to meet the seven baseline resilience requirements under the most demanding circumstances – such as a complete input sourcing cut-off from authoritarian regimes – and what is needed in the short-, medium- and long-run to achieve the baseline resilience requirements. Third, a strategic framework for addressing the identified vulnerabilities have to be developed, to identify relevant, effective and efficient mitigations for enhancing the resilience and robustness of supply chains, particularly in critical sectors. Finally, a continuous real-time uncertainty assessment and monitoring, collating data and intelligence across allies and partners will be utmost important in the face of the rapidly growing and dynamically changing hybrid threats. This can be done, for example, by deploying a private blockchain such as Hyperledger to establish a securely shared oversight of GSC transactions in the most critical sectors, allowing the Alliance to respond quickly when new risks and ambiguities – such as the energy weaponisation against Europe by Russia – emerge.

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