



Enhancing Resilience

Model-based Simulations

d'Artis Kancs, PhD
Science Research Innovation
Implementation Centre, Latvian
National Armed Forces
d'artis.kancs@ec.europa.eu



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.



The rise of Global Supply Chains (GSC)

- Increasing fragmentation of production processes - firms increasingly decide to outsource the production of inputs to a foreign upstream supplier
- In 2020s, most international trade and investment takes place within GSC; 70% of international trade involve exchanges of raw materials, parts and components
- Why? Trade liberalisation, declining transport costs and improving communication technologies allow firms to source their inputs more efficiently; increasing global competition



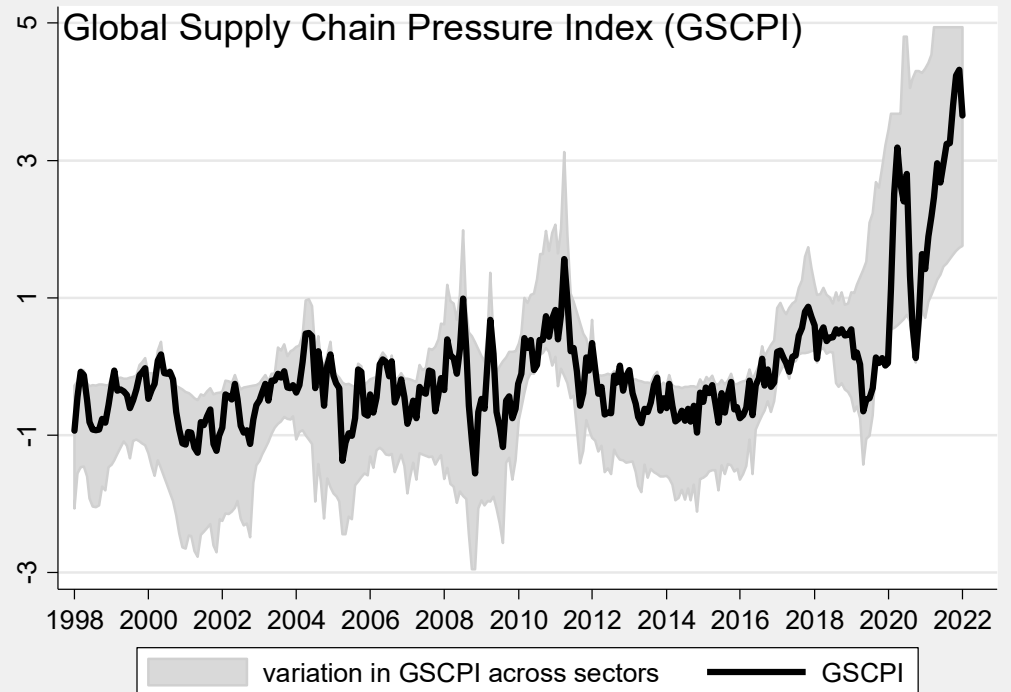
Increasing fragility & vulnerability of GSC

- Because of outsourcing, off-shoring and insufficient investment in resilience and robustness, many supply chains have become highly complex and fragile
- GSC are efficient but brittle – vulnerable to breaking down in the face of a pandemic, a war or a natural disaster
- Escalating GSC-disruption-caused losses and increased frequency of global crisis
 - Vulnerability of critical sectors and essential services?
 - Implications for security and defence?



Global Supply Chain Pressure Index

- GSCPI is one of indices tracking the state of global supply chains
www.newyorkfed.org/research/policy/gscpi



- GSC pressure at historically high levels since 2020
 - High vulnerability of GSCs, e.g. supply or demand ruptures



Accelerating intensity and expanding landscape of hybrid threats

- “Hybrid methods of warfare – such as propaganda, deception, sabotage and other non-military tactics – have long been used to destabilise adversaries. What is new about attacks seen in recent years is their speed, scale and intensity.”

NATO, 2022

- “Building resilience is paramount when it comes to countering hybrid threats. A good understanding of the underlying causes of exploitable vulnerabilities is required. As hybrid threats target multiple sectors of society in complex ways, resilience has to be addressed.”

European Centre of Excellence for Countering Hybrid Threats, 2022



Resilience & robustness to GSC shocks

"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".

Secretary General Stoltenberg, World Economic Forum 2022



How GSC-resilient are our societies and economies?

- Interested in understanding the potential consequences of natural disasters, pandemics, military and hybrid aggression on the GSCs
- Knowing economies' foreign exposure important to identify potential vulnerabilities before major GSC-disruptions occur
- To understand the foreign exposure via the GSC channel, need to know *where are things made?*
- This core question can be answered:
 - at different sides (location of output, inputs);
 - viewing through different lenses (micro, macro)



Viewing through alternative lenses

- The firm-level (micro) perspective
 - The firms are the unit of analysis, they are the ones that decide whether or not to participate in GSCs
 - Firms upstream and downstream face contracting problems – moral hazard or incomplete contracts
 - Integrating vertically/internationally solves the informational problem
- The value-added (macro) approach
 - Countries and industries are the unit of analysis
 - Production is allocated internationally, and each stage of production contributes to the final product
 - International trade statistics and global input-output tables



Firm-level foreign exposure

Answering the where-are-things-manufactured question at the firm level:

- First-level answer - a bird's eye view
 - Look at the production location of firm's outputs
- Second-level answer - more informative
 - Trace the first-level production location of inputs => a directly observable dependence on foreign inputs
- Third-level - the whole truth of company foreign exposure
 - Take account of the entire recursive sequence of all the inputs into all the inputs

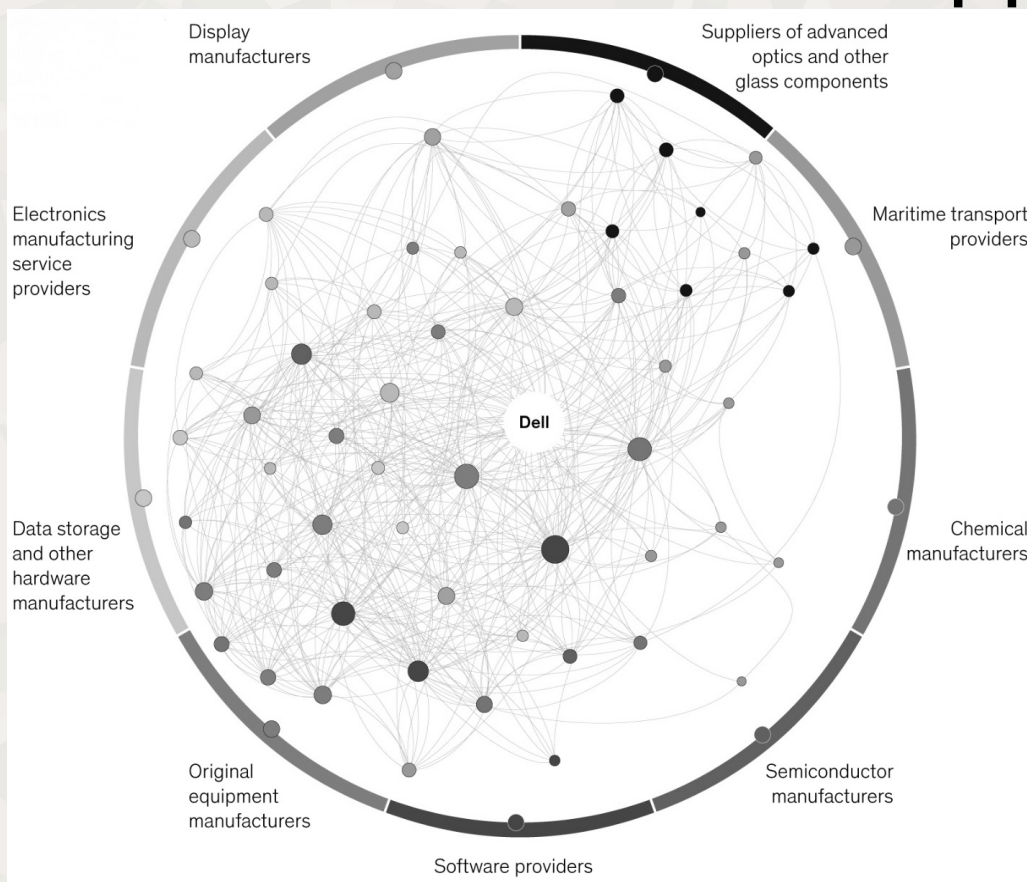


Example: Airbus [Defence and Space]

- A product rolls off the assembly line in Stevenage, UK
 - We can say Airbus was made in Stevenage
 - First-level truth, but it is not the whole truth
- Stevenage plant buys inputs from other sectors located at home and abroad
 - Trace the first-level production location of inputs
 - Airbus has 1,676 publicly disclosed tier-one suppliers
- Entire recursive sequence of all the inputs into all the inputs
 - Airbus works with >12,000 tier-two suppliers & below worldwide
 - Third-level answer yields the whole truth of foreign input reliance



Example: Dell [Military and Defence] ≈5,000 world-wide tier-two suppliers



www.dell.com/en-us/dt/oem/military.htm
www.dell.com/en-ca/dt/oem/defence.htm
Bloomberg Global Supply Chain Data

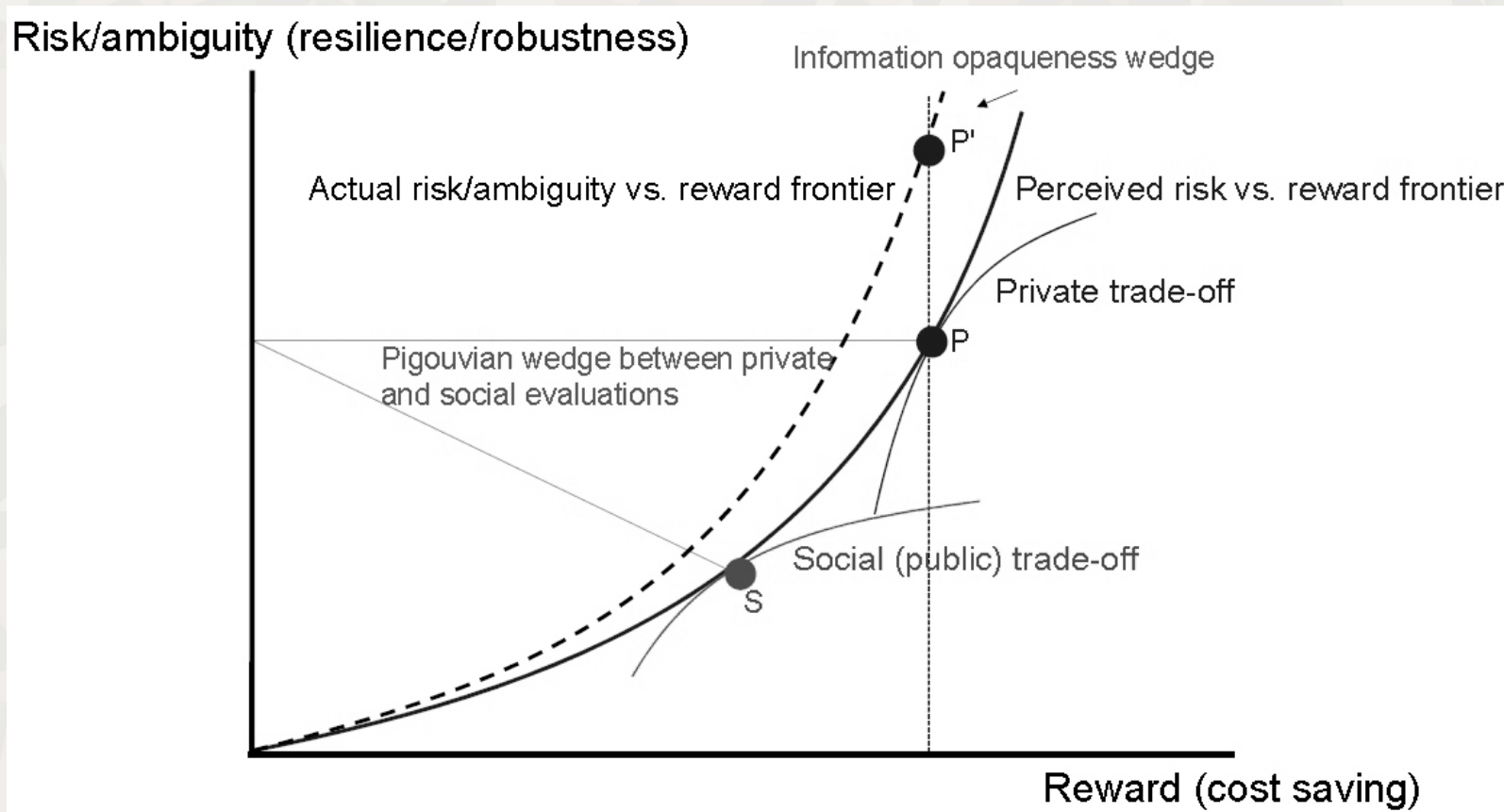


Why domestic company foreign supply chain exposure is important for policy?

- Externalities: wedge between private & social evaluations
 - Cost versus resiliency/robustness trade-off for firms
 - Private companies prefer more risk for any given level of reward
 - Social evaluation of the risk-reward trade-off will put a greater stress on the risk than private evaluation
- Market imperfections: GSC complexity, intransparency
 - Companies do not know all the suppliers of their suppliers, GSC participants know rarely the whole truth of their foreign exposure
 - Private misjudgements as to how fragile GSCs actually are may lead to a misperception of actual vulnerability
- Increasing (mis)use of foreign supply dependence as hybrid threats by adversaries



Firms' efficiency-robustness trade-off, externalities and market failures





Accelerating evidence-base for 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
- However, the collection of these data takes time, which typically lasts several years
 - Delays in a potential response to shocks
- New technologies & big data offer new opportunities to monitor and trace arising GSC bottlenecks in real time
 - Blockchains allow to safely record and manage real-time data
 - Hyperledger is one such private blockchain – already used by many enterprises and medium-sized companies within the Alliance



Viewing through alternative lenses

- The firm-level (micro) perspective
 - The firms are the unit of analysis, and they are the ones that decide whether or not to participate in GSC
 - Firms upstream and downstream face contracting problems – moral hazard or incomplete contracts
 - Integrating vertically/internationally solves the informational problem
- The value-added (macro) approach
 - Countries and industries are the unit of analysis
 - Production is allocated internationally, and each stage of production contributes to the final product
 - International trade statistics and global input-output tables



Industry-level foreign exposure

Domestic industry foreign dependence viewed from different sides

- Sourcing-side foreign exposure
 - Foreign Input Reliance (FIR) measures the input-side exposure
 - Foreign sources used as intermediate inputs into production
- Selling-side foreign exposure
 - Foreign Market Reliance (FMR) measures sector's/country's reliance on foreign markets on the sales side
 - FMR relies upon a cost-accounting identity for production
- Total foreign exposure
 - Total Foreign Reliance' (TFR): input side + sales side
 - Allows to compute an infinite sequence of all inputs and sales



Foreign Input Reliance (FIR, %)

- FIR measures the share of foreign sources used as intermediate inputs into domestic production
- Row nations' reliance on inputs from column nation for manufacturing production, 2019
- Colours indexed to share sizes; darker greens indicate higher FIR

| (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 |

Data from Inter-Country Input-Output (ICIO) Tables <http://oe.cd/icio>



Change in Foreign Input Reliance (ppt)

- Row nations' reliance on inputs from column nation for manufacturing production, 2019 vs. 2000
- Red-shaded cells indicate FIR decreases; green-shaded cells indicate FIR increases

| (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 |

Data from Inter-Country Input-Output (ICIO) Tables <http://oe.cd/icio>



Foreign Market Reliance (FMR, %)

- FMR measures the share of foreign markets on the sales side
- Row nations' total input sales to column nations' manufacturing industries, 2019
- Colours indexed to share sizes; darker greens indicate higher FMR

| (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 |

Data from Inter-Country Input-Output (ICIO) Tables <http://oe.cd/icio>



Change in Foreign Market Reliance (ppt)

- Row nations' total input sales to column nations' manufacturing industries, 2019 vs. 2000
- Red-shaded cells indicate FMR decreases; green-shaded cells indicate FMR increases

| (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 |

Data from Inter-Country Input-Output (ICIO) Tables <http://oe.cd/icio>



GSC stress-test: model-based simulations

- The firm-level optimal resilience strategy depends on:
 - Nature of shock (frequency, idiosyncrasy, distribution)
 - Institutional framework
- The country/industry optimal resilience strategy depends on:
 - Political priorities - *"we should not trade long-term security needs for short-term economic interests"* Secretary General Jens Stoltenberg, World Economic Forum 2022
 - Political feasibility constraints (robustness/resilience constraint and society's tolerability constraint)



GSC stress-test: firm-level simulations

- Study the optimal firm efficiency-robustness behaviour under extreme events (scenarios)
- Explore this question with a conceptual model simulating relevant shock scenarios
 - Assume the simulated shock is extreme - all suppliers in the affected location perish
 - Nature of the shock differs across scenarios
- Firms solve the efficiency-robustness trade-off
 - In the pursuit of efficiency, a decentralised supply chain could become vulnerable to aggregate shocks



GSC stress-test: firm-level simulations

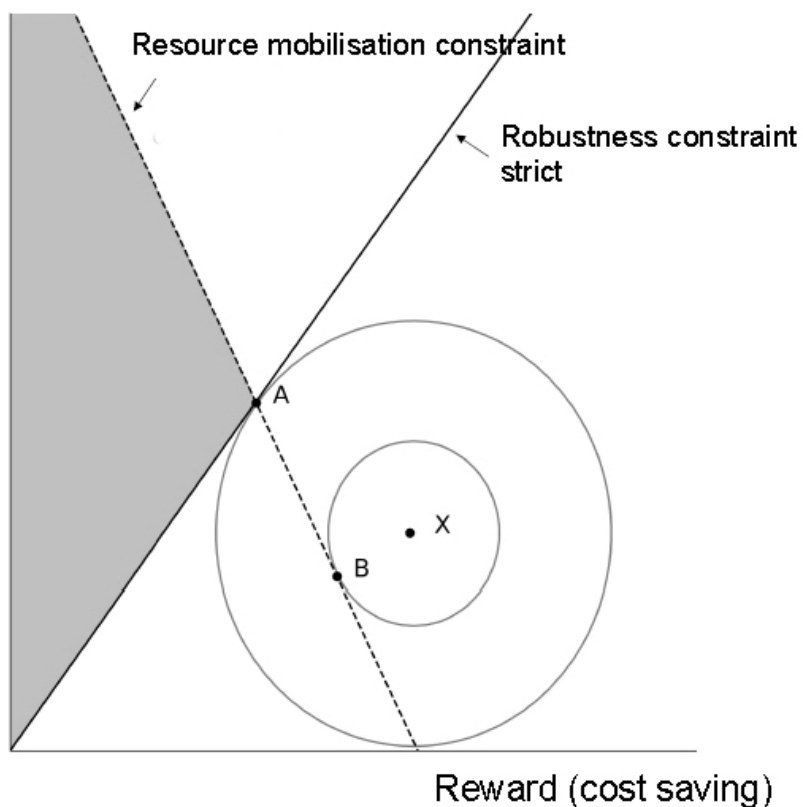
Simulation scenario construction, key assumptions

| Scenario | Baseline, no shocks (S0) | Demanding circumstances (S1) | Most demanding circumstances (S2) |
|----------------------|-----------------------------|---|---|
| Shock characteristic | | | |
| - 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 |

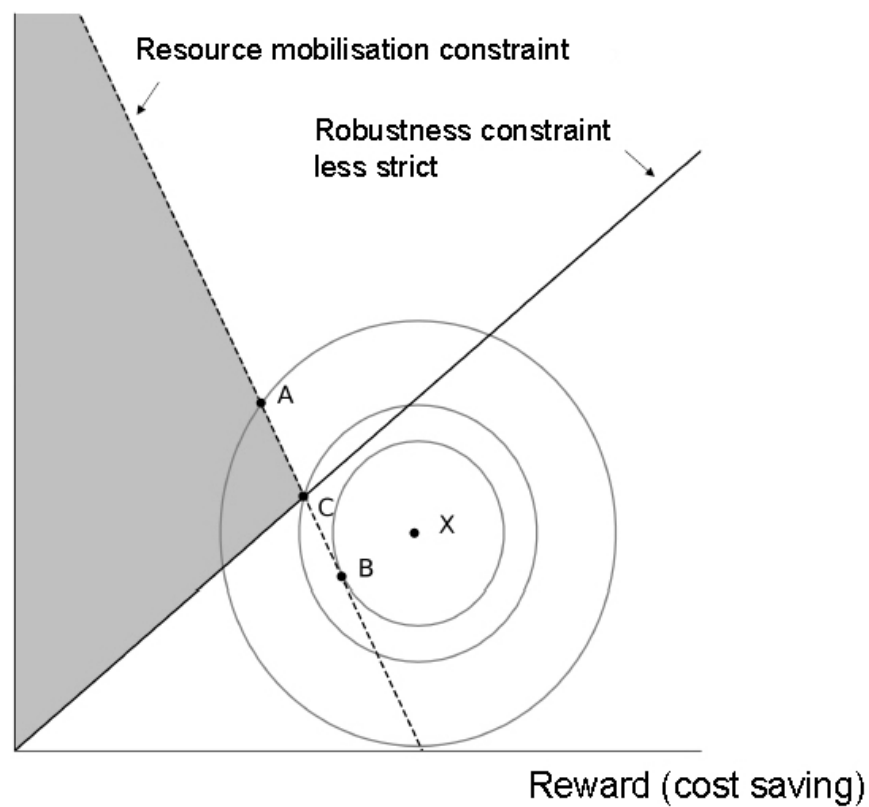


Welfare maximisation and constrained policy optimisation

Risk/ambiguity (resilience/robustness)



Risk/ambiguity (resilience/robustness)





GSC stress-test: firm-level simulations

Model-based counterfactual simulations, main results

| | Scenario | Demanding | Most demanding |
|--|--|--|---|
| | Baseline (S0) | circumstances (S1) | circumstances (S2) |
| Firm response | | | |
| 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 |
| excess capacity/ cost in normal times | zero/ zero | half the time/ medium | all the time/ high |



GSC stress-test: model-based simulations

- The firm-level optimal resilience strategy depends on:
 - Nature of shock (frequency, idiosyncrasy, distribution)
 - Institutional framework
- The country/industry optimal resilience strategy depends on:
 - Political priorities - "*we should not trade long-term security needs for short-term economic interests*" Secretary General Stoltenberg, World Economic Forum 2022
 - Political feasibility constraints (robustness/resilience constraint and society's tolerability constraint)



GSC stress-test: macro-level simulations

- Resilience baseline requirements determine critical sectors and essential services which must be maintained under the most demanding circumstances
 - energy supplies
 - food and water
 - communication networks
 - transport systems
- The challenge of “*not trading long-term security needs for short-term economic interests*” is framed as a constrained optimisation with two constraints:
 - robustness/resilience constraint
 - tolerability constraint



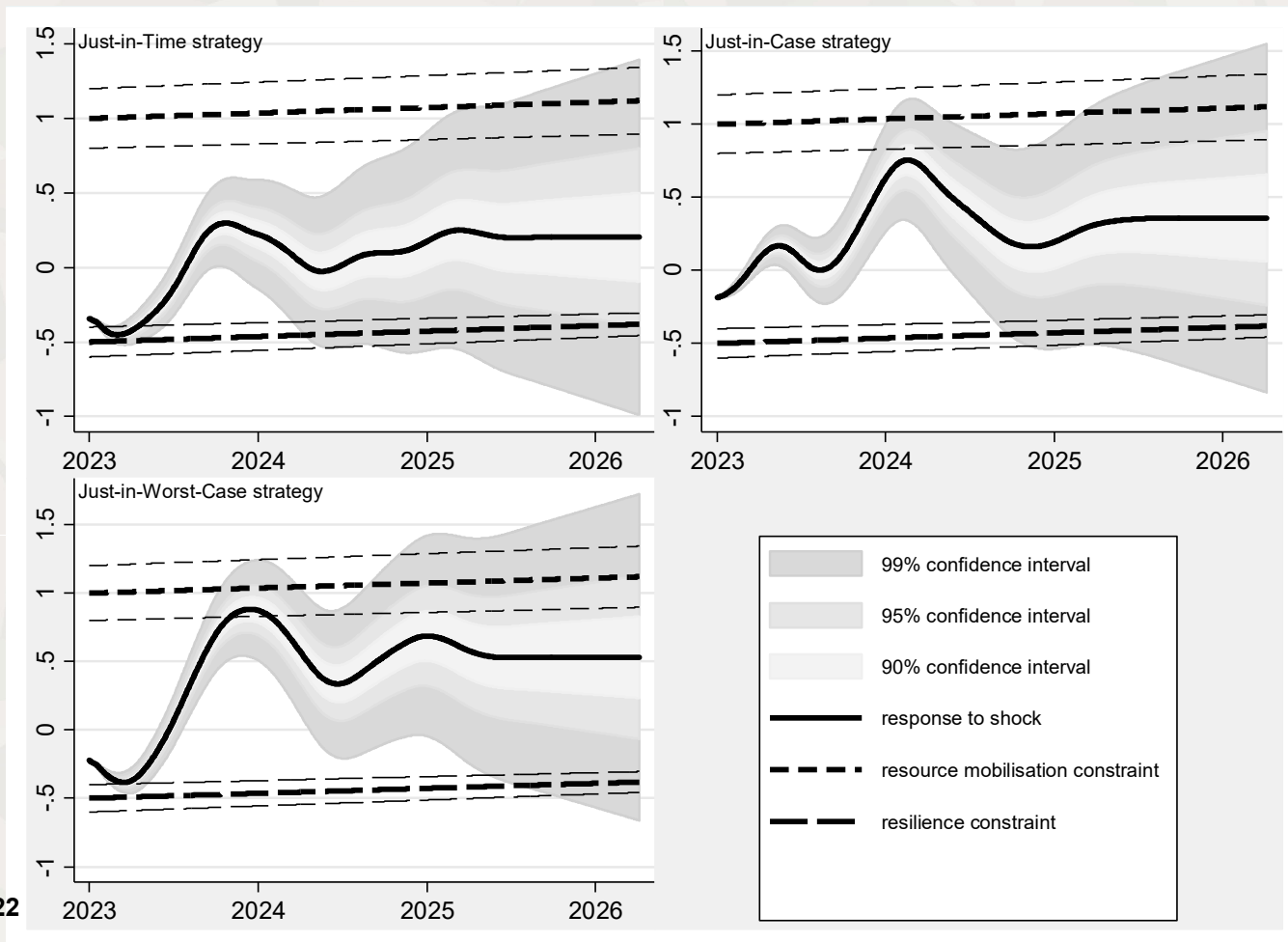
GSC stress-test: macro-level simulations

Goal: achieve the baseline resilience while doing as little damage as possible to the society's socio-politico-economic fabric

- Robustness constraint: ensuring the baseline resilience requirements on foreign input sourcing and output sales
- Resource mobilisation constraint: not asking the impossible of domestic producers - they will agree to temporarily forgo possible gains or accept losses, especially when it is in the name of a good cause, but tolerance of forgoing profits is not infinite



Simulation results: optimal strategies





GSC stress-test: macro-level simulations

- A resilient supply chain is one which optimally deals with risk; functions under demanding circumstances
 - Consider for non-critical sectors
- A robust supply chain is one which optimally deals with ambiguity; functions under the most demanding circumstances
 - Consider for 'critical sectors'
- A distinction between 'critical sectors' and 'non-critical sectors' is important to manage load to domestic producers and possible adverse effects on the tolerability constraint



Conclusions

- Increasing fragility and vulnerability of GSCs
 - Complexity, intransparency and foreign dependency
 - Intensity of hybrid threats accelerating and landscape expanding
- The robustness/resilience of GSCs depends on:
 - Type of shocks (frequency, idiosyncrasy, distribution)
 - Flexibility to substitute on the sourcing and selling sides
 - Market frictions
 - Redundancy with excess capacity
- Pro-active policy can counteract the depreciating vulnerability
 - Ensure demanding circumstance-resilient in non-critical sectors
 - Ensure most demanding circumstances-robustness in critical sectors



Lessons for defence and security policy

- One policy approach is to provide information and/or subsidies to increase voluntary investments in resilience
 - Minimum information on suppliers (and the suppliers of suppliers), including possibly assessment of inventories for critical inputs
 - Align private incentives by providing a subsidy: e.g. in 2020, Japan set up a fund to compensate firms that diversify out of China
- A more controversial but increasingly common policy alternative is to mandate investments in GSC-resilience
 - Mandatory standards ensure a wider adoption of robust sourcing
 - Investments to mitigate GSC risks and ambiguity in presence of hybrid threats



Lessons for decision-support models

- Scenario simulations and GSC stress-tests can reveal and assess the potential impacts before the events occur
- Ex-ante vulnerability assessment of the relevant shocks (frequency, idiosyncrasy, distribution) is key to the success of timely responses to enhance the GSC resilience
- Model-based simulations can provide density forecasts that communicate the known unknowns but also acknowledge the (possibility of) unknown unknowns



Thank you for attention! Questions?

d'Artis Kancs, PhD
Science Research Innovation
Implementation Centre, Latvian
National Armed Forces
d'artis.kancs@ec.europa.eu



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.