Enhancing Resilience: Model-Based Simulations[1]

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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, e.g. the recent attempts of energy weaponisation by Russia. 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 resilience 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. 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 to meet the 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 weaponisation of energy 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 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

[1] The authors are solely responsible for the content of the paper. The views expressed are purely those of the authors and may not in any circumstances be regarded as stating an official position of the NATO, European Commission or the Latvian National Armed Forces. Any remaining errors are solely ours.

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

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 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, the Resilience Data Analytics Tool of the ACT's Innovation Hub and the Aggregated Resilience Model. 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). 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 visualization and allows the identification of potential shocks to the Alliance's resilience. Our modelling framework - 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 domestic industries, 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 AND FOREIGN DEPENDENCE

Because of 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. The GSCs of 2020s are efficient but brittle – vulnerable to breaking down in the face of a pandemic, a war or a natural disaster. The GSC-disruption-caused losses are escalating and the frequency and intensity of hybrid threats is increasing, particularly during the recent years. 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.

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 such 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 1, the GSC pressure is at historically high

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

levels since 2020, which is signalling an escalating probability of GSC ruptures. Already the World Economic Forum (2021) was 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."

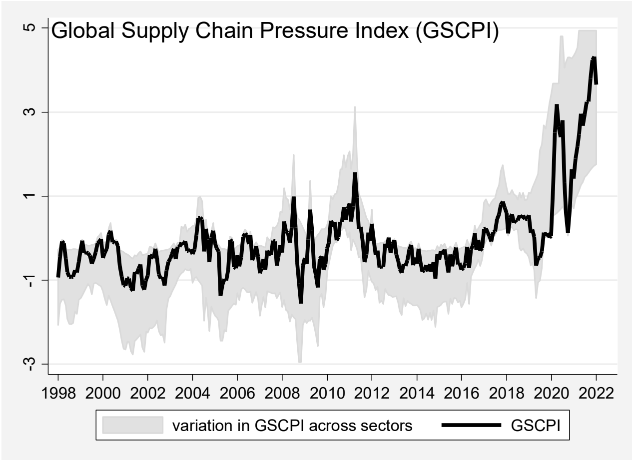

Figure 1: Global Supply Chain Pressure Index (GSCPI) 1998-2022. Source: Computed based on www.newyorkfed.org/research/policy/gscpi.

In light of the increasing fragility of GSCs and expanding hybrid threats, in this section we aim to understand the actual domestic industries' foreign GSC dependence. Knowing economies' international exposure is important to identify potential vulnerabilities and allow for policy actions where needed before major GSC-disruptions occur. We approach this question by querying recent statistical data through different levels of aggregation. 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 by looking how the industrial production is allocated internationally and how each stage of production contributes to the final product. This approach provides an alternative to the micro view by concentrating on countries and industries as the unit of analysis. The macro-approach to measuring GSCs connects national 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 approach and value-added approach an understanding of the domestic economy's foreign exposure via the GSC channel requires to know 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

In the micro approach, the firms are the unit of analysis; they are the ones that decide whether to participate in GSCs. Firms upstream and downstream face contracting problems – moral hazard or incomplete contracts. Integrating internationally and vertically help to solve the informational problem. Considering international trade statistics, the observed world trade flows are best understood as the aggregation of individual firm-level decisions related to the destinations to which firms export their products, but also the origin countries from which they source intermediate inputs, or the 'platform' countries from which they assemble goods for distant destination countries. Inspired by the theoretical "micro" literature (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 which builds on Antras and de Gortari (2020) and Jiang et al. (2022) is introduced graphically by focusing on the key decisions of a firm. For the sake of brevity, in the graphical analysis we abstract from other GSC-related decision of firms, such as staggered GSC participation, buyer-supplier matching, relational nature within GSCs.[4]

To organise thoughts, we briefly review the cost versus resilience/robustness trade-off already mentioned in section 1. Profit maximising companies (participating or not in GSCs) aim to ensure a certain resilience/robustness of the production process while keeping the cost optimisation and customer satisfaction in mind. Formally, the risk-reward trade-off refers to 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 (e.g. Lettau and Ludvigson 2003). In the context of GSCs, a key trade-off in both resilience and robustness decisions at the firm level involves diversification of risks 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 2. 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. 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 2.

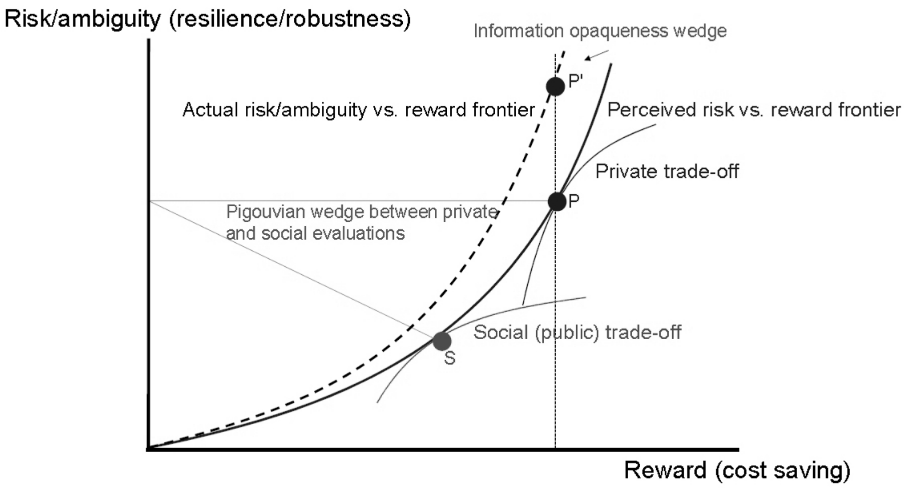

Figure 2: Firms' efficiency-robustness trade-off, externalities and market failures. Source: Based on Baldwin and Freeman (2022).

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. In contrast, the public usually cares relatively more about risk/ambiguity (resilience/robustness). The indifference curve shapes reflect that 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

[4] For more complete theoretical foundations of these channels of adjustment, we refer to Antras and de Gortari (2020).

private sector, point P in Figure 2. 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.[5] 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.

Second, the equilibrium efficiency-robustness outcome is likely to be socially inefficient 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, 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 sourcing and supply chains. 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 actually sourced results in private misjudgements about the actual vulnerability of GSCs. In Figure 2, the supply chain opaqueness-caused externalities 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 2. 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.

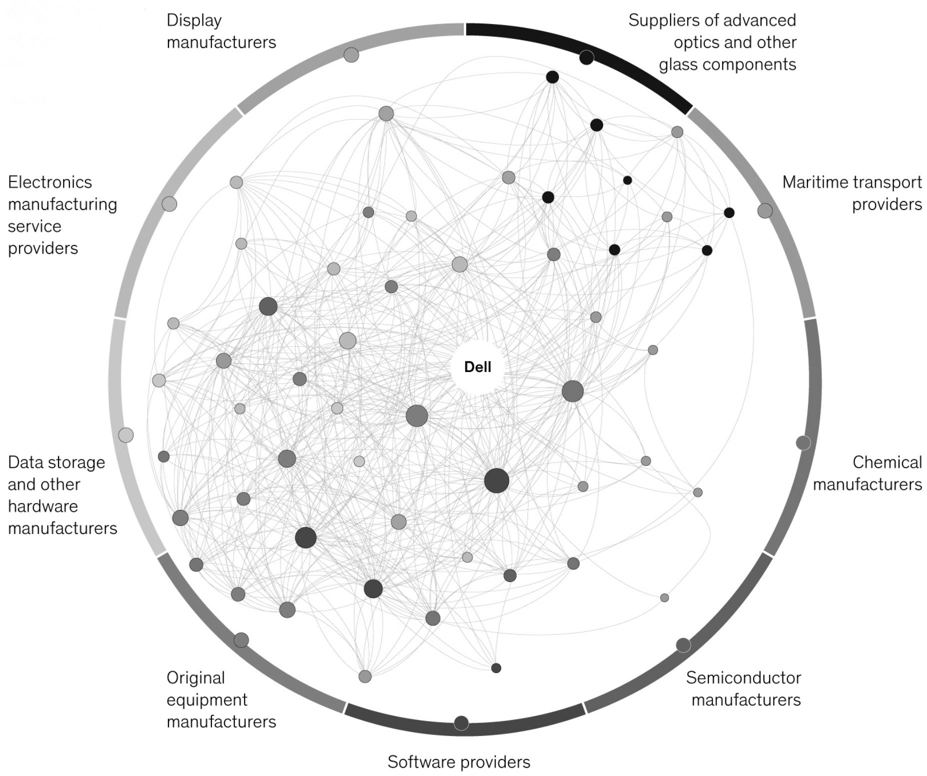

Figure 3: Dell [Military and Defence] exposure to GSCs. Source: Computed based on www.dell.com/en-us/dt/oem/military.htm; Bloomberg global supply chain data; and www.dell.com/en-ca/dt/oem/defence.htm data.

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

How exposed are domestic companies to foreign input supplies and output markets? This question can be answered at several levels. When a product rolls off the Airbus Defence and Space assembly line in Stevenage, UK, we can say it was made in Stevenage. 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 many merits. 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 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 3 provides another example from the semiconductor industry, where the global supply chains of Dell [Military and Defence] are depicted. According to the Bloomberg Global Supply Chain Data, Dell has nearly 5,000 worldwide tier-one and tier-two suppliers. The fact that the total number of actual global input suppliers are not exactly known even to these large public companies illustrates well the complexity and opaqueness of GSCs.

Why is the domestic company supply chain foreign exposure important after all? Summarising the insights from the perspective of a single firm, the equilibrium efficiency-robustness allocation may be inefficient socially in the presence of externalities and market failures. Typically, the efficiency-robustness allocation of private sector firms is skewed toward efficiency more than it would be socially optimal, and private misjudgements as to how uncertain a GSC actually are, may lead to a misperception of the actual vulnerability. An even more important argument for a policy intervention 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 energy supply stop to EU Member States in 2022.

2.2 Macro Perspective: Foreign Exposure at the Aggregate Level

In our second - the value-added (macro) approach - the unit of analysis is a country or an industry. 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 to shed light on value-added trade flows across countries and the implied degree to which production processes have become globalised. We will draw 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 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. As in the firm-level analysis, it is useful to think about the domestic industries' exposure to GSCs by attempting to answer the same key question - where are things made? As noted above, the domestic industry's foreign dependence can be viewed from different sides. For example, this core question can be answered by evaluating the input-side foreign exposure or the output-side foreign exposure. The magnitude of foreign exposure can also be measured by the total foreign exposure of domestic producers yielding a more complete empirical portrait of GSC exposure.

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 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).[6] For example, the 11.8 in the row for Canada (CAN) and 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 highlighted primarily in shaded. 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 between the USA manufacturing production's reliance on Chinese inputs, 9.9%, and China's manufacturing production's reliance on US inputs, 3.7%.

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.

(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

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 FMR (more foreign market-dependent). Overall, the G7 economies' foreign market exposure with respect to China is high (higher than the bilateral

[6] 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.

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 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 exposure. However, the collection of these data takes time, which typically lasts several years and hence implies delays in a potential response to shocks. In the case of the firm-level evidence, the necessary data are collected via numerous sequential surveys following the entire recursive upstream and downstream sequence of all the input providers for all inputs. In the case of the 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 arising GSC 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 of the blockchain – and the management of the stored data performed by the various participants – can be controlled depending on how the blockchain is configured (Ciaian et al. 2021). There are several types of distributed ledgers that could potentially offer safe real-time solutions for recording, tracking and securing of sensitive data. Public blockchains allow anyone to access them; private blockchains are only open to selected users; 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.[7] It was initiated as an open-source distributed ledger by the Linux Foundation in 2016. The

[7] www.hyperledger.org/

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 reliance via GSCs. In this section, we look forward - what can firms and policy undertake to achieve a robust/resilient supply chain? Model-based simulations will help us answer this question. In particular, we aim to understand the potential consequences of extreme events - like natural disasters, pandemics, military and hybrid aggression - on GSCs and the involved domestic industry resilience and robustness under alternative strategies. We undertake GSC stress tests by simulating counterfactual shock scenarios. According to our modelling framework explained next, the optimal firm efficiency-robustness strategy depends on the institutional framework (policy constraints) and the nature of expected shocks (frequency, idiosyncrasy, distribution).

3.1 Modelling Framework and Policy Constraints

In order to study the challenge of "not trading long-term security needs for short-term economic interests" in a formal model, we frame it as a constrained optimisation with two constraints: a robustness/resilience constraint and a resource mobilisation constraint. We aim to formally address the trade-off 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 resource mobilisation constraint implies that governments do not ask the impossible of domestic economies and society. 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 should be taken into account.

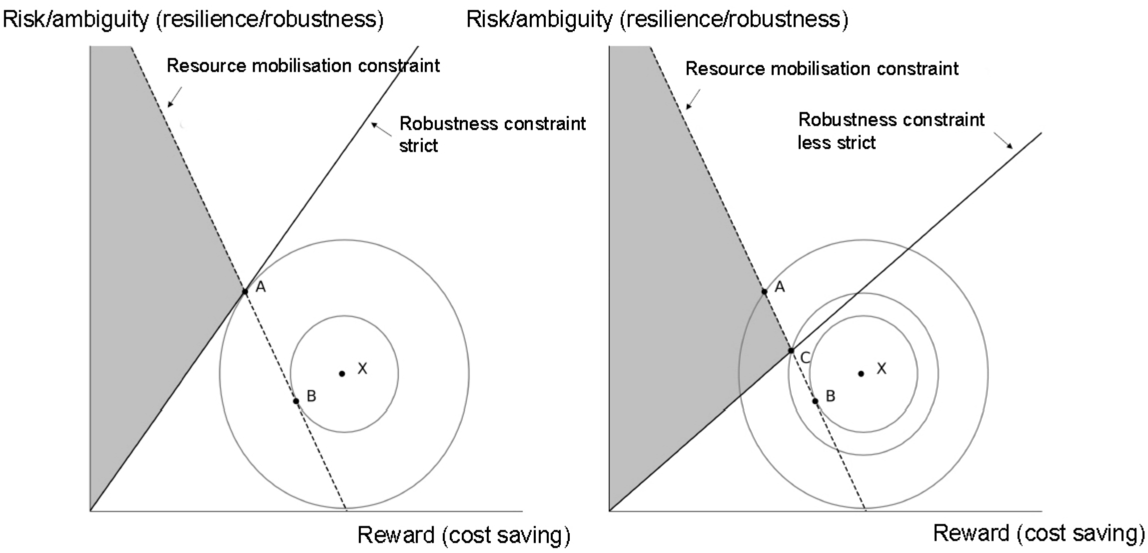

Figure 4: Welfare maximisation and constrained policy optimisation. Source: Based on Antras and de Gortari (2020) and Jiang et al. (2022).

Figure 4 shows the key intuition of the constrained optimisation problem in a static setup graphically.[8] The aggregate welfare is represented by indifference curves (circles), with each circle representing a 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 2); 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 4. 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 4 also illustrates a scenario with less stringent 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).

3.2 Shocks and Simulation Scenarios

Our benchmark is a decentralised supply chain (in absence of 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: a no-shock Baseline (S0) and two scenarios with exogenous shocks to GSCs. Scenario (S1) 'Demanding circumstances' corresponds to the standard approach in the GSC literature. In S1, the expected GSC shocks are frequent, idiosyncratic (shocks to the firm) with a priori known distribution. In scenario (S2) 'Most demanding circumstances', we study an environment in which the expected GSC shocks are infrequent, aggregate with an unknown distribution. Particularly, the S2 scenario will 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.

Table 2: Simulation scenario construction, key assumptions.

Scenario / Shock characteristic	Baseline, no shocks (S0)	Demanding circumstances (S1)	Most demanding circumstances (S2)
- Frequency	--	frequent	infrequent
- Idiosyncrasy	--	idiosyncratic (shock to a firm)	aggregate (systemic shock)
- Distribution	--	known distribution, shock distribution is given	unknown distribution, distribution's support is known
Example of shock	--	exchange rate volatility	Covid-19, Russia's war

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).

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

Given that the nature of the shock will differ across scenarios, shock-related variables will differ between the simulated scenarios and will provide the main source of heterogeneity in the optimal firm responses between scenarios. In all counterfactual scenarios, we assume that the simulated shock is extreme - all suppliers in the affected location perish. The key modelling assumptions in the counterfactual scenario construction are summarised in Table 2.

3.3 Simulation Results

The simulation results are summarised in Figure 5. A key distinguishing feature in the optimal firm strategy under different shock scenarios is the absence/presence of uncertainty in firm optimisation. The optimal firm strategy in the no-uncertainty-baseline (B0) 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 GSC shocks 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 5). Under the 'Most demanding circumstances' scenario (S2), the optimal firm strategy implies resilience through 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 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 is rather different under the S1 scenario, which depending on model parameters implies that only around half the time the firm has an excess capacity (top right panel in Figure 5). The GSC-related costs are higher than under S0, but lower than under S2. The shaded areas in Figure 5 provide confidence intervals at 90%, 95% and 99% levels.

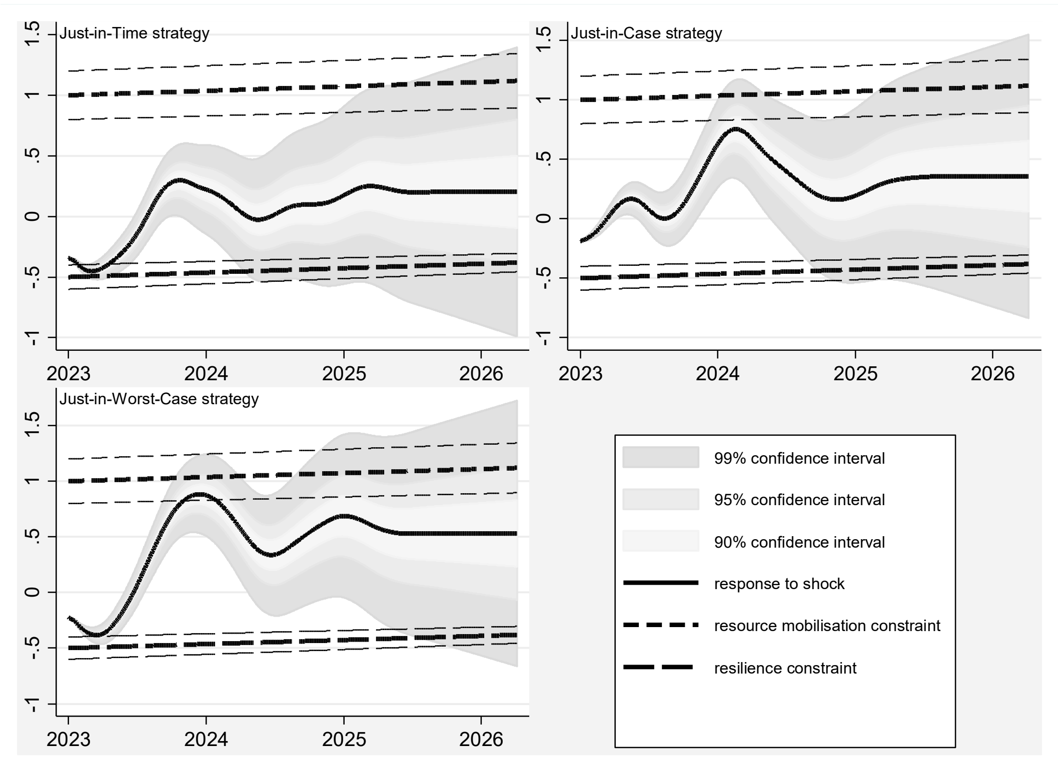

Figure 5: Simulation results: optimal efficiency-robustness strategy under three shock scenarios with resilience constraint and resource mobilisation constraint. Notes: Y-axis measures percentage deviations in GSC; X-axis refers to response periods in time.

The optimal firm response strategy illustrated in the top right panel in Figure 5 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 5 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 are summarised in Table 3. 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 very 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.

Table 3: Summary of differences in the optimal firm strategy under the simulated scenarios.

Scenario Firm response	Baseline (S0)	Demanding circumstances (S1)	Most demanding circumstances (S2)
optimal firm strategy	‘Just-in-Time’	‘Just-in-Case’	‘Just-in-Worst-Case’
efficiency-robustness trade-off	maximise efficiency	maximise efficiency under risk	maximise efficiency under ambiguity
robust decision rule	inefficiency aversion: the stock at firm held to a minimum	risk aversion: amount of inventory that maximises profit	ambiguity aversion: maximise payoff in the worst-case scen.
excess capacity/ cost in normal times	zero/ zero	half the time/ medium	all the time/ high

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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