ISSN 2529-332X

Supply chain stress tests for critical inputs: a proof-of-concept

SINGLE MARKET ECONOMICS PAPERS

Working Paper 27

BEATRICE DUMONT
XOSÉ-LUÍS VARELA-IRIMIA

EUROPEAN COMMISSION

Directorate-General for Internal Market, Industry, Entrepreneurship and SMEs
Directorate A – Strategy & Economic Analysis
Unit A1 – Chief Economist Unit

Contact: GROW-A1@ec.europa.eu

European Commission
B-1049 Brussels

Supply chain stress tests for critical inputs: a proof-of-concept

Single Market Economics Papers

Beatrice Dumont

Xosé-Luís Varela-Irimia

LEGAL NOTICE

EN PDF ISBN 978-92-68-20580-8 ISSN 2529-332X DOI: 10.2873/1355245 ET-01-24-002-EN-N

Manuscript completed in September 2024

1st edition

Luxembourg: Publications Office of the European Union, 2024

Supply Chain Stress Tests for Critical Inputs: A Proof-of-Concept

Pr. Dr. Beatrice DUMONT (Sorbonne Paris University-CNRS & College of Europe & Climate Economics Chair & Visiting Research Fellow at DG GROW in 2022/23)

Dr. Xosé-Luís VARELA-IRIMIA (Chief Economist Team, DG GROW)[1]

We acknowledge support from DG GROW. This economic paper was prepared under the economic advisory programme of DG GROW of the European Commission.

Abstract:

This article aims to develop a 'proof of concept' for testing the resilience of sectoral supply chain networks at firm level against an exogenous shock to critical inputs. The rationale for implementing supply chain resilience testing at the sector level is that outsourcing may be individually rational at the company level, but collectively suboptimal in terms of risk management at the supply chain level. The analysis focuses on the wind power sector in Europe using data from the FactSet Supply Chain Relationships database. The methodology is based on the construction of a matrix of resilience coefficients linking upstream and downstream firms, and affecting the diffusion of shocks. We implement Monte Carlo simulations and examine how idiosyncratic shocks propagate from firms to firms. Our findings show that supply chain stress tests can help identifying relatively weaker firms or more exposed sectors/countries and that the lack of critical inputs (downstream shock) can translate onto an upstream shock for suppliers of complementary inputs. At a more detailed level, our results show that the specificities of each firm network of suppliers-customers are a strong determinant of their resilience.

---

[1] The opinions expressed in this paper do not necessarily reflect the views of the European Commission.

1. Introduction

The fragmentation of supply chains across countries is deemed to have brought cost-efficiency gains and facilitated technology diffusion[2]. However, this modular production structure[3] is now being called into question, as it has proved, since the Covid 19 pandemic, to have a low resilience to shocks[4], and possibly important negative spillover effects (Costinot & al., 2013)[5]. In fact, we have witnessed since the pandemic a series of exogenous shocks that have led to significant volatility in commodity markets (IMF, 2023), and massive supply chain disruptions (Bonneau & Nakaa, 2020). These shocks have revealed vulnerabilities in terms of sources of supply and have highlighted that security of supply is also a question of economic security. As stressed by OECD Secretary General Angel Gurria (2021) "(...) in today's interconnected world, shock events can quickly cascade across borders and economic sectors, and have devastating effects on people' lives, jobs, and opportunities, and on their trust in governments, institutions, and markets" [6].

Under these circumstances, the question arises whether policymakers should intervene. Indeed, the structure of global value chains is the outcome of decisions made by private firms based on both productivity and risk. It would thus be logical to consider that, after all, it is the responsibility of firms to ensure the resiliency of their supply chains, and that there is no need to implement due diligence laws. However, due to the existence of market failures/externalities, and the increase in the number of cases of economic coercions in international trade, policy intervention may be necessary, in particular to monitor some supply chains deemed critical.

First, outsourcing can be individually rational at the firm-level but collectively sub-optimal in terms of risk management at the supply-chain level. It may be due to a divergence in public/private risk preferences, and more precisely a potential difference of incentives to diversify/hedge against shocks between companies and governments. Risk externalities can thus justify public intervention, especially in a context of a supply-chain network where the decision of each node neglects, or is unable to account for, the impact on the other nodes.

---

[2] See Amiti & Konings (2007); Grossman & Rossi-Hansberg (2008); Halpern & al. (2015); World Bank (2019).
[3] As opposed to a sequential production chain.
[4] Meier & Pinto (2020) show that US sectors with a large exposure to intermediates imports from China, contracted significantly more than other sectors and that they suffered from larger declines in production, employment, imports, and exports.
[5] Costinot et al. (2013) show that the microstructure of the value chain matters as it delivers distinct predictions about the impact of spillovers within value chains.
[6] Available at fostering economic resilience in a world of open and integrated markets: risks, vulnerabilities and areas for policy action (oecd.org)

Second, individual firms do not internalize the full risks of their actions. Not because they do not want it, but because companies are likely to face opacity about the identities of the firms involved in their supply chain beyond tier one. A consequence of this limited visibility is that firms cannot fully identify the risks of potential disruptions. To counterbalance this information asymmetry, some large companies have recently adopted contingency plans and implemented their own stress tests.[7] However, gathering information about supply chains involves trade-offs between collecting costs and data quality, and often concerns tier-one suppliers only[8]. Moreover, such information is often considered as strategic, and therefore a trade secret[9]. As a result, misjudgements on how risky a supply chain is, can lead to a coordination failure. This policy problem has been conceptualized by Baldwin & Freeman (2022) as a standard risk-reward trade-off[10]. Both firms and society would prefer less risk for any given level of reward, but the public cares relatively more about risk. In such a context, policy intervention could be justified if there is a Pigouvian wedge between private and social evaluations.

Third, trade restrictions, especially those concerning critical raw materials have multiplied by five since 2009, and 10% of the value of their global exports faced at least one export restriction measure[11], affecting their availability (IMF, 2023; OECD, 2023). As these export controls are not targeted at a specific country, but are instead country-agnostic, they could potentially impact any EU's manufacturers. These export restrictions should be a clarion call that over-dependence on China (or any other country) in any part of a value chain puts an economy at risk[12]. In this context, many countries are increasingly looking to "de-risk"—from their dependencies vis-à-vis China to meet their supply needs[13]. But contrary to its major

---

[7] The telecoms group *BT* for instance has recently conducted stress tests on its supply chain to prepare for the disruption from a potential conflict between China and Taiwan. *See Financial Times* of April 16, 2023, *BT hold China Taiwan war games to stress test supply chains*. Available at https://www.ft.com/content/bb1f4951-eef5-4b3d-990a-f29d6fa28d54

[8] According to a study by the McKinsey Global Institute (2020, p. 44), beyond the first tier, which is easily identifiable, companies rely on a network of thousands of suppliers. This means that companies face opacity above the first tier and cannot fully identify the risks of potential disruptions. Available at Risk-resilience-and-rebalancing-in-global-value-chains-full-report-vH.pdf (mckinsey.com)

[9] According to Marshall et alii, (2016) "External pressure [to disclose supply chain information] has come from government regulations, best practices of peers, and changing expectations from salient stakeholder groups such as NGOs". (…)". Recent examples of new regulatory pressure in the United States include the 2010 Dodd-Frank Wall Street Reform and Consumer Protection Act and the California Transparency in Supply Chains Act 2010.

[10] This concept derives from portfolio theory (*see* Campbell et al., 2005).

[11] According to the OECD (2023, p.38), it even exceeded 30% for some critical minerals. Trade restrictions have been mainly imposed by China, Vietnam, Argentina, Russia, Kazakhstan, and Indonesia. In practice, these restrictions do not prevent exports altogether, but they require exporters to seek a license to ship these critical minerals. This means identifying importers and end users, and stipulating how these metals will be used. These restrictions cause delays, increase administrative costs, and the risk of rejection. It is also unclear how many licenses are issued.

[12] According to the newspaper *Le Monde* (July 1, 2024) in 1992, Deng Xiaoping (the leader of the People's Republic of China) gave a speech that will go down in history: "The Middle East has oil, China has rare earths. Like oil for the Middle East, rare earths are of the utmost strategic importance for China. We must take advantage of this". It is worth noting that since then, his successors have been inspired to cultivate this advantage.

[13] Since the rare earth export controls were enacted, Japan has shifted nearly 30% of its rare earths import mix from China to other countries, like Mongolia, Australia, and Vietnam, and invested in Australian producer *Lynas*, the world biggest producer of rare earth metals outside China. The United States also took steps to diversify, decreasing China's share of its rare earth imports from about 100% in 2010 to 80% in 2020. However, such a move takes time to unfold given the costs involved in modifying supply

trading partners, the European Union (EU) did not take major steps to diversify and is still relying on China for 98% of its rare earths in 2022 (IEA, 2023)[14]. The fear is that economic coercion through restrictions or boycotts on specific exports, like critical raw materials, could jeopardize the efforts of the EU to reach carbon neutrality and have adverse effects on growth. More generally, trade barriers linked to critical materials could split up nations into rival blocs and lead to a fragmentation of global trade (IMF, 2023)[15].

In such a context, policymakers have rediscovered the critical importance of having resilient supply chains and have brought the issues of open strategic autonomy and technological sovereignty to the fore[16]. This explains the increased temptation for policymakers to implement de-risking policies to enhance the resilience of supply chains. In practice, this translates into calls to adopt a “near-shoring”[17] or “friend-shoring” agenda[18]. However, the efficiency of such de-risking policies is not proven. Studies show, for instance, that reshoring increases aggregate volatility by reducing source diversification (D’Aguanno, 2021). By contrast, depending on the setting, policies that encourage diversification of foreign suppliers tend to lower volatility by reducing exposure to individual economies (Casselli, 2020, Baldwin & Freeman, 2021)[19]. Considering the European Union’s policy quadrilemma to simultaneously uphold economic security, foster sustainability, maintain the competitiveness and a relative autonomy[20] of its industry, it is important to make sure that de-risking policies will not forego the benefits from trade specialisation and openness. In practice, this implies that de-risking policies should only be implementing to some specific supply chains deemed critical for the EU, namely when the incentives private actors are facing are sufficiently misaligned with the public interest to justify intervention. We should indeed not replace the risks related to supply chains by new policy hazards.

---

chains. Moreover, China’s manufacturers have a competitive cost advantage that may keep international competitors out of the market until prices rise sufficiently.

[14] In April 2023, the European Union proposed a Critical Raw Material Act to make the EU more self-sufficient in the production of critical materials. The aim is to locate 10% of critical metal requirements and 40% of the processing industry within the EU. The project also includes an ambitious recycling target (to increase the share of recycled metals in supply to 15%) and a target for diversification of supply sources (to prevent any single country from holding more than 65% of the European market) by 2030. Available at European Critical Raw Materials Act (europa.eu)

[15] Depending on the scenario, the cost of this fragmentation could range from 0.2% to up 7% of global GDP (IMF, 2023).

[16] See EU Economic Security Strategy Joint Communication (June 2023c). This strategy proposes to carry out a thorough assessment of risks to economic security in four areas. One of them encompass risks to the resilience of supply chains, including energy security. Available at An EU approach to enhance economic security (europa.eu)

[17] i.e., a relocation of some production geographically closer to the final production sites or country of sales.

[18] i.e., moving supply chains to jurisdictions that do not pose serious geopolitical risks. An ECB survey (2023a) of leading firms operating in the euro area shows that 42% of firms based in the EU plan to relocate their sourcing to “friendly” countries within the next 5 years in response to supply chain risks. This compares with only 11% in the 5 previous years. China is the country the most frequently mentioned in terms of perceived risks, either to the company’s own supply chain or that of its sector.

[19] This depends however on the variance/covariance of shocks across trade partners.

[20] Industrial autonomy can only be partial. It depends notably on the availability (and access to) of natural resources, but also of the existence of technological competences and skilled employees in the EU.

For policymakers to make informed decisions and devise the most appropriate de-risking policies, it is thus important to develop new tools to assess risks to and from supply chain. In this respect, the idea to implement supply chain stress tests for critical inputs is gaining attention among policymakers. There are indeed similarities with the rationale for stress test in the banking sector where problems to a single bank may translate into aggregate shocks. Moreover, stress tests have proven in practice to be an important monitoring tool in the banking sector. They could potentially be adapted to supply chains to analyse risk factors and identify potential points of failures and/or choke points for inputs that are deemed critical.

This article aims at developing a ‘proof-of-concept’ of such a tool in the form of a stress test of supply chains for critical inputs, with a special emphasis on the role of the network formed by firms. To do so, we use detailed data on firms direct and indirect suppliers and customers to reconstruct a value chain. As supply chains differ considerably by industry, product characteristics, company’s strategies, distribution channels and so on, and given the proof-of-concept nature of this paper, we focus on a single sector, that of the wind energy sector[21], as it is supposed to form the backbone of EU energy security in the short term and carbon neutrality by 2050. From an empirical point of view, we opt for a single scenario, namely an export ban from China on processed critical raw materials. With China having a massive hold on the worldwide supply chain of critical raw materials[22], an export ban could potentially disrupt supply chains in several sectors, raise costs, and affect production, especially that of green technologies[23]. Such a scenario is an adverse but plausible one. It allows us to analyze the resilience (or not) of firms in the wind energy sector to withstand such a shock and is justified by the fact that in recent years, export controls (trade) restrictions[24], notably by China[25], have triggered a cycle of *tit-for-tat* retaliations, and have moved to the forefront of

---

[21] The EU faces foreign dependencies in the wind energy sector. *See* European Commission (2021 & 2023a, p.6) “(…) China dominates global supply chains, from mining and refinement to production, which are critical for the production of e-vehicles and wind turbines”.

[22] According to the last report of the IEA (2023) and that of the European Commission (2023), the critical metals refining and processing industry is largely located in China, and more generally concentrated in a small number of countries. China, for instance, produces 90 percent of the word’s gallium and 60 percent of germanium. Likewise, it is the world’s number one graphite producer and exporter and refines more than 90 percent of global graphite.

[23] According to some experts from the Stimson Center (2023), the effectiveness of the Chinese export bans of 2010 has been undermined by massive smuggling, which is supposed to have accounted for 40% of China’s rare earth exports. We assume here that the ban is strictly respected, and that smuggling is inexistent. See Why China’s Export Controls on Germanium and Gallium May Not Be Effective • Stimson Center

[24] It is noticeable that these measures depart from previous ones in the sense that they are undermining the legitimate objective of export controls — which are only intended to target dual-use items and technologies, i.e., goods that can be used for both military and civilian applications.

[25] In 2010, China enacted a series of export measures on pure rare earth, earth oxides, and rare earth salts to Japan, the United States, and the European Union. Those export controls took the form of a 40% lower quota (compared to 2009) for the export of rare earths. In addition, in 2011 China imposed a tariff of 15–20% on the export of rare earths and further reduced the quotas by 32.5%. Both in 2010 and 2011, China also raised export tax rates on some rare earth metals, rare earth oxides, rare earth fluorides and rare earth carbonates. In 2012, as a reaction, Japan, the EU, and the U.S. filed a suit against China at the World Trade Organization (WTO) against these export restrictions. China lost the suit, and the WTO led countermeasures that eased prices and increased China’s export of rare earths. However, China adopted in return more stringent export licensing measures at the end of 2014. Most recent export restrictions, announced in July 2023 by China’s Ministry of Commerce, include eight gallium and six germanium products, two minerals essential for respectively the manufacture of photovoltaic cells and optical fibers but also bans on graphite commonly used in semi-conductors, electric vehicles, aerospace, chemical and steel industries.

trade policy. From a methodological point of view, we compare vulnerabilities at the level of firms, sectors and countries. We also compare these results across a range of hypotheses on sectoral coverage of relevant suppliers/customers, the degree of substitutability within and across sectors and the heterogeneity of resilience parameters drawn from probability density functions using Monte Carlo simulations. Our findings show that supply chain stress tests can help identifying relatively weaker firms or more exposed sectors/countries and that the lack of critical inputs (downstream shock) can translate onto an upstream shock for suppliers of complementary inputs. At a more detailed level, our results show that the specificities of each firm network of suppliers-customers are a strong determinant of their resilience. From a policy perspective, this means that microstructures of industrial eco-systems on the overall production network matter and that it is therefore important to promote awareness of the importance of the upper (lower) tiers to develop more effective shields against shock propagation.

This article contributes to the literature in two ways.

First, it relates to a growing body of work that challenges the view of Lucas (1977) that micro-economic shocks would average out and thus would have negligeable aggregate effects. More precisely, these papers posit that micro shocks are transmitted in the economy through industry linkages (Long & Plosser, 1997; Carvalho, 2010; Acemoglu et al., 2012 & 2016; Carvalho & Gabaix, 2013). Acemoglu et al. (2016) show, for instance, that depending on the setting, an industry-level shock could spread through a network of interconnections and play a sizeable role in macro-economic fluctuations, compared to what is typically presumed in macroeconomics[26]. Despite these findings, spillovers within networks of firms have received little attention in the empirical literature, as it is difficult to identify firm-specific shocks. In the same vein, while supplier-customer relationships are formed at the level of firms, most studies so far, are based on models that approximate the nature of these interactions at the industry level. They do not tackle for instance, issues such as firm-specific relationships and the possibility of firm failures (Carvalho & Tahbaz-Salehi, 2019). Our paper tries therefore to fill a gap in the literature by looking at how idiosyncratic shocks propagate from firm to firm in

---

See MOFCOM Regular Press Conference (July 6, 2023) citing national security reasons. These restrictions took effect on December 1, 2023. In the same month, China also banned the export of technologies used in rare earth extraction and separation and in some rare earth magnets over national security. See Key Changes and Updates to Chinese Export Controls in 2023 | Insights | Mayer Brown. New Chinese regulations announced on July 1, 2024, and that will come into force on October, 2024, require the Chinese State Council to set up an information system for the traceability of rare earth products. Under this new regulation, companies involved in the extraction, smelting and separation of rare earths, as well as the export of rare earth-based products, must set up a system to track product flows, record these flows "faithfully" and integrate them into a traceability system. Available at China's New Rare Earth Rules Seek Product Traceability Details (asiafinancial.com)

[26] As stressed by Horvath (1998), the empirical evidence on the importance of sector linkages for the aggregation of sector-specific shocks is mixed and depends on the level of aggregation. As stressed by Baldwin & Freeman (2022), supply chains could also be a source of “shock diversification rather than magnification”.

production networks and gradually be amplified, in the particular sector of wind energy generation.

Second, our paper departs from macro approaches traditionally used to assess the impact of exogenous shocks. Indeed, we use firm-level data to document firms' input sourcing decisions and their location (upstream-downstream) in the supply chain. As stressed by Johnson (2018), one of the advantages of using firm-level data over macro data is that it allows us to model interactions between firms and their partners (both domestic and non-domestic), rather than inferring them by combining industry-level information with trade data. Moreover, another advantage of using granular data on supply chain, compared to aggregated industry level data, is that it captures heterogeneity in supply chains linkages across firms and thus the specific shape of the network. To do so, we use a commercial dataset *FactSet Supply Chain Relationships*, which collects information on supply chain relationships. We depart here from the methodology followed by the OECD (2023ab) that reconstructs production networks from firm-level value-added tax (VAT) transaction data, matching it with business registry data. Our choice to use commercial data, instead of administrative data, relies on the fact that, even if VAT data can shed light on intra-firm transactions and can be used to map firms' linkages and interdependencies within supply chains, it covers just transactions with domestic partners. VAT data does not cover cross-border transactions, which can only be recovered aggregated at the country (destination or origin) by product level, using customs data that do not identify firm-level relationships.[27] When opting for this commercial dataset, we are well aware that it is important to keep in mind the biases induced by the data collection process, which tends to overrepresent larger companies. However, we are comforted in our choice by the findings of a recent paper from Bacilieri et al. (2023) who have compared some standard production network properties across several available (administrative vs. commercial) datasets[28].

---

[27] Another drawback of using VAT data is that, in general, it does not report all sales and purchases of firms, due to reporting thresholds below which transactions are not reported. As a result, some edges can be lost, especially those where the typical transaction amount is low, but firms trade often enough to reach the threshold in the given reporting period. Moreover, some transactions reported by a customer and a supplier can display a different reported value or a negative value. This is not an anomaly in itself, as it corresponds to reimbursements or invoice modifications, but it complicates the network analysis. Last, VAT data exists in all OECD countries, except for the USA.

[28] Bacilieri et al. (2023) provide benchmark results from two administrative datasets (Ecuador and Hungary) and compare their network properties to those obtained with the commercial dataset *FactSet(c)*. The authors show that administrative datasets with no reporting thresholds have remarkably similar quantitative properties, while a number of important properties are biased in datasets with missing data. The authors exploit the change of VAT reporting thresholds in Hungary to show that as the threshold decreases the network properties of the Hungarian network resemble more closely those from the Ecuadorian network (in Ecuador there is no reporting threshold). However, the properties of the Hungarian network retrieved when reporting thresholds were in force tend to be similar of those from FactSet data. Given that the Hungarian VAT reporting thresholds were fairly small, it is likely that many connections captured by the missing links may not be relevant for the analysis of large industrial sectors, which would tend to be characterized by relatively large transactions. From this perspective, it is reassuring to see that the network properties stemming from FactSet data resemble those of a dataset where potentially less relevant transactions are dropped. Clearly, one should be cautious when analyzing individual firms' supply networks using the FactSet Supply Chain Relationships data, as there will be most likely missing links. Nevertheless, the fact that aggregate network properties are fairly preserved provides some basis for the assumption that the absent links may be mostly randomly missing, which would be helpful in making inference from the dataset.

Against this backdrop, the reminder of the paper is organized as follows. Section 2 gives an overview of what stress tests are about. Section 3 turns to the choice of the wind energy sector, depicting its supply chain, as well as the challenges it is facing. Data is presented in Section 4. The methodology that has been developed regarding stress tests is detailed in Section 5. The tests that have been conducted and the results are discussed in Section 6. Finally, section 7 discusses the limits of this proof-of-work exercise and suggests lines for further improvement.

2. Stress tests in a nutshell

The problem of supply chain resilience is somehow akin to that faced by the banking sector. As stated by the adage "a chain is as strong as its weakest link", supply chains, like banks are vulnerable to instability. Supply chains are subject to shocks[29] that can be multi-faceted (pandemics, export controls, natural disasters, domestic prioritization, transport bottleneck, labour shortages, lack of extra inventory or excess capacity, structural shifts such as the green & digital transition, cyberattacks, secondary impacts of sanctions…) [McKinsey, 2020].

In the banking sector, stress tests simulate extreme but plausible economic and financial conditions to measure the ability of banks to withstand such shocks. They have proven to be an essential (but not unique) tool to assess systemic risk of banking entities. One key element of stress tests in the banking sector is the drafting of different scenarios. "Baseline scenarios" are based on projections from national central banks while "adverse scenarios"[30] reflect risk assessments made by the supervisor and assume the materialisation of severe financial stability risks[31]. Results of these stress tests help to gauge the solvency of EU banks and whether banks have enough capital to withstand an economic shock. However, stress tests are also not a monolithic bloc. In practice, European banking supervisors conduct several types of stress tests[32] depending on the objective of banking regulation. For instance, the proximate objective of micro-prudential regulation is to limit distress of individual institutions, while macro-prudential regulation aims to ensure the stability of the banking & financial system

---

[29] Shocks have to be understood here as high impact/low frequency events.

[30] The convention used in the calibration of adverse scenarios is one of « no policy change ». This means that neither monetary policy nor fiscal policy reactions are assumed under the adverse scenario over and above what is already embedded in the baseline scenario.

[31] In the EU, this is done by the European Systemic Risk Board (ESRB). Risk assessments in the EU are made by the European Banking Authority (EBA).

[32] In the banking sector, different types of stress tests are implemented by different supervisors: (1) Annual stress tests: either (1.1)-EU-wide stress tests led by the European Banking Authority (EBA) based on capital requirements, complemented by ECB's stress test under the Supervisory Review and Evaluation Process (SREP) or (1.2)-Thematic stress tests (climate & cybersecurity stress tests; sensitivity analysis of liquidity & interest rates risk) or (1.3)-Forward-looking vulnerability analyses (linked to Covid 19 or the war in Ukraine to cite some examples). (2) Stress tests as part of comprehensive assessments and (3) Stress tests for macroprudential purposes (focusing on financial stability and system-wide effects rather than individual banks). See ECB (2023b). Available at https://www.bankingsupervision.europa.eu/banking/tasks/stresstests/html/index.en.html

in its global dimension[33]. In both cases, instruments of regulation differ somehow. That being said, stress tests should not be considered as a panacea and should be complemented by other instruments[34].

To draw a parallel with stress tests in the banking sector, it is possible to envision a micro/macro monitoring of supply chains. In practice, this would mean implementing sectoral (macro) supply chain stress tests that could focus on system-wide risks and their aggregate impacts, notably disruptions in supply chains across and within different ecosystems. This could also translate into the implementation of firm-level (micro) supply chain stress tests that could examine the impact of supply chains disruptions at the firm-level, and thus the risk of corporate bankruptcy for firms deemed as “strategic” for the autonomy of the EU.

To our knowledge, except for some stress tests that have been undertaken in transportation services (Adenso-Diaz et al. 2018) and in the South-Africa lamb chain (Jordaan & Kirsten, 2019), there has been no application so far of stress tests on supply chains. Due to the scarcity of the literature on stress tests outside the banking sector, and thus the inability “to stand on the shoulders of giants”, the present work must be considered as a proof-of-concept exercise only, and thus as “exploratory”. At the present stage, it has no pretention to offer a ready-to-use tool. Moreover, even if it is tempting here to draw parallels with stress tests in the banking sector, one needs to be cautious in undertaking such an exercise. Indeed, stress tests in the banking sector are compulsory and imply that banks comply with micro/macro prudential regulation. In addition, stress tests in the banking sectors provide a uniform framework. This seems difficult to implement such uniform framework to supply chains, as stress tests depend crucially on the specific graph of the chain.

Our aim here is to design a supply chain stress test to examine the ability of the wind energy supply chain to bounce back once disrupted. It is indeed important for public authorities to monitor the disruptions and points of failure in supply chains deemed critical, and above all to get information on the ability of EU firms to achieve homeostasis at different exposure levels if one wants to reduce EU strategic dependencies in the energy sector. To do so, the analysis is conducted under an adverse but plausible hypothetical scenario designed to determine whether the supply chain in the wind energy sector can withstand a shock. This stress test also verifies if firms in the wind energy sector have access to a diversified pool of suppliers to

---

[33] Macro prudential supervision is analogous to the oversight of the forest, while micro prudential supervision is analogous to the oversight of individual trees.

[34] If we refer to one the most recent bankruptcy in the banking sector, that of *Credit Suisse* in 2023, it is worth noting that before being taken over by *UBS*, *Crédit Suisse* had a capital adequacy ratio of 14,1%, which enabled it, in theory, to absorb losses, and a liquidity ratio, which reflected its ability to self-finance in the short term, of 144%. By comparison, the French bank *BNP Paribas*' ratios were below 12.3% and 132% respectively.

survive the shock formalised in the scenario. Due to the proof-of-concept nature of this exercise, we only test an export ban to the EU for Chinese companies selling processed critical raw minerals. To do so, we retrieve the wind energy supply chain and test it by simulating disruptions to one or several nodes. This disruption consists of a complete break of the Chinese supplying links for processed critical raw minerals considered as “critical” inputs by the European Commission (2023a)[35].

3. Specificities of the wind energy sector

Considering the nature of this proof-of-concept exercise and the fact that supply chains significantly differ from one sector to another, we restricted our analysis to the wind energy sector. Many factors have justified this choice.

First (**capacity expansion**), in the framework of its *Fit for 55 package*[36], the EU plans to boost the share of renewable energy and reduce its greenhouse gas emissions by at least 55% (compared to 1990) by 2030. This EU target implies that the current share of renewable energy in the EU will almost double, bringing it to 42.5% of the total energy by 2030[37]. Within renewal energies, onshore, but above all offshore wind energy, is expected to form the backbone of the zero-carbon electricity supply for the EU[38]. According to the EU Reference Scenario 2020[39], becoming carbon-neutral by 2050[40] requires for the EU a huge expansion in wind energy installed capacity (see Figure 1): from 204 GW in 2022 (188GW onshore and 16GW offshore representing 15.9% of EU’s electricity generation[41]) to more than 500 GW in 2030 and 1300 in 2050 (European Commission, 2023b). But as stated by the European Commission (2023), “a record 16 GW of wind power installations were added in 2022, that is a 47% increase compared to 2021. This is however well below the 37 GW per year required to achieve the EU 2030 target for renewable energy” by 2030[42].

---

[35] See also Korniyeko et al. (2017).

[36] See https://www.consilium.europa.eu/en/policies/green-deal/fit-for-55-the-eu-plan-for-a-green-transition/

[37] On 30 March 2023, the European Parliament and the Council reached a provisional agreement to raise the share of renewable energy in the EU’s overall energy consumption to 42.5% by 2030 with an additional 2.5% indicative top up that would allow to reach 45%.

[38] This prevalence is confirmed by data from the IEA’s World Energy Outlook (2022) which states that wind energy is supposed to be the leading source of electricity generation by 2027.

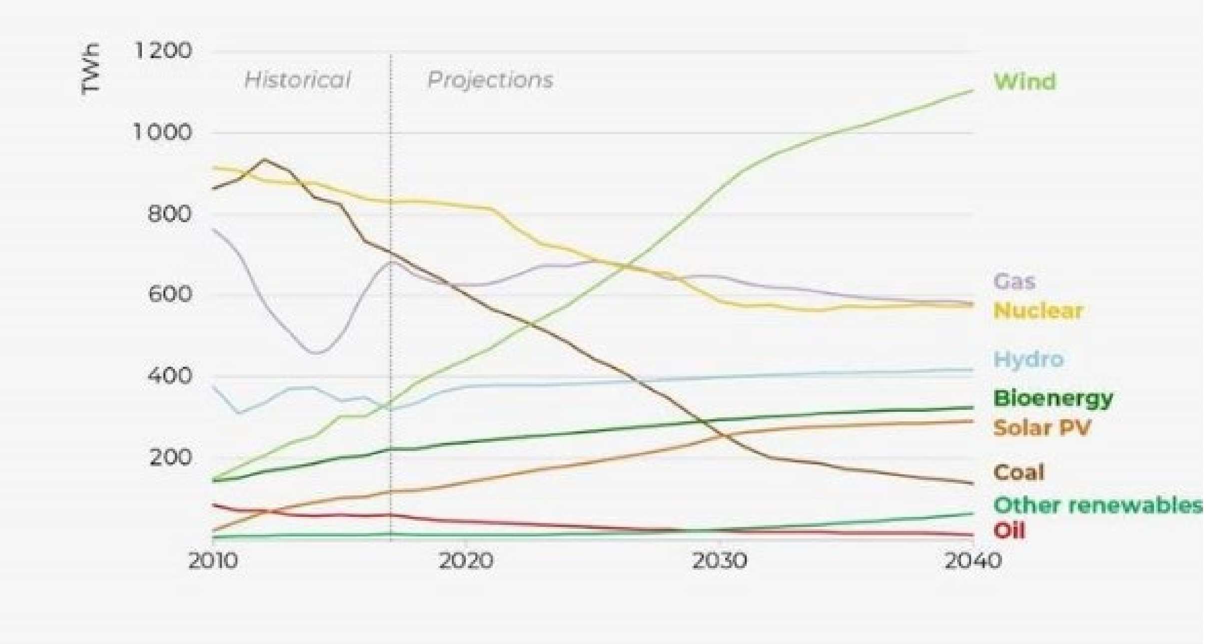
[39] Available at https://energy.ec.europa.eu/data-and-analysis/energy-modelling/eu-reference-scenario-2020_en

[40] Together with solar, wind power is considered as one of the energy sources that could help Europe break free from Russian fossil fuels, as it is expected to contribute much to capacity additions, in contrast with other renewable energy sources.

[41] Source: How is EU electricity produced and sold? - Consilium (europa.eu)

[42] See Press release from the European Commission (2023). Available at Immediate actions for the European wind power industry (europa.eu)

Figure 1: Electricity generation by source in the EU, 2019-2050 in the Sustainable Development Scenario



Source: International Energy Agency, World Energy Outlook 2020, p.156.

Scaling up wind energies to meet a zero net pathway will require massive investments in production capacities in a shorter investment cycle than previously foreseen[43], and among the whole supply chain, from installation vessels to cranes, ports, grids and skilled workers. This is an ambitious target, especially since the European Green Deal assumes an energy transition "made in Europe".[44] However, data from GWEC (2022) show that wind energy is not growing nearly fast or widely enough to realize a secure and resilient energy transition. Indeed, the EU is building wind farms at half the rate it should be to meet the REPowerEU Plan targets[45], so there is a non-null probability that these high renewable targets will not translate into orders. Among the reasons often underlined to explain this slow pace, one finds permitting bottlenecks (Energy Monitor, 2023; European Commission, 2023)[46], but also lawsuits against wind projects (MX Underwriting Europe, 2023)[47]. Indeed, approval processes are complex and can take many years[48].

---

[43] The EU energy security strategy REPower EU sets out a series of measures to reduce the EU's dependence on Russian fossil fuels by accelerating the clean energy transition. Published on 18 May 2022. Available at REPowerEU: affordable, secure and sustainable energy for Europe (europa.eu)

[44] The European Commission Clean Tech Plan sets the bloc's production capability to be able to meet at least 85 per cent of the EU's requirements as the EU tries to reach its target of net zero emissions by 2050. Available at COM_2023_684_1_EN_ACT_part1_v11.pdf (europa.eu)

[45] Available at REPowerEU (europa.eu)

[46] There is five-times more wind capacity in permitting than under construction in the EU. Available at Could too much permitting reform hurt EU renewables? (energymonitor.ai)

[47] Available at Barriers-to-Wind.pdf (energymonitor.ai)

[48] As per the EU's Renewable Energy directive, Member States are required to grant permits for new greenfield wind projects within two years, but this has not been the case with a procedure lasting up to five years in some Member States.

Second (**rising costs**), starting with the 2015 Paris Climate Agreement,[49] wind energy prices have become cheaper at a much faster rate than anticipated (Wiser et al., 2021). This was achieved through technological advances and economies of scale[50]. However, since 2020, rising commodity prices are reversing this long-term downward trend in the cost of renewables, making clean energy transitions more costly. In this respect, the price of some raw materials has multiplied[51], driven by supply chain bottlenecks, inflation (Wind Europe, 2022) and competition for resources. Delays have for instance more than quadrupling the freight costs since 2020 (Reuters, 2022)[52]. Added to these pressures, the production of key raw materials, minerals, and components for which the EU is mainly dependent on imports, is concentrated in countries affected by conflicts and geopolitical tensions. This could become a crunch issue in the coming years, as demand for certain critical minerals is expected to increase dramatically (IEA, 2023, p.65)[53]. Even if the rise in commodity prices is slowly reversing, prices remain volatile and regulatory uncertainty remain high[54].

Third (**reduced revenues downstream**), the wind industry started seeing a steep decline in prices and increased competition back in 2017 as some governments moved away from fixed, subsidized tariffs for power toward an auction-based system that favours the lowest bidders. For instance, offshore wind energy auctions in Europe have witnessed intense competition resulting in subsidy-free bids across major countries like Germany and The Netherlands[55]. These zero-subsidy bids are gaining traction and have driven a race to the bottom with some countries allowing negative bidding where developers pay for the right to build a wind farm. As a result, firms in this sector are under enormous pressures on the cost side and on the price side. These pressures, in turn, drag back profitability downstream despite rising demand for renewable energy.

Lastly (**profitability**), financial reports of EU wind turbine manufacturers show that some equipment makers in the wind energy sector operate at a loss[56]. *Siemens Gamesa* for instance

---

[49] See https://unfccc.int/process-and-meetings/the-paris-agreement
[50] The overriding factor in cost reduction has been the increase in turbine size.
[51] According to Wind Europe, (2022) but also GWEC (2022 & 2023), wind turbine production costs have surged by 40% and much of this has been absorbed by suppliers as there was no indexation of contracts to rising prices. Soaring raw material costs have hurt the wind industry as turbines are 90% made of metals, like steel and aluminium.
[52] Reuters (May 5, 2022). Available at Focus: Wind turbine makers struggle to find pricing power | Reuters
[53] In the Announced Pledge Scenario (APS), projections of the IEA (2023) for future mineral demand (based on the latest policy and technology development) show that demand more than doubles by 2030 and is 3.5 times higher by 2050. In the Net Zero Emission (NZE) Scenario, an even faster deployment of clean energy technologies implies an increase in demand for critical minerals by three-and-a-half times in 2030 and 2050, compared with 2022.
[54] The European Commission implemented a price cap of €180 per MWh for wind and solar revenues plus additional national measures.
[55] To ensure the viability of new wind offshore projects, the auction procedures are now shifting to multiple criteria to assess tenders.
[56] According to the CEO of *Siemens Gamesa*, Mr Jochen Eickhold (2022), “every time we sell a turbine, we lose 8 percent”.

reported an annual loss of 940 million euros in fiscal year 2022 and 4.6 billion euros in 2023[57]. The renewable energy businesses of *General Electric Vernova* reported a loss of 1.44 billion dollars in 2023 versus 2 billion dollars in 2022[58]. Beside the support from the Innovation Fund, wind turbine manufacturers also benefit from the Temporary Crisis and Transition Framework (TCTF) rules for State aid in support of wind manufacturing in the EU[59]. All these factors point to the fact that the wind energy sector does not have a sustainable configuration. According to the *Bundesverband WindEnergie* (2023), to be viable, the wind power price index would have to go up by approximatively 40 to 45%. Data from the wind industry also shows that wind turbine manufacturers are facing a scissor effect. On the one hand, they are engaged in a race to produce more powerful turbines, which means they have to invest heavily in research and development. On the other hand, rising production costs, quality issues[60], and a shortage of raw materials have a negative impact on their profitability. More generally, poor financial performances raise issues about the future of the wind industry[61], notably about turbine producers' ability to invest in new technologies. The fear here is to repeat the bitter experience of the EU solar panel industry[62].

These considerations apart, it is of utmost importance to have the “right” definition of the relevant wind power supply chain, “from cradle to grave”. From a theoretical point of view, a value chain refers to the full lifecycle of a product or process, i.e., the full range of activities which are required to bring a product or service from conception through the different stages of production, including material sourcing, consumption and final disposal/recycling after use. In practice, supply chains can be very complex with manifold links in multiple countries. We are more particularly interested here in the wind power global value chain, where a chain of activities is divided/fragmented among enterprises located in different countries. At this stage, the available data did not allow us to analyse all the full supply chain. For instance, the database we use does not encompass data on recycling. However, this latter being quite marginal at the present time, it should not influence too much our results, notably because “approximately 75% of the total cost of energy for a wind energy project is related to upfront

---

[57] Available at https://www.siemensgamesa.com/-/media/siemensgamesa/downloads/en/investors-and-shareholders/periodic-information/2022/q4/q4-activity-report-year-2022-siemens-gamesa.pdf and Siemens Gamesa suffers €4.3bn loss - reNews - Renewable Energy News

[58] Source: GE Vernova's Renewable Energy reduces loss to USD 1.4bn in 2023 (renewablesnow.com). *Enercon GmbH* does not publish its financial results. It is said to have received in July 2022 about 500 million euros from the German government’s WSF economic stabilization fund to help it deal with the impact of global logistics problems arising from COVID-19. See *Reuters* https://www.reuters.com/article/germany-energy-enercon-state-idINL8N2YM45C

[59] The company *Enercon GmbH* has received in 2022 government support of 500 million euros via the Economic Stabilisation Fund. Available at Wind turbine maker Enercon to get $513 mln in German pandemic aid | Reuters

[60] See Press release by Reuters as of August 7, 2023. Available at What are the issues with Siemens Gamesa's wind turbines? | Reuters

[61] The Danish wind turbine manufacturer *Vestas* recorded losses of 1,572 million euros in 2022 but returned to profitability in 2023, according to *Vestas*’ financial reports. Available at https://www.vestas.com/content/dam/vestas-com/global/en/investor/reports-and-presentations/financial/2023/2023%20Q1%20Investor%20Presentation.pdf.coredownload.inline.pdf and Vestas Annual Report 2023 – A return to profitability

[62] According to data from GWEC Market Intelligence (2023), China had in 2022 a market share of about 60% in global turbine blad manufacturing, compared to 13% for Europe, 11% for India and 8% for the U.S.

costs such as the cost of the wind turbine, foundations, electrical equipment and grid connection"[63] (Wind Europe, 2019).

4. Presentation of the data

We use commercial data in order to map critical supply chains and perform a more thorough analysis and identification of potential vulnerabilities. More precisely, to build the EU wind supply chain, two types of data have been used.

First, to identify a so-called "EU supply chain in the wind sector", we have extracted from the *WindPower©* database, the list of wind turbine manufacturers which have both their headquarters in the EU and equipped at least one wind farm in the EU territory over the period 2017-2022. The *WindPower©* database provides detailed raw statistics on wind energy and its supporting markets from a variety of players in the worldwide industry — wind farm developers, operators and owners, turbine manufacturers, to name only a few — and provides additional information about regions, countries, types and numbers of turbines, hub heights, installed capacities in MWs/GWs and commissioning dates[64]. Both large projects, but also the smaller, independent ones are listed in this database.

The sample data contains 27 turbine manufacturers with their respective market shares based on installed capacities. Considering the nature of this proof-of-concept exercise, we have only analysed, at this stage, the supply chain of four turbine manufacturers, which altogether account for roughly 90% of the EU market[65] (Wind Europe data, 2023).

Additionally, we have collected data from the *FactSet Supply Chain Relationships* database©*.* The structure of the data is dyadic, identifying pairs of companies involved in one of the different types of relation registered in the database (customer, supplier, competitor and up to 13 types of partnerships). The database covers approximately 5500 entities in the EU since 2011, 6500 in North America, 16500 in Asia and about 3100 in the rest of the world. Relationship information is sourced from public primary sources (such as annual reports or press releases) and reverse-linked to non-disclosing parties, i.e., if firm A reports that firm B is its customer then a supplier-customer relation between A and B is recorded even if B does not report A as being its supplier. Relationship statuses are updated regularly, allowing for a

---

[63] Available at Economics | WindEurope

[64] At this stage, only data on market shares have been used.

[65] Given the proof-of-concept nature of this paper, the identity of the chosen manufacturers is anonymized, such that they are referred to as companies A, B, C and D.

comprehensive and consistent overview of the relationship graph of each company over time[66]. The database also reports relationship keywords to qualify more specifically the nature of the relationship, qualitative measures of the importance of the relationship, and revealed revenue dependencies (only for supplier-customer relationships). All this provides meaningful relationship-specific context. However, these extensions have not been used so far, mostly due to the large proportion of missing data. The database focuses primarily on public (listed) and large firms, which tend to be relatively more represented than private and smaller companies. However, while the data coverage is geared towards large firms, many small and non-listed firms nevertheless show up in relationships with large firms, hence the overall network is much larger than the set of listed firms. Assuming that the publicly reported links are likely to be the most relevant ones for the companies concerned[67], the database allows the reconstruction of supply chains that, despite not being representative for the whole economy (or a whole sector), can capture the most relevant players and their major dependencies. Through network analysis it becomes then possible to identify weak links in these relationships.

Our sample of supply chain links runs from January 2017 to May 2023. The same pair of companies can appear several times if they engage on different types of relations (e.g., partnerships and customer-supplier or if they have different relationships over time). However, for the purpose of this exercise, only supplier-customer relations have been retained and duplicates have been eliminated. Relationships have been pooled to provide a more stable picture of the EU wind supply chain from a mid- to long-term perspective. In the database, firms are allocated to sectors according to a *FactSet*^(C) proprietary classification (known as RBICS). The RBICS classification can reach a level of disaggregation up to six digits, although in our supply chain data the maximum level of disaggregation is only two digits. Despite this apparent low level of disaggregation, the design of the RBICS classification does not make it unsuitable for sectorial analysis[68.] Additionally, the database contains a mapping of the companies into the NACE rev.2 classification, reaching a level of disaggregation of up to four digits (although in this case the information is missing for some companies). In order to identify the firms constituting the wind supply chain, we have exploited the information in both sectorial classifications to filter out the companies not relevant, as explained below.

For the purpose of this proof-of-concept exercise, we have only compiled at this stage a list of customers and suppliers of the four aforementioned European wind turbine manufacturers.

---

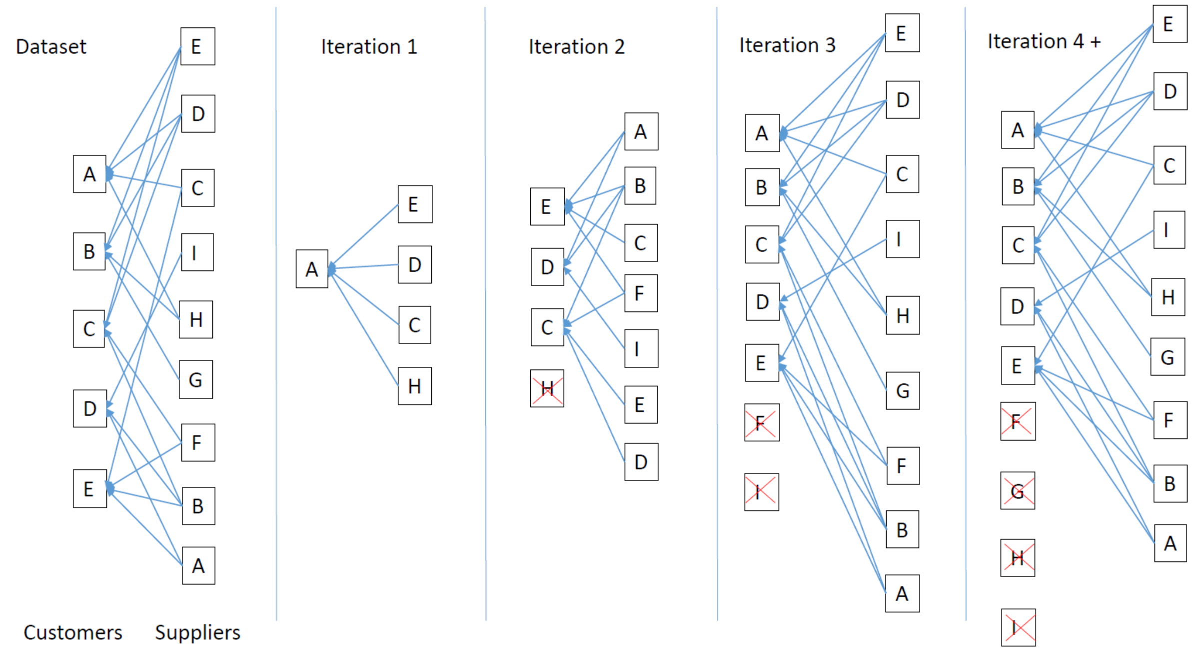
[66] It seems that FactSet(C) follows the policy of discontinuing a relationship in the dataset if after one year of the start date there is no factual evidence of its renewal or continuation. This is intended to not to inflate the database with ended relations which may have not been publicized as such.

[67] It seems safe to assume that if a company decides to report on a specific relationship, it is because it perceives that this can be valuable for itself, for example in terms of reputation or visibility.

[68] There are 37 different sectors at the two-digit level of disaggregation.

For the upstream, we have taken the respective suppliers and matched them with the whole list of company links. Then, we have treated the suppliers as "customers" to recursively retrieve the suppliers of suppliers, until no further links are identified in the data. Figure 2 illustrates this iterative process. The first column on the left displays the customer-supplier links in the dataset. Let's assume that we would like to retrieve the upstream supply chain of firm A (which would constitute tier 0)[69]. In tier -1 (second column in Figure 2), we first identify the direct suppliers of firm A in tier 0, namely firms E, D, C and H[70]. This becomes iteration 1 in Figure 2. In tier -2 (iteration 2 in Figure 2), the suppliers of these direct suppliers are then identified. Note that firm H has no suppliers in the dataset so that it can be disregarded for the next tiers. The process is repeated until some stopping rules, further discussed *infra*, are fulfilled. In the example of Figure 2, the process would stop at iteration 4 because from there on, the same set of supplier-customer links is identified in each subsequent iteration. Note that in iteration 4, the set of firms on the left is the same as the set of customers in the dataset and the set of their suppliers contains this same set of customer companies. This would lead to infinite iterations not adding any new information if the process would not be stopped. Hence the importance of introducing stopping rules.

Figure 2: Iterative process to retrieve firms in the supply chain.



Source: authors

---

[69] These firms may not be starting points of the graph representing the supply chain. In our application case, the four main European wind turbine manufacturers form the tier 0 and are neither starting points nor endpoints of the graph of the supply chain.

[70] We use the convention that tiers upstream tier 0 are numbered negatively while tiers downstream are numbered positively.

We repeated this procedure for the downstream firms, reversing the roles of “suppliers” and “customers”. To avoid links artificially duplicated, after the iterative process we only keep a unique pair of companies (“supplier-customer”) allocated to the lowest[71] tier in which they appear.

A problem of circularity may appear if firm A supplies firm B which is a supplier of firm C, which in turn supplies firm A. In such a case, even if the resilience coefficients are greater than zero, the different rounds of shocks make them act in an infinite multiplicative form that converges to zero because these coefficients are less than one. Such a circularity thus leads to a total default of all firms involved in the circular loop.

The iterative process to retrieve the supply chain would be almost endless without stopping rules to define when it can be considered that a firm is a starting point or an endpoint in a supply chain. Typically, in the sector studies, wind turbine manufacturers may have electricity producers as customers, which in turn have many firms as customers. Conversely, wind turbine manufacturers have these electricity companies as suppliers, as they need electricity for the functioning of their plants. We are not necessarily interested in including these downstream and upstream firms in the analysis of the wind turbine manufacturers supply chain. Therefore, we have tried various filters based on the activity sector of firms, which restrict the supply chain to firms belonging to some industrial sectors relevant for wind turbines:

- Filter 1: only relations where the supplier has as NACE division: 7, 8, 9, 20, 22, 23, 24, 25, 26, 27, 28, 29, 30, 32, 33, 41, 42, 43, 49, 50, 51, 52, 62, 71, 72, 74 are kept.
- Filter 2: only relations where the supplier has as NACE division: 7, 8, 20, 22, 23, 24, 25, 26, 27, 28, 32, 33, 62, 71, 72, 74 are kept.
- Filter 3: only relations where the supplier is in a "clearly" RBICS industrial sector are kept: "Aluminum", "Chemicals: Major Diversified", "Chemicals: Specialty", "Computer Communications", "Computer Processing Hardware", "Electrical Products", "Electronic Components", "Electronic Equipment/Instruments", "Electronic Production Equipment", "Engineering & Construction", "Industrial Machinery", "Industrial Specialties", "Metal Fabrication", "Miscellaneous Manufacturing", "Other Metals/Minerals", "Semiconductors", "Steel".
- Filter 4: filter 2 AND filter 3 simultaneously.

Table 1 reports the counts of links and firms according to the different filters. The first two filters are based on NACE divisions to identify the activity of firms, with Filter 2 being more restrictive

---

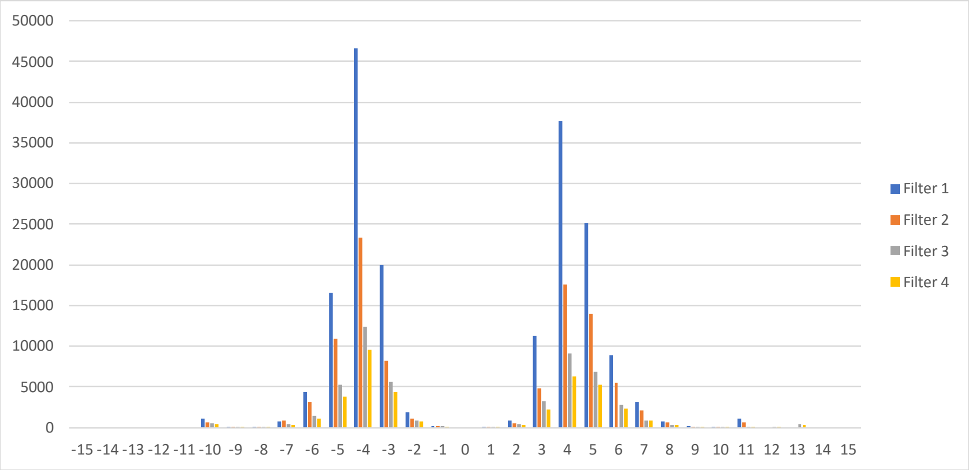
[71] Lowest understood as closest to tier 0.

than Filter 1 (firms from the automobile industry -NACE division 29- for instance are excluded). Filter 3 makes use of the RBICS classification specific to the *FactSet Supply Chain* database instead of the NACE division code. Table 1 reveals that applying the RBICS classification is much more restrictive than applying the NACE division criteria, resulting in approximately a 40% drop in the counts of links and firms. Filter 4 combines the two classifications and is thus the most restrictive of the four filters.

Table 1: Counts of links and firms in the supply chain

	Filter 1	Filter 2	Filter 3	Filter 4
# of non-redundant upstream links	91763	48308	26603	20425
# of non-redundant upstream firms	16070	10845	6771	5411
# of non-redundant downstream links	89096	45788	24298	17975
# of non-redundant downstream firms	21540	12843	7618	5656
# of non-redundant firms in total	29821	18677	11236	8658

Figure 3: Distribution of firms across the different tiers of the process.



Regardless of the filter used to retrieve the supply chain, Figure 3 highlights that most of upstream and downstream firms are detected in our database between the third and fifth tiers. As regards headquarters by country (See Figure 4.a and 4.b), firms from China and the United States clearly dominate both upstream and downstream in the value chain, followed by firms from Asian countries (Japan, South Korea, India, Taiwan). Most of the companies located upstream, in the supply chain of the four wind turbine manufacturers studied, are located outside Europe. For those firms located within the EU, firms from Germany rank first, followed by British and French firms. The upstream and downstream parts of the supply chain look rather symmetric in terms of firms' location. It is also rather robust whatever the filter used to retrieve the supply chain, except for firms whose headquarters is located in Africa and South America as they are more numerous when applying Filter 1, i.e., the less restrictive filter.

Figure 4.a: Count of upstream firms by country (Filter 4).

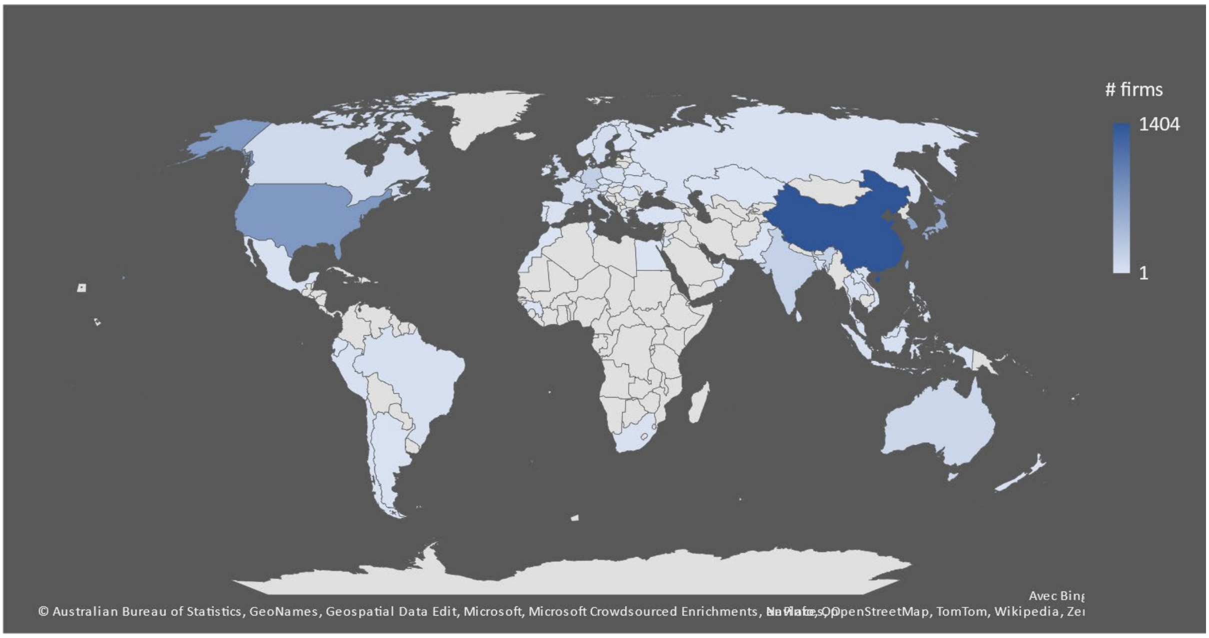
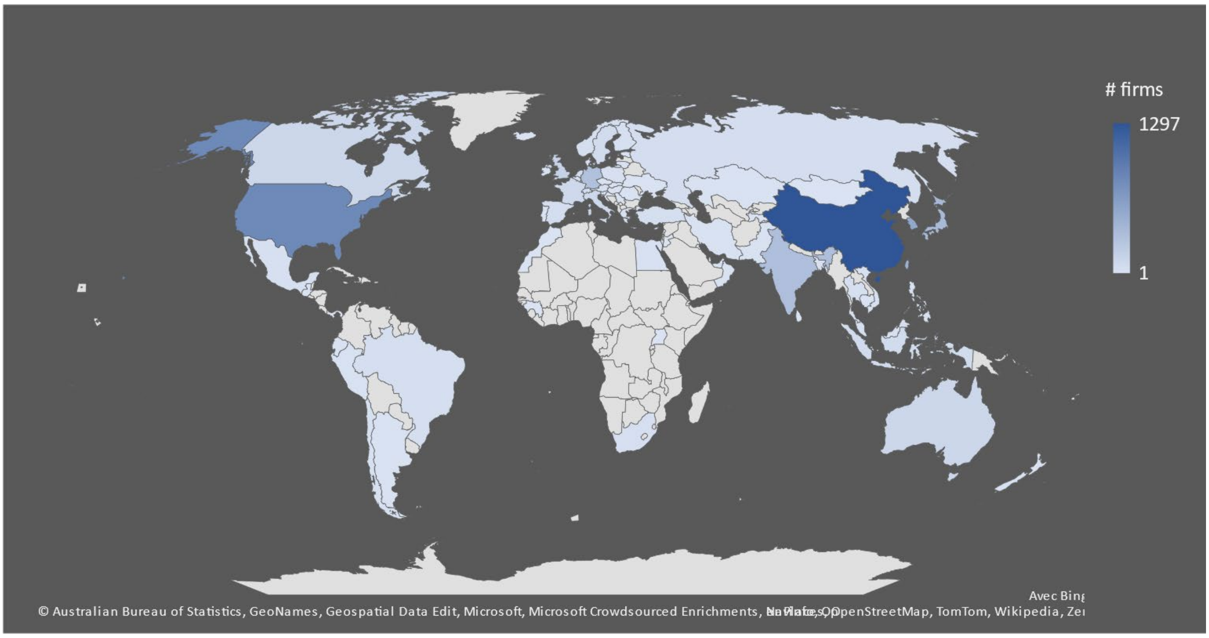


Figure 4.b: Count of downstream firms by country (Filter 4).



Finally, the distribution of firms among the different RBICS industrial sectors displayed in Figure 5 indicates that firms from all these sectors belong to the supply chain, even if there is a predominance of firms from the “Industrial Machinery”, the “Semiconductors” and the “Electrical Products” sectors both upstream and downstream. On Figure 5, sectors are ranked according to their frequency in the upstream part of the supply chain, but this ranking only marginally changes when considering the downstream part of the supply chain. At a first glance, it may be surprising that the downstream part of the supply chain involves firms in many different industrial sectors. A more thorough examination of the supply chain indicates that some customers of wind turbine manufacturers are conglomerates that not only buy wind turbines to exploit their own wind farms but also produce and sale equipment for other firms. Two examples are illustrative of this.

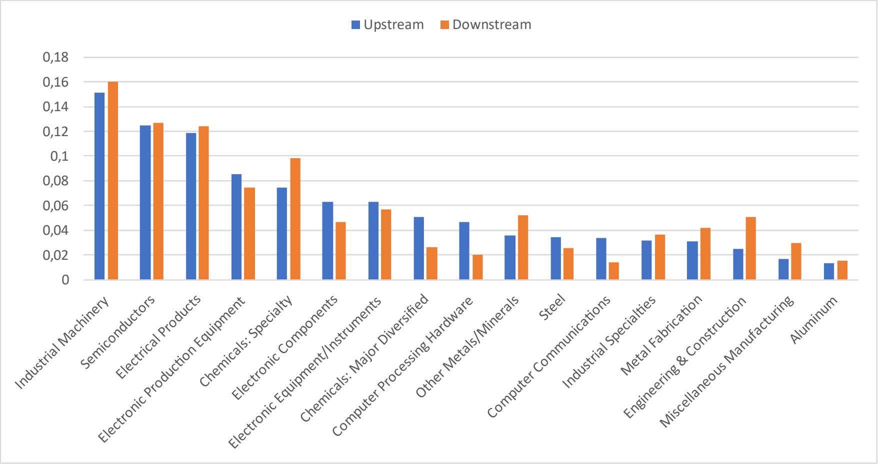
The first is that of the company *N*,[72] which is a direct customer (tier 1) of *B* and *C* because part of its activity is the production of energy, among which renewable electricity. Nevertheless, another major activity of *N* is also the production of aluminium that is sold to many other industrial firms that are therefore detected as indirect customers (tiers 2 or more) of *B* and *C*. The second example is that of *X*, an Asian company that manufactures and markets connectors, cable assemblies, and power packs, which are used in computer and communication industries. This company also has a cascade of subsidiaries, among which *Y*, which in turn, has as a subsidiary *Z*, acting as a renewable energy arm of *X* and investing in wind farms[73]. Both *X* and *Z* appear as direct customers (tier 1) of *D* in the database. *X* also appears as a supplier of other industrial firms, including *Z*. In that example, it is thus the nexus of its subsidiaries that makes the industrial firm *X* appear as a customer of *D*. Its own customers appear as indirect customers of *D*.

Similar problems may arise in the upstream part of the supply chain, even if it is less surprising to detect firms belonging to many different industrial sectors among the direct and indirect suppliers of wind turbine manufacturers. Let consider for instance the case of the Japanese firm *J*, which is detected as a direct supplier of *D* in the database. According to the database, *J* has more than a hundred of direct suppliers in 15 different RBICS sectors, including the “Chemicals: Specialty” sector. The Asian firm *K* is for instance one of its suppliers and thus appears as an indirect supplier of *D*. It is nevertheless unclear to what extent *D* is dependent on *K*.

---

[72] Actual company names are replaced by letters to preserve anonymity.

Figure 5: Distribution of upstream and downstream firms according to the RBICS industrial sector (Filter 4).

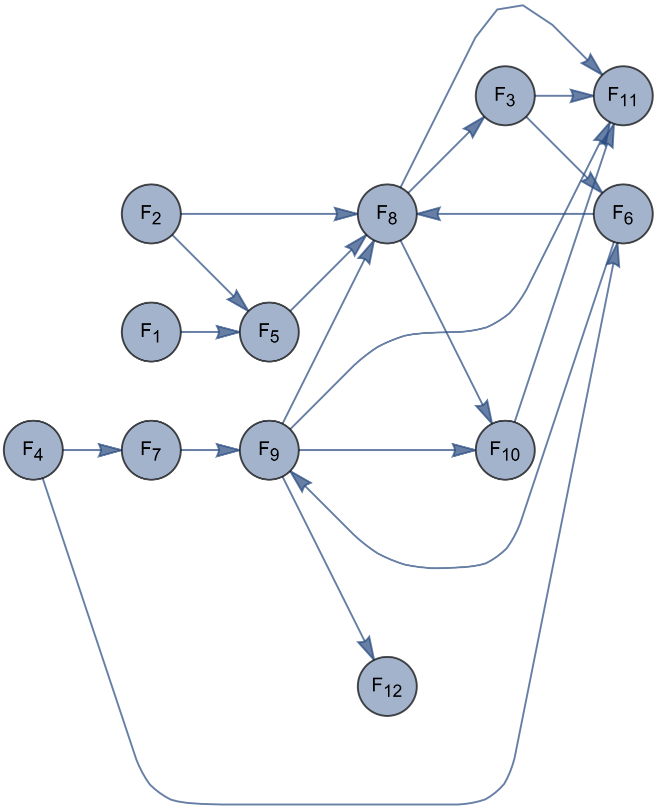


5. Methodological aspects

5.1. Supply chains as graphs

The starting point of the analysis is the graph formed by the supply chain where each firm F_n ($n \in \{1, \cdots, N\}$) is a node and each supplier-customer link is an oriented edge of the graph. The simple graph (compared to the case studied) in Figure 6 is used for illustrative purpose all along the text. The corresponding supply chain involves twelve firms ($N = 12$). The labelling of firms is chosen so that it reflects their positioning within the supply chain, a low (resp. high) value of the subscript n indicating that the firm is rather upstream (resp. downstream) in the supply chain.

Figure 6: Graph of the illustrative supply chain



The above graph illustrates the business-as-usual state of the supply chain, where the diversity of direct suppliers of each firm corresponds to its optimal individual sourcing strategy, without consideration of the consequences in terms of supply risk for downstream firms. Each firm F_n chooses its direct suppliers, which correspond to the sources of the edges that point to the node associated with the firm. Conversely, it has no control of its indirect suppliers, i.e., the suppliers of its suppliers. As a result, when choosing its direct suppliers, a firm exerts an externality in the form of a supply risk transmission on downstream firms.

The graph of supplier-customer links can be represented by a network square matrix Ω with N rows and columns corresponding to the different firms involved in the supply chain. Element $\omega_{i\,j}$ in row i and column j takes value 1 if and only if F_j supplies F_i (and thus there exists a supplier-customer link of type $F_j \to F_i$ in the graph) and value 0 otherwise. The network matrix of our illustrative supply chain is given in Table 2.

Table 2: Network matrix of the illustrative example

	F_1	F_2	F_3	F_4	F_5	F_6	F_7	F_8	F_9	F_{10}	F_{11}	F_{12}
F_1	0	0	0	0	0	0	0	0	0	0	0	0
F_2	0	0	0	0	0	0	0	0	0	0	0	0
F_3	0	0	0	0	0	0	0	1	0	0	0	0
F_4	0	0	0	0	0	0	0	0	0	0	0	0
F_5	1	1	0	0	0	0	0	0	0	0	0	0
F_6	0	0	1	1	0	0	0	0	0	0	0	0
F_7	0	0	0	1	0	0	0	0	0	0	0	0
F_8	0	1	0	0	1	1	0	0	1	0	0	0
F_9	0	0	0	0	0	1	1	0	0	0	0	0
F_{10}	0	0	0	0	0	0	0	1	1	0	0	0
F_{11}	0	0	1	0	0	0	0	1	1	1	0	0
F_{12}	0	0	0	0	0	0	0	0	1	0	0	0

Rows with only zeros signal firms that are starting points of the graph. Conversely, columns with only zeros enable to identify firms that are endpoints of the graph. In the illustrative example, F_1, F_2 and F_4 are starting points of the graph and correspond to firms that are uppermost in the supply chain. F_{11} and F_{12} are endpoints of the graph and correspond to firms that are downmost in the supply chain.

The construction of the network matrix requires information on supplying relationships among firms. As we do not have additional information on the share of purchases made by each firm from their different suppliers, a more sophisticated matrix accounting for these shares could not be constructed[74]. Typically, instead of having 1 in row i and column j if and only if F_j supplies F_i, the element in row i and column j could have reported the share of purchases of F_i from F_j so that, except for firms that are starting points of the graph, the coefficients on each row would sum to 1.

For the specific purpose of our stress test, a matrix Θ of random resilience coefficients, the exact role of which is discussed *infra*, is associated to the network matrix Ω. A non-zero resilience coefficient $\theta_{i\,j}$ is more specifically introduced for each link $F_j \rightarrow F_i$ in the graph. It measures the resilience of firm F_i to a shock on its supplier F_j. Resilience coefficients range between 0 and 1. The higher the value, the less sensitive firm F_i is to a shock affecting its supplier F_j. The resilience coefficients are key components of the measurement of stress along the supply chain.

---

[74] Such information was too sparse in the database to allow for the construction of this kind of alternative matrix.

5.2. Measuring stress

We define $y_{i\,t}$ as an aggregate measure of the degree of resilience of firm F_i at iteration t of the stress test. This measure is normalised to 1 under the business-as-usual state of the supply chain, which serves as the benchmark for the stress test. Therefore, any upstream disruption in the supply chain implies that $y_{i\,t} \leq 1\ \forall i \in \{1, \cdots, N\}$ for $t > 0$. The value of $y_{i\,t}$ reflects to what extent the access of firm F_i to its direct and indirect suppliers is preserved following a disruption in the supply chain. Conversely, $s_{i\,t} = 1 - y_{i\,t}$ must be thought of as the degree of "stress" incurred by a firm due to disruption in the supply chain.

The stress test proceeds iteratively. The initial shock at iteration $t = 0$ is captured by setting $y_{i\,0} < 1$ for $i \in \Psi$, with $\Psi \subset \{1, \cdots, N\}$ the subset of firms directly affected by the initial shock and $y_{i\,0} = 1$ for all the other firms. The initial shock may reflect any kind of macro or micro disruption, from natural disasters to major strikes, trade litigation or geopolitical conflicts. The first round of the stress test ($t = 1$) consists in computing the impact on the aggregate measure of resilience of the customers of firms $i \in \Psi$. The second round ($t = 2$) of the stress test looks at the consequences of changes in the degree of resilience of firms that are affected in the first round on the degree of resilience of their own customers and so on, iteratively.

Let's assume for instance that in the supply chain illustrated in Figure 6, the initial shock affects firm F_4 so that $y_{4\,0} = 0.5$. The first round of the stress test then concerns the two direct customers of F_4, namely firms F_6 and F_7. The second round of the stress test then turns to the transmission of the impact affecting F_6 and F_7 on their own customers, which are firms F_8 and F_9. Note that firm F_9 is affected through two channels, one as a customer of F_6 and the other as a customer of F_7. Note also that loops can be involved in the iterative stress test. For instance, in the illustrative example provided by Figure 7, firm F_9 is a supplier of F_8, which is a supplier of F_3, which in turn supplies F_6, which finally supplies F_9, thus closing a loop. The iterative process may lead to either the total collapse of the supply chain at some iteration T (i.e. $y_{i\,T} = 0\ \forall i \in \{1, \cdots, N\}$) or its convergence to a new degraded steady state, i.e., with some firms having a non-null degree of resilience.

The iterative process heavily relies on the functional form linking the degrees of resilience at round t+1 with those at round t. We propose the following functional form, inspired by the

Constant Elasticity of Substitution (CES) functional form commonly used to describe production function[75]:

$$y_{i\,t} = y_{i\,t-1} \times \begin{cases} 1 & if \quad \sum_{j=1}^{N} \omega_{ij} = 0 \\ \left(\sum_{j=1}^{N} \omega_{ij}\right)^{-\sigma/\sigma-1} C_{i\,t} & if \quad \sum_{j=1}^{N} \omega_{ij} > 0 \end{cases} \quad \forall t > 0 \qquad \text{(1.a)}$$

with

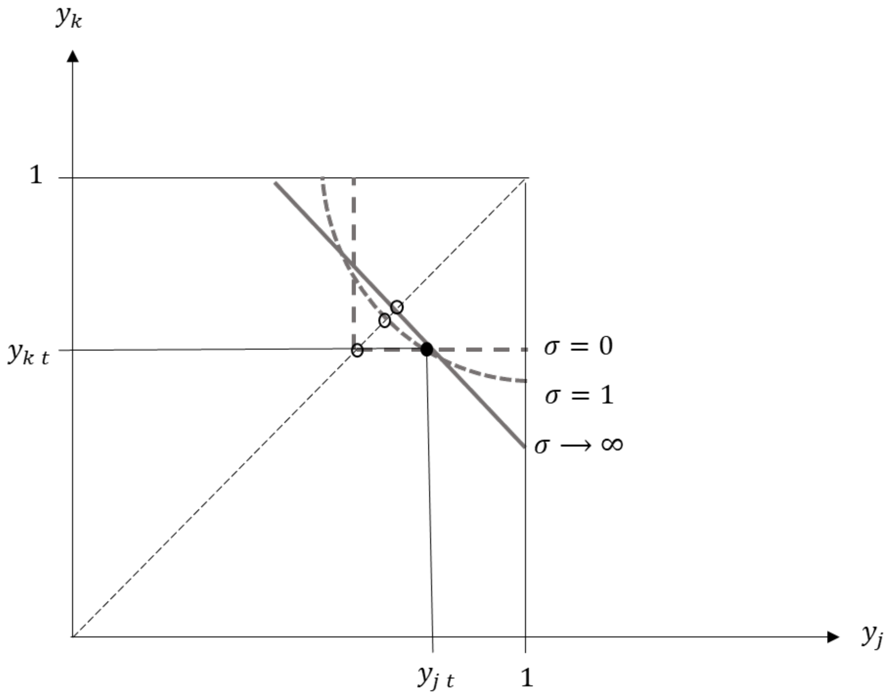
$$C_{i\,t} = \left(\sum_{j=1}^{N} \omega_{ij}\left(\theta_{ij} + \left(1-\theta_{ij}\right) y_{j\,t-1}\right)^{\frac{\sigma-1}{\sigma}}\right)^{\sigma/\sigma-1} \qquad \text{(1.b)}$$

The first row of (1.a) states that the resilience of firm F_i remains unchanged if the firm is a starting point of the graph. The second row of (1.a) recursively defines the degree of resilience of firm F_i at iteration t of the stress test as a function of the degree of resilience of its suppliers at the previous iteration $t-1$. The first component in this second row is a normalisation factor that induces that the degree of resilience always ranges between 0 and 1. The second component denoted by $C_{i\,t}$ and defined in (1.b) is the one that really captures the stress contamination. The subcomponent $\theta_{ij} + \left(1-\theta_{ij}\right) y_{j\,t-1}$ is a linear combination of 1 (i.e. insensitivity to a stress on direct suppliers) and the degree of resilience of suppliers at the previous iteration of the test, with respective weights θ_{ij} and $\left(1-\theta_{ij}\right)$. The higher the resilience parameter θ_{ij}, the less sensitive is firm F_i to a stress affecting its suppliers. This subcomponent is embedded in a standard CES functional form to yield $C_{i\,t}$, except the factors ω_{ij} introduced in the summation to make firm F_i dependent to its direct suppliers only.

---

[75] Barrot & Savagnat (2016) and Boehm & alii. (2019), for instance, provide causal evidence that the scope for trade linkages to generate cross-country spillover depends on the elasticity of substitution with respect to downward inputs. They show that input linkages with strong complementarities are a key mechanism through which shocks are transmitted across borders.

Figure 7: Influence of parameter σ



Parameter σ in (1) captures to what extent there is substitutability or complementarity between direct suppliers of a firm within the supply chain. Figure 7 illustrates this idea for a firm F_i having two direct suppliers F_j and F_k, in the simplified case where the resilience coefficients are $\theta_{ij} = 0$ and $\theta_{ik} = 0$. It is assumed that at iteration t, the two suppliers' degrees of resilience are respectively $y_{j\ t} < 1$ and $y_{k\ t} < 1$ (black dot in Figure 7). If σ goes to infinity, any alternative combination of the degrees of resilience of its direct suppliers, such that one degree is decreased by an amount Δy, whereas the other is increased by the same amount Δy, let the new degree of resilience of firm F_i unchanged. Graphically, this case corresponds to a displacement along the continuous line passing through point $(y_{j\ t}\,, y_{k\ t})$ and having a slope equal to -1. It can be interpreted as a perfect substitutability case to the extent that a one-by-one change in its direct suppliers' degrees of resilience let the degree of resilience of the firm unchanged. It is useful for comparison with other values of σ to consider a variation Δy leading to a point on the bisector represented by an empty dot at the intersection between the line and the bisector. At the opposite, if $\sigma = 0$, a decrease in the degree of resilience of one of its suppliers implies a decrease of its own degree of resilience for firm F_i, even if the degrees of resilience of its other suppliers remain unchanged. It also means that any asymmetry between the degrees of resilience of its direct suppliers is worthless for firm F_i as it yields the same degree of resilience for the firm than if all its direct suppliers had a degree of resilience aligned on the lowest one. As a result, all points lying on the dashed square passing through point

$(y_{j\,t}\,, y_{k\,t})$ and having their right angle on the bisector yield the same degree of resilience for firm F_i. This case can thus be interpreted as a perfect complementarity case. As the dot at the right angle has a lower abscissa and ordinate, compared to the similar dot on the bisector in the case where $\sigma \rightarrow \infty$, it means that with $\sigma = 0$, a stress on its direct suppliers has a more detrimental impact on the degree of resilience of firm F_i. For $\sigma \in]0, \infty[$, the set of points leading to an unchanged degree of resilience for firm F_i, compared to that reached at point F_i, is a decreasing and convex curve. In the specific case where $\sigma = 1$, the subcomponent $C_{i\,t}$ in (1.b) takes a Cobb-Douglass form, as illustrated by the fine doted curve in Figure 7. Note that the associated dot at the crossing between the iso-resilience curve and the bisector lies between the two dots on the bisector associated to the previous cases $\sigma \rightarrow \infty$ and $\sigma = 0$, so that the degree of resilience for firm F_i is intermediate between that of these two cases. Finally, note that when resilience parameters θ_{ij} and θ_{ik} are non-null and take different values, the slope of the isocurve of resilience on Figure 7 is no longer symmetric, with respect to the bisector, and the sensitivity of firm F_i, with respect to shocks on its direct suppliers becomes asymmetric.

5.3. Nested model

Equation (1) treats all suppliers on a similar basis, assuming that the degree of substitutability or complementarity between two suppliers is the same whether the two suppliers belong to the same sector or not. Conditional on the availability of information on the main sector of activity of firms along a supply chain, it is worth introducing a nested version of (1) that allows us to have different degrees of substitutability or complementarity between firms. It is more specifically expected here that the degree of substitutability between suppliers within a same sector is higher than the degree of substitutability between suppliers from different sectors. We thus assume that the set of firms belonging to the supply chain at stake can be partitioned in K subsets Λ_k $(k\epsilon\{1, \cdots, K\})$ corresponding to activity sectors. Firms are gathered in these subsets according to their main activity. Let Φ_i denote the list of sectors in which firm F_i has at least one supplier. φ_i stands for the cardinal of Φ_i. The aggregate measure $y_{i\,t}$ of the degree of resilience of firm F_i at iteration t of the stress test is now defined by

$$y_{i\,t} = y_{i\,t-1} \times \begin{cases} 1 & if \quad \varphi_i = 0 \\ (\varphi_i)^{-\sigma_B/\sigma_B - 1} \left(\sum_{k\epsilon\Phi_i} y_{k\,i\,t}{}^{\frac{\sigma_B - 1}{\sigma_B}} \right)^{\sigma_B/\sigma_B - 1} & if \quad \varphi_i > 0 \end{cases} \quad \forall t > 0$$

(2.a)

with

$$y_{k\,i\,t} = \left(\sum_{j \epsilon \Lambda_k} \omega_{ij}\right)^{-\sigma_W/\sigma_W - 1} C_{k\,i\,t} \tag{2.b}$$

and

$$C_{k\,i\,t} = \left(\sum_{j \epsilon \Lambda_k} \omega_{ij} \left(\theta_{ij} + \left(1 - \theta_{ij}\right) y_{j\,t-1}\right)^{\frac{\sigma_W - 1}{\sigma_W}}\right)^{\sigma_W/\sigma_W - 1} \tag{2.c}$$

Like in (1.a), the first row of (2.a) states that the resilience of firm F_i remains unchanged if the firm is a starting point of the graph. The second row of (2.a) defines the aggregate measure of resilience of firm F_i as a CES function of sub-aggregate measures $y_{k\,i\,t}$ of resilience of the firm, computed by sectors of activity of its suppliers. The first component in this second row aims at normalizing the maximum value of the measure of resilience to 1. In (2.a), parameter σ_B captures the degree of substitutability or complementarity between sectors in which firm F_i has suppliers. In turn, the sub-aggregate measures $y_{k\,i\,t}$ of resilience of the firm for each supplying sector are defined in (2.b) in (2.c), in a similar way than the aggregate measure in (1.a) and (1.b), except that the CES function is limited to suppliers within the sector k. In (2.b) and (2.c), parameter σ_W captures the degree of substitutability or complementarity within sectors in which firm F_i has suppliers.

5.4. Comments on calibration

The stress test detailed in the previous sections involves a potentially high number of parameters if, in addition to the elasticities of substitution σ in the non-nested model, or σ_B and σ_W in the nested model, a different value of the resilience coefficient θ_{ij} is allowed for each link $F_j \rightarrow F_i$ in the graph representing the supply chain. In the absence of case studies of firms at the different links of the supply chain to infer the value of parameters, we have to rely on some *a priori* calibration and to implement a sensitivity analysis.

The guideline for calibration is to select parameters' values so that there is neither a too rapid collapse of the supply chain, nor a too high inertia, so that results of the stress test underscore heterogeneity across firms in terms of their resilience to stress. The underlying idea is thus to put the emphasis on the role of the specific network of suppliers and customers that features the supply chain under scrutiny. The stress test is iterated up to a number of iterations that yields no additional change in the aggregate measure of resilience of firms. To limit the dependence of the results on specific values of the parameters, Monte Carlo simulations can be implemented. As they are potentially numerous, the case of resilience coefficients deserves some discussion. It is more specifically convenient to assume that Θ is a matrix of random resilience coefficients defined as follows:

$$\begin{cases} \theta_{ij} = 0 & if \quad \omega_{ij} = 0 \\ \theta_{ij} \sim Beta(\alpha, \beta) & if \quad \omega_{ij} = 1 \end{cases} \tag{3}$$

Resilience coefficients are thus identically and independently drawn from a Beta distribution with two parameters α and β. As a result, the calibration problem is reduced to the calibration of these two parameters.

In the illustrative example introduced with Figure 7, the sensitivity analysis of the non-nested model reveals that unless σ is sufficiently high, and the resilience coefficients θ_{ij} are drawn from a distribution with a sufficiently high mass on the right (i.e., close to 1), the supply chain rapidly collapses. The case of a rapid collapse is not very informative, as it does not help identifying which firms are the most fragile along the chain and should therefore attract more attention. A sufficiently high value of σ is key to avoid a rapid collapse of the supply chain because it guarantees that suppliers are sufficiently substitutable and that a shock affecting one of them can be circumvented thanks to the other. Similarly, sufficiently high values of the resilience coefficients are required because, as suggested by equation (1.b), they limit the magnitude of shocks transmission from one iteration to the other. In the illustrative example developed from Figure 7, $\sigma = 2$ and a beta distribution with parameters $\alpha = 5$ and $\beta = 1$ reveals to be a good compromise as it limits the magnitude of shocks transmission, while keeping a significant heterogeneity across the different links of the supply chain. An example of the matrix Θ of resilience coefficients drawn from this probability density function is reported in Table 3. It serves as a basis for the following elements of illustration.

Table 3: Example of a random draw of the matrix Θ of resilience coefficients

	F_1	F_2	F_3	F_4	F_5	F_6	F_7	F_8	F_9	F_{10}	F_{11}	F_{12}
F_1	0	0	0	0	0	0	0	0	0	0	0	0
F_2	0	0	0	0	0	0	0	0	0	0	0	0
F_3	0	0	0	0	0	0	0	0,797	0	0	0	0
F_4	0	0	0	0	0	0	0	0	0	0	0	0
F_5	0,987	0,617	0	0	0	0	0	0	0	0	0	0
F_6	0	0	0,754	0,903	0	0	0	0	0	0	0	0
F_7	0	0	0	0,742	0	0	0	0	0	0	0	0
F_8	0	0,631	0	0	0,851	0,943	0	0	0,789	0	0	0
F_9	0	0	0	0	0	0,812	0,934	0	0	0	0	0
F_{10}	0	0	0	0	0	0	0	0,748	0,656	0	0	0
F_{11}	0	0	0,942	0	0	0	0	0,954	0,839	0,984	0	0
F_{12}	0	0	0	0	0	0	0	0	0,820	0	0	0

Table 4 displays the vector of aggregate measures of the degree of resilience of the N firms at iterations $t = 0$ (initial shock), $t = 5$, $t = 10$, $t = 20$, $t = 100$. As shown by the last column, the aggregate measure of resilience falls to zero for almost all firms that are not starting points of the value chain, except firm F_8 which appears a little bit more resilient. More interestingly, the previous columns highlight that firm F_7 is more at risk than the others. Of course, these results are contingent on the specific resilience coefficients reported in Table 3. To avoid this, we implement a Monte Carlo simulation approach, taking a large number of random draws of the resilience coefficients in order to construct a probability distribution of the aggregate measures of the degree of resilience of firms.

Table 4: Example of results at different iterations (minimum aggregate index of resilience in grey)

	iteration 0	iteration 5	iteration 10	iteration 20	iteration 100
F_1	1	1	1	1	1
F_2	1	1	1	1	1
F_3	1	0,998955	0,979283	0,747639	2,48319*10^-7
F_4	0,5	0,5	0,5	0,5	0,5
F_5	1	1	1	1	1
F_6	1	0,88368	0,778018	0,536165	3,85067*10^-6
F_7	1	0,500677	0,250677	0,062839	9,79818*10^-7
F_8	1	0,993306	0,95209	0,740214	0,00339739
F_9	1	0,941326	0,78684	0,429889	1,44351E-05
F_{10}	1	0,988679	0,882192	0,373787	4,48036*10^-12
F_{11}	1	0,997415	0,971964	0,797842	0,00366014
F_{12}	1	0,988817	0,889503	0,439319	1,40967*10^-7

The previous illustration is based on only one draw of the matrix Θ of resilience coefficients, and one value for parameter σ of the CES function used to compute the aggregate resilience index of firms. To limit the dependence of the results on a specific draw of the matrix Θ and a specific choice of the CES parameter(s), Monte Carlo simulations are implemented.

The implementation of Monte Carlo simulation for the resilience coefficients is immediate given the way of generating them defined in equation (3). As regards the parameters of the CES function(s), we must define the probability distribution from which they can be drawn. Though any distribution defined over the set of positive or zero real numbers can be candidate, we retained the Gamma distribution due to its ability to integrate both an asymmetry and a mode that can be either positive or equal to zero. To implement the Monte Carlo simulations in the non-nested model, we draw several thousand values of σ from a $\Gamma(k\,,\delta)$ distribution for each firm involved in the supply chain, in parallel to as many random draws of the matrix Θ. The two parameters of the $\Gamma(k\,,\delta)$ distribution are chosen following the same guidelines as those described above. More specifically, they are chosen so that the mass of values guarantees that the supply chain does not collapse too rapidly and that, conversely, a sufficiently high degree of discrimination in terms of the final resilience of firms at the steady state of the stress test is obtained.

The case of the nested model deserves more attention. Indeed, it is expected that the parameter σ_B, capturing the degree of substitutability or complementarity between sectors, is lower than the parameter σ_W capturing the degree of substitutability or complementarity within sectors. Therefore, the Monte Carlo simulation proceeds in two steps. In a first step, a different value of σ_W is drawn from a $\Gamma(k_W, \delta_W)$ distribution for each firm. In a second step, a $\Gamma(k_B, \delta_B)$ distribution is used to generate values of σ_B. Nevertheless, we impose the condition that $\sigma_B \leq \sigma_W$ by drawing the value of σ_W from the truncated version of the $\Gamma(k_B, \delta_B)$ where, for each firm, truncation occurs on the right of the value σ_W drawn in the first step for the firm.

6. Results

6.1. Stress definition and implementation

The first step of the stress test consists in identifying which group of firms is affected by the initial shock (a Chinese ban on processed critical raw materials) within the supply chain, and what is the magnitude of this initial shock, given that these inputs are an important, and so far difficult to substitute, component to produce wind turbines.

To do this, we have identified Chinese firms involved in the extraction and processing of rare earths materials. We have then introduced a shock on these Chinese firms that corresponds to a total drop in their accessibility (i.e., we set their initial aggregate index of resilience in the supply chain of *A*, *B*, *C* and *D* to 0). These firms have been identified by searching for the keywords “rare” or “earth” in the name of upstream firms, in addition to the country code being “CN”. The keyword “rare” is systematically associated with “earth” or “-earths”, whereas there is one firm name where the keyword “earth” is not associated with “rare”, namely the firm *Earth-Panda Advanced Magnetic Material*. Nevertheless, this firm produces permanent magnet products based on rare earth. We also checked on the web if other Chinese firms were referred to when searching for Chinese firms specialised in rare earths materials, but we were not able to identify additional firms by doing so. The name and *FactSet* ID of the firms that we have selected for the initial shock with the sectoral Filter 4 in order to retrieve the supply chain are reported in Table 5. The tiers at which the firms appear in the supply chain are also reported. The Chinese firms involved in the extraction and/or processing of rare earth materials spread all along the upstream part of the supply chain, from tiers close to the wind turbine manufacturers (tiers -2 or -3) to tiers much further upstream (up to tiers -5 and -6).

Table 5: FactSet ID and name of Chinese firms identified as extracting or processing rare earths

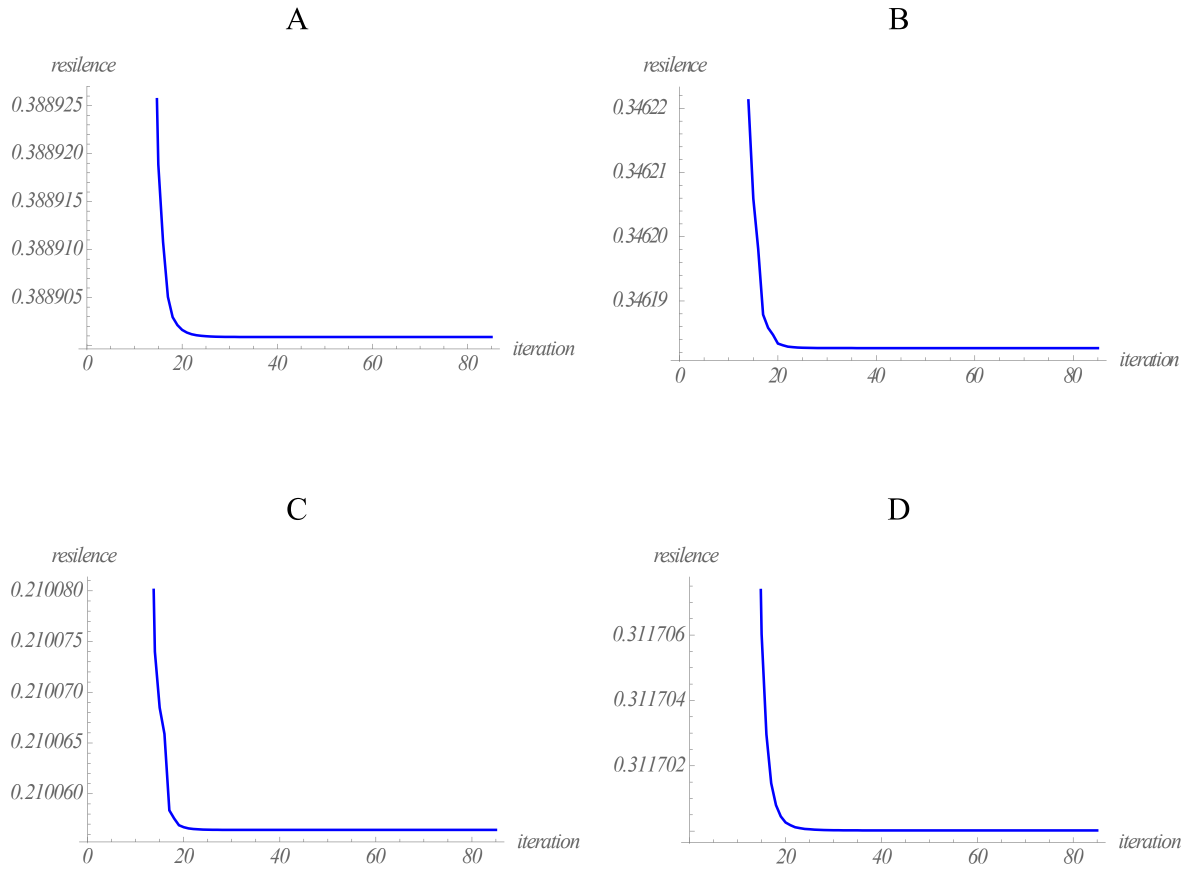
FactSet ID	Name of the company	Tier
0JXTP0-E	JL MAG Rare-Earth Co., Ltd.	-3; -4; -5
062XTP-E	China Northern Rare Earth (Group) High-Tech Co., Ltd.	-2; -3; -4
0JQKNN-E	China Rare Earth Co. Ltd.	-2
0FYW7V-E	Earth-Panda Advanced Magnetic Material Co., Ltd.	-2; -3; -4
0DK62Z-E	Fujian Changting Golden Dragon Rare-Earth Co., Ltd.	-3
062NW3-E	China Rare Earth Resources & Technology Co., Ltd.	-4; -6
0CP0KG-E	Gansu Rare Earth New Material Co. Ltd.	-4
08M0W5-E	Ganzhou Chenguang Rare Earths New Material Co., Ltd.	-5
0DJM1Q-E	Baotou Xinyuan Rare Earth Hi-Tech & New Material Co. Ltd.	-3

The next step of the stress test consists in implementing the iterative formula (1) or (2), depending on whether the non-nested version, or the nested version of the model, is applied. Thereafter, we focus on results obtained with the nested version of the model applied to the supply chain as retrieved from using Filter 4, and with Monte Carlo simulations for all parameters. Corresponding results obtained with the non-nested version of the model, Monte Carlo simulations for the resilience coefficients only (CES parameters are set equal to expected values of the Gamma distribution), and filters 1 to 4 are reported in the appendix.

The parameter values used in this application for the distribution $\Gamma(k_B\ ,\delta_B)$ of the CES function between sectors are chosen such that $E[\sigma_B] = 0{,}05$ and $V[\sigma_B] = 0.05^2$. In parallel, parameter values used for the distribution $\Gamma(k_W\ ,\delta_W)$ of the CES function within sectors are chosen, such that $E[\sigma_W] = 0{,}2$ and $V[\sigma_W] = 0.1^2$. For the non-nested model, whose results are displayed in the Appendix, we used $\sigma = 0{,}1$. As regards the beta distribution of resilience coefficients, we choose $\alpha = 1/2$ and $\beta = 3/2$, which yields an expected value of $1/4$ and a standard deviation of $1/4$ for the distribution of these coefficients.

Our Monte Carlo method relies on 2000 random draws of both the resilience matrix and the CES parameters. In each random draw, different values of the resilience matrix and CES parameters are drawn for each firm. For each draw, we iterated the computation of the resilience index eighty-five times to browse the network of firms forming the supply chain, and then stopped. The stopping rule reveals to be largely sufficient to make the stress test reach a steady state for the four wind turbine manufacturers, as shown by Figure 8 (see Appendix A for the non-nested model, where fifty draws were enough to reach convergence). Figure 8 displays the dynamics of the average aggregate index of resilience across the different Monte Carlo simulations for each of the four wind turbine manufacturers. It highlights that, whatever the firm under consideration, the resilience index drops rapidly during the first iterations of the test, and then stabilises. The steady state seems to be almost reached after twenty iterations, but the index still changes marginally, up to seventy-five iterations. As a result, an upper bound of eighty-five iterations has been chosen to make sure that no changes occur for ten successive iterations. A similar pattern is observed with the non-nested model, except that convergence is reached earlier (see Appendix A). On average, the resilience aggregate index is close to 0.388 for *A*, 0.346 for *B*, 0.21 for *C* and 0.311 for *D*. The shock considered is thus rather drastic for the four firms, as they can keep at most a little bit more than one third of their initial capacity and one fifth at worst. Nevertheless, the figures obtained with the nested model and with sector filter 4 are significantly higher than those obtained with the non-nested model and reported in Appendix A: It seems that the non-nested model (with $\sigma = 0{,}1$) exacerbates the consequences of the shock. Of course, comparing the nested and the non-nested model is not obvious as their specification is different, and their number of parameters differs. However, it clearly appears that using sector filter 4 reduces the impact of the initial shock, whereas sector filter 1 maximises its impact (*Cf.* Appendix A).

Figure 8: Convergence of the stress test to a steady state with the nested model



6.2. Results at the aggregate level for the nested model, upstream the supply chain

The magnitude of the stress impact on wind turbine manufacturers depends on the transmission of the stress shock in the upstream layers of the value chain. Figure 9 displays the distribution of the resilience index within each layer in the “violin” form for each layer in abscissa, with the width of the violin indicating the density of the value of the index reported in ordinate. Figure 9 highlights that, whatever the upstream layer considered, the distribution of the resilience index is much more asymmetric compared to its distribution for the four wind turbine manufacturers in layer 0. To draw Figure 9, 2000 random draws of the resilience parameter of all firms have been generated. Then, results for firms within a same layer have been selected to produce Figure 9. This Figure captures both the heterogeneity across firms within each layer and the uncertainty surrounding the parameter values. However, it does not distinguish *intra*-firm variance and *inter*-firm variance of the resilience index. Results show that almost all firms in the upstream layers remain unaffected by the initial shock. By contrast, a few of them are highly impacted and, to a similar magnitude, compared to the four firms gathered in layer 0. Such a high asymmetry in the distribution of the resilience index for the upstream firms is consistent with the high diversity of firms in these layers. Moreover, as already outlined, a significant number of firms involved in the supply chain are conglomerates. These companies are in fact involved in many other supply chains that do not necessarily rely on processed critical raw materials, whereas the four firms in layer 0 are pure players in the wind turbine industry.

Figure 9: Distribution chart of the resilience index in upstream layers

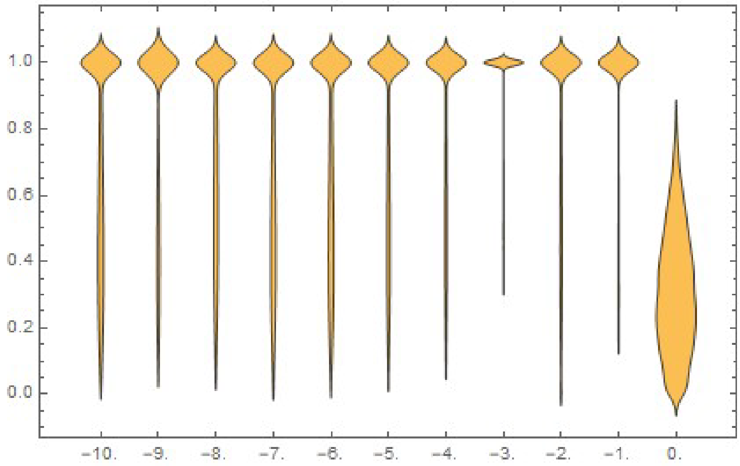
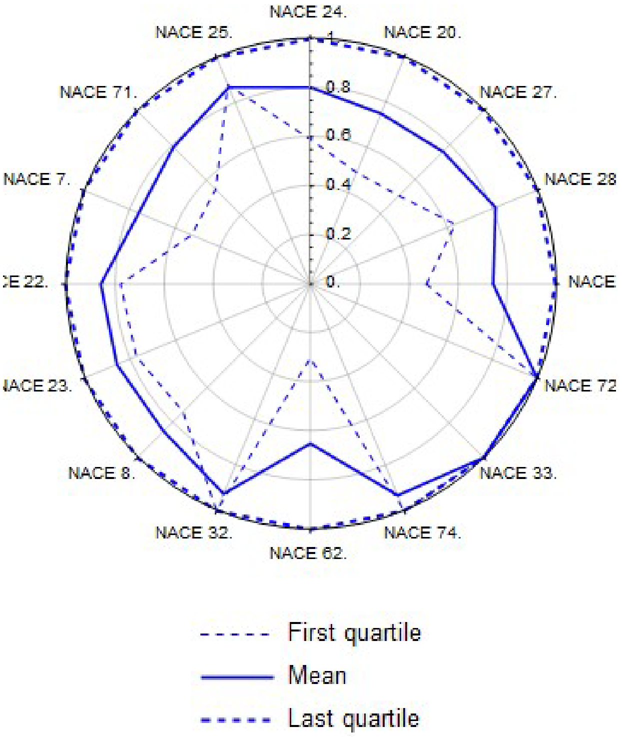


Table 6: Upstream NACE sectors ranked in increasing number of firms

NACE 24	Manufacture of basic metals
NACE 20	Manufacture of chemicals and chemical products
NACE 27	Manufacture of electrical equipment
NACE 28	Manufacture of machinery and equipment n.e.c.
NACE 26	Manufacture of computer, electronic and optical products
NACE 72	Scientific research and development
NACE 33	Repair and installation of machinery and equipment
NACE 74	Other professional, scientific and technical activities
NACE 62	Computer programming, consultancy and related activities
NACE 32	Other manufacturing
NACE 8	Other mining and quarrying
NACE 23	Manufacture of other non-metallic mineral products
NACE 22	Manufacture of rubber and plastic products
NACE 7	Mining of metal ores
NACE 71	Architectural and engineering activities; technical testing and analysis
NACE 25	Manufacture of fabricated metal products, except machinery and equipment
NACE 71	Architectural and engineering activities; technical testing and analysis
NACE 25	Manufacture of fabricated metal products, except machinery and equipment

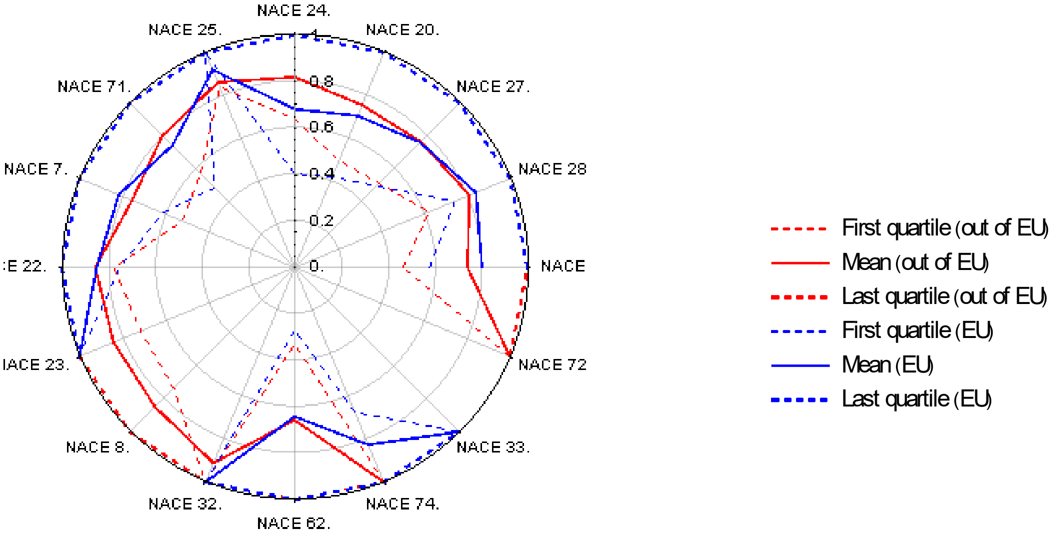
Figure 10: Comparison between NACE sectors in the upstream layers



Results are more contrasted when gathering upstream firms according to their main NACE sector of activity rather than their layer (Figure 10). The detailed labels of NACE sectors are reported in Table 6. The continuous line (in blue) in the radar graph (10) indicates the average resilience index obtained for all firms within the sector and all random draws of the Monte Carlo simulations. The two thin dashed lines indicate the first and last quartiles. Like in Figure 9, the underlying distribution of the resilience index in Figure 10 captures both firms' heterogeneity within a NACE sector and uncertainty surrounding the values of the different parameters. The NACE 72 sector “Scientific research and development” and NACE 33 sector “Repair and installation of machinery and equipment” have none of their firms affected by the initial shock on processed critical earth materials. At the opposite, the NACE 62 “Computer programming, consultancy and related activities” sector is the most affected one, with an average index of resilience below 0.7 and a first quartile below 0.4, meaning that a quarter of the firms in this sector have a resilience index below 0.4. Other sectors exhibit an average index of resilience close to 0.8 but still differ in terms of the dispersion of the index with some having a relatively large gap between their first and last quartiles (NACE 7 “Mining of metal ores”; NACE 20 “Manufacture of chemicals and chemical products” and NACE 27 “Manufacture of electrical equipment”) and other having a narrow gap between these quartiles (NACE 32 “Other manufacturing”; NACE 22 “Manufacture of rubber and plastic products” and NACE 23 “Manufacture of other non-metallic mineral products”).

Figures 11 complements Figures 10 by comparing EU versus non-EU firms from NACE sectors in the upstream layers. It shows that for those sectors in which the EU has upstream firms, the resilience of these firms does not strongly depart from that of non-EU firms.

Figure 11: Comparison between EU versus non EU firms from NACE sectors in the upstream layers

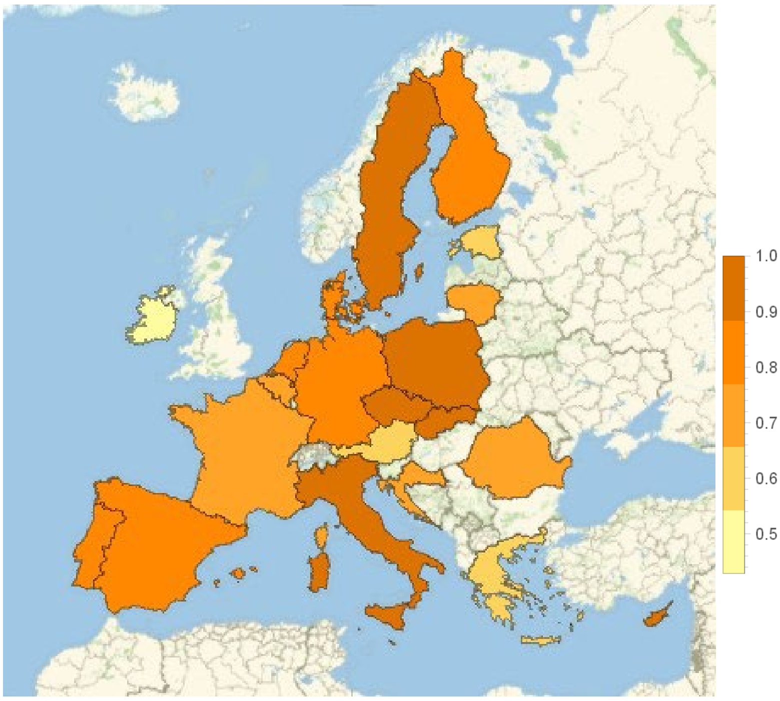


At this stage, it is worth recalling that EU countries generally differ in terms of sectoral specialization, but also in terms of sourcing of inputs for a same sector. As a result, it is expected that countries are differently impacted by a same initial shock upstream a supply chain. Figure 12 illustrates this differentiated impact with a focus on the specific case of EU member states. It reveals that the least resilient EU member state is Ireland with a resilience index close to 0.5, and to lesser extent Austria, Greece and Estonia, whereas countries like the Czech Republic, Hungary, Italy, Poland and Sweden are the most resilient ones with a resilience index above 0.9. Countries known for their large development of wind power, both in terms of cumulated capacity of commissioned wind farms and installed base of domestic wind turbine manufacturers, namely Germany, Denmark and Spain, are in a medium position with an average index of resilience between 0.8 and 0.9. Looking ahead, this means that from a policy point of view, a uniform de-risking strategy at the EU level could be beneficial for some EU countries but detrimental for others.

Figure 13 complements Figure 12 by positioning four EU member states with significantly different average resilience index, namely Germany (DE), Denmark (DK), Poland (PL) and

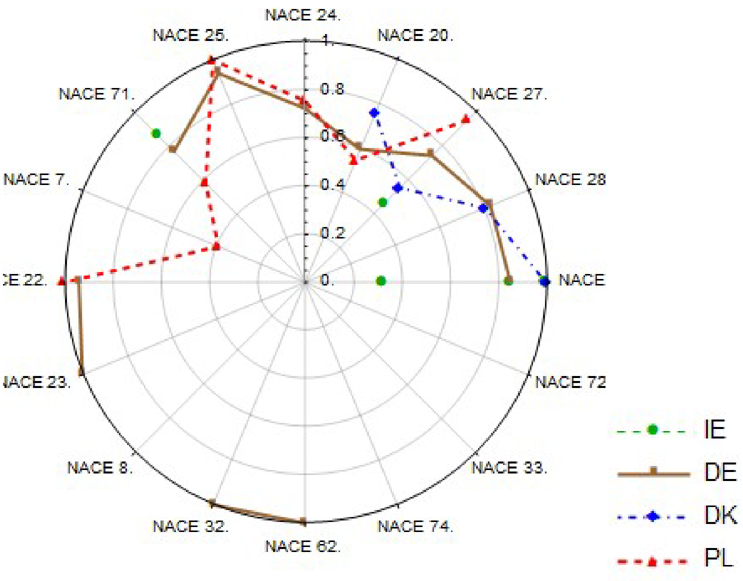
Ireland (IE), in terms of their average resilience index disaggregated at the sectoral level. Relatively smaller countries like Ireland and Denmark have firms in a smaller set of sectors and thus, more heavily depend on the resilience of these few sectors. It is also likely that within these few sectors, results for smaller countries depend on fewer firms. Consistently with that remark, Ireland has firms in only three sectors upstream and exhibits a low average index of resilience in two of these sectors, compared to the three other countries. Nevertheless, in the third sector (NACE 71 "Architectural and engineering activities; technical testing and analysis"), Ireland outperforms Germany and Poland, probably because, even if it only has few firms in that sector, these firms are particularly resilient compared to those of Germany and Poland. Interestingly, Figure 13 shows that Poland is the only member state, among the four considered, that has firms in the NACE sector 7 "Mining of metal ores". However, Polish companies in that sector have a low average resilience index.

Figure 12: Average index of resilience of their upstream firms for EU Member States



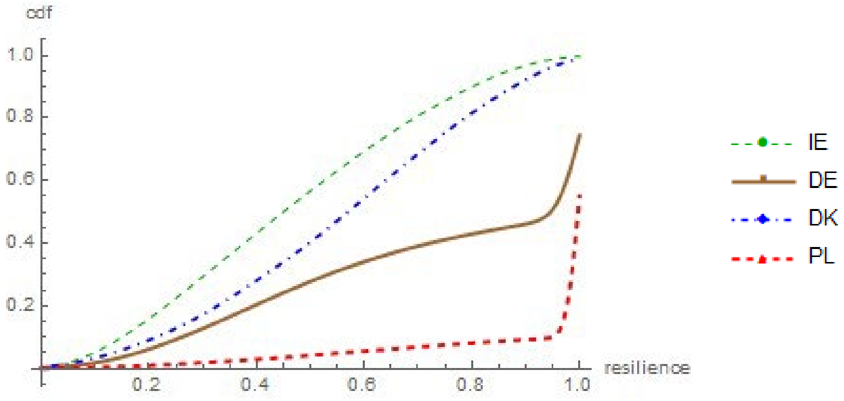
(those not coloured have no firms upstream the supply chain)

Figure 13: Comparison between NACE sectors and EU Member States



Our stress test allows us to provide a more in-depth explanation of heterogeneity across countries within a same sector. An illustrative example is given by Figure 14 in the case of the NACE 27 sector "Manufacture of electrical equipment". Figure 14 displays the cumulative density function of the resilience index for upstream firms in the NACE 27 sector and located in each of the four countries also analyzed in Figure 13. Our results show that only 5% of Polish firms have a resilience index less than approximately 0.5, whereas this index is about 55% in Ireland and 40% in Denmark. Overall, our results show a strict dominance of Ireland (the least resilient Member State) compared to other MS.

Figure 14: Comparison within NACE 27 sector and EU Member States



(Cumulative Density Functions of the resilience index of firms)

6.3. Results at the firm level for wind turbine manufacturers

So far, results from the stress test have been presented at a more-or-less granular level, from the layer level to the inter-sectoral and national level, and then the intra-sectoral and national level. Our stress test is also able to generate heterogeneous results at the firm level, even when comparing firms within a same sector and/or a same country. Thereafter, we illustrate this capacity by focusing on the comparison between the four wind turbine manufacturers, the supply chain of which we have retrieved. For that purpose, we first display in Figure 15 the partial density functions and the cumulative density functions of the index of resilience of the four wind turbine manufacturers. The partial density functions reveal that the distribution of the aggregate resilience is unimodal with a higher mode for *A* compared to *B*, which in turn has a higher mode, compared to *D*. The company *C* is the one exhibiting the lowest mode. This ranking corresponds to an overall switch of the distribution to the left when the mode decreases. This is confirmed by the comparison between the cumulative density functions with a striking dominance of the distributions from *D* to *A*. Our stress test thus shows that *A* is the wind turbine manufacturer that is the most resilient to a shock on Chinese rare earth extraction and processing, followed by *B*, then *D*. The company *C* appears to be significantly less resilient to such a shock. Again, this ranking is robust to a switch to the non-nested model and whatever the choice of the filter to retrieve the supply chain (See Appendix B). This is an interesting result as we showed earlier that Germany fared better than Denmark in NACE 27. However, this ordering in terms of nationality does not hold when we consider the results for the four wind turbine manufacturers.[76] It turns out that the firm-level perspective suggests a different picture than the aggregated one.

---

[76] Further details on the relation between the two orderings are omitted in order to preserve anonymity.

Figure 15: Comparison of the distribution of the aggregate index of resilience at the final iteration of the stress test for the four wind turbine manufacturers

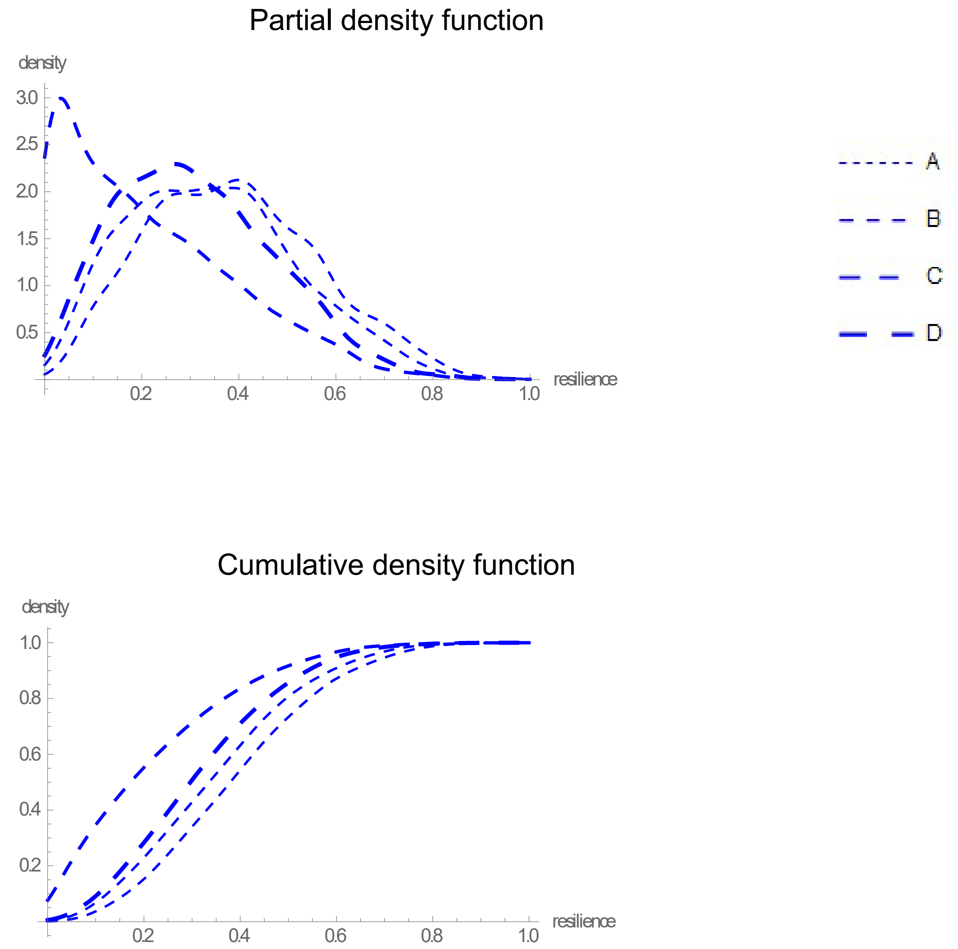
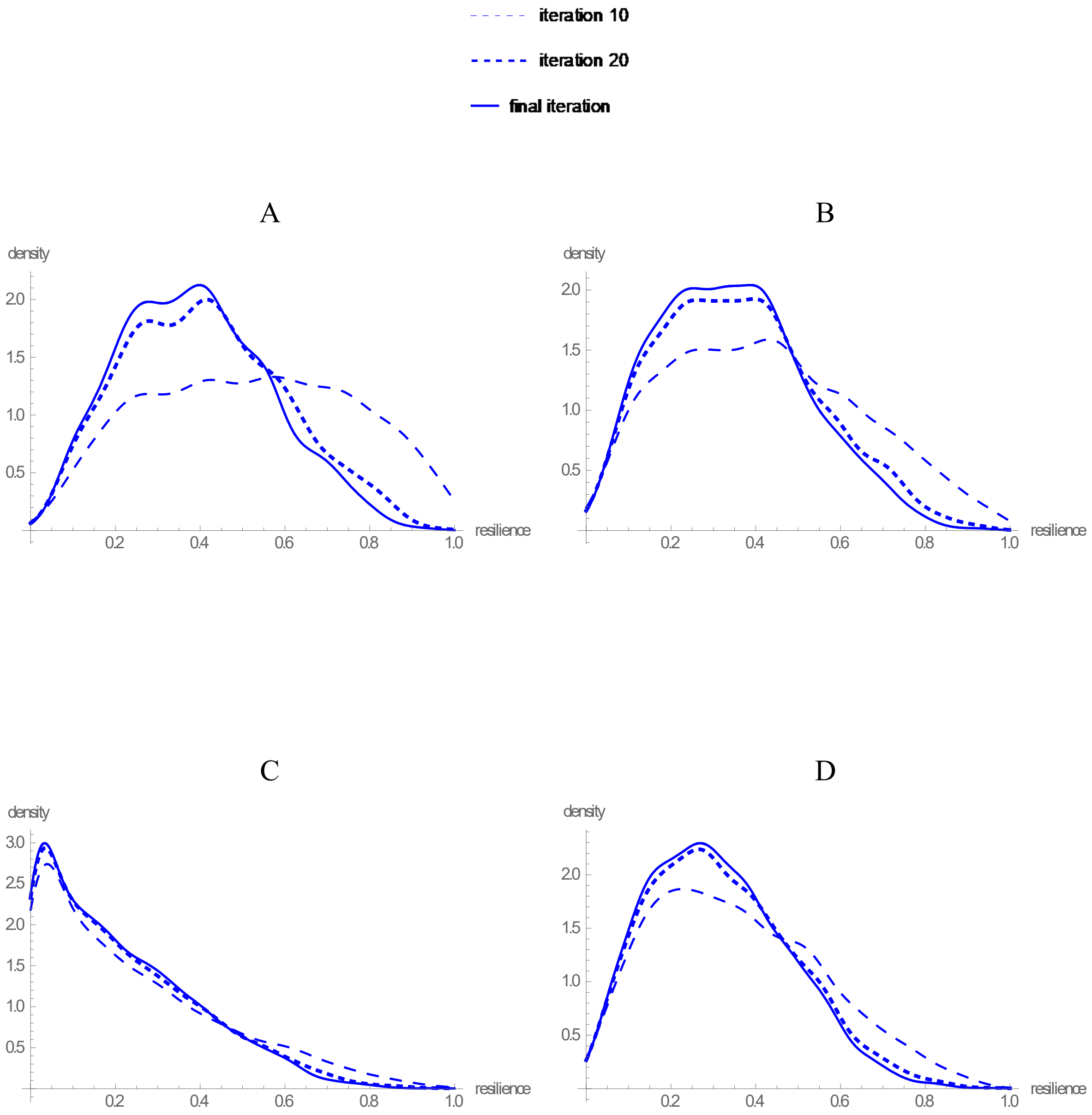


Figure 16: Distribution of the aggregate index of resilience at different iterations of the stress test



As the parameters used for the four firms are drawn from the same distributions to process the Monte Carlo simulations, the difference in the shape of the partial and cumulative density functions can only been explained by differences in the networks of suppliers. This is confirmed by Figure 16 where the shape of the partial density of the resilience index for *C* does not vary much from iteration 10 of the stress test onwards, suggesting that key suppliers of that firm are affected by the shock and "contaminate" *C* as soon as the tenth iteration. By contrast, *A* and *B*, and to a lesser extent *D*, have the partial density function of their resilience index still significantly displaced between the tenth and twentieth iteration, while being more concentrated on the right. These three firms are thus less affected by the shock and when affected, it is due to firms that are on some layers much more upstream. These observations are robust to a switch from the nested model to the non-nested model and, to whatever is the choice of the filter to retrieve the supply chain (see Appendix C).

7. Conclusive remarks

Issues of supply chain disruptions are bound to be with us for a while. Beyond micro shocks, these disruptions can have detrimental macro-economic effects. This leads to question whether policymakers should intervene, and whether they should be instrumental in ensuring supply chain resiliency. However, at this stage little is known in the economic literature about what resilience means at a country or global level. The same holds for the desirability of having public policies to promote resilience. That is why it is important to deepen our analysis of critical supply chains by applying stress tests and assessing their level of riskiness.

This article has tried to address this issue and thus to fill a gap in the literature by developing a supply chain stress test for critical inputs. To develop this proof-of-concept exercise, we have used firm-level data to document firms' input sourcing decisions and their location (upstream/downstream) in the supply chain.

Our findings show that supply chain stress tests can help identifying relatively weaker firms or more exposed sectors/countries. Our results show that the lack of critical inputs (downstream shock) can translate onto an upstream shock for suppliers of complementary inputs. At a more detailed level, our results also show that the specificities of each firm network of suppliers-customers are a strong determinant of their resilience. In terms of policy recommendations, our results stress the importance to go beyond country/regional aggregation and monitor trade between firms. Indeed, microstructures of industrial eco-systems, (i.e. the position of individual firms), on the overall production network, matter. It is thus important to track risks over time to ensure resilience and to promote awareness of the importance of the upper (lower) tiers to develop more effective shields against shock propagation.

In this respect, the idea of having supply chain monitoring tools seems to be gaining ground. The International Monetary Fund (IMF), for example, is now seeking to measure the economic impact of extreme weather events on shipping, and to assess how disasters affect trade and supply chains[77]. Together with stress tests, these types of instruments analyze how global

---

[77] See IMF and University of Oxford Launch "PortWatch" Platform to Monitor and Simulate Trade Disruptions

supply chains are exposed to present and future disruptions. These new tools, still experimental, offer cutting edge analytical tools to produce actionable insights for policymakers, but also private actors to respond to disruptions quickly and more efficiently, so as ultimately to increase resiliency. Considering the diversification and magnification of shocks, the development of such tools should be further encouraged, as they can underpin the design of better-informed policies.

That being said, stress tests should not be considered as a “regulatory talisman” and are best used in combination with other tools, as they are sensitive to methodological choices. Validity of the results is indeed affected by several factors, such as data granularity and quality, severity or scope of the different scenarios studied and model risks. Results are also conditional on assumptions in the methodology, notably with regards to the stopping rules. These limits are not specific to our study. In the banking sector, where stress tests are well established, some scholars, like Tarullo (2020), argue that regulators seem to have forsaken the original purpose of stress tests namely, to ensure the resiliency of the banking system, and that they tend to shift towards little more than a predictable compliance exercise. Others, like Shahhosseini (2014)[78], consider that stress tests have negative unintended consequences and should therefore be complemented by other instruments.

To avoid the above-mentioned pitfalls, future research should focus on the nature of the shocks. One of the issues is how do we think the unthinkable, and having done so, how to act on it? Following the input from Simchi-Levi & Simchi-Levi (2020), further research could also try to quantify under different scenarios “the time to recover”, i.e., the time it would make for a particular node in a supply chain to be restored to full functionality after a shock. In the same way, it could be interesting to analyse the “time to survive”, i.e., the maximum duration that a supply chain can match supply with demand after a shock[79]. More generally, data availability limits the applicability of the obtained results. *Firs*t, in presenting our results, we are mindful that our analysis has some limitations, as we treat on equal feet all suppliers within a same sector (we have relations of type 0-1), which is obviously not the case. In a complementary work, we aim at adding data on shares of revenues to put weight on relationships. In the same vein, having a resilience matrix based, at least partially, on expert knowledge could improve the representativeness of the exercise. However, obtaining such expert knowledge may be

---

[78] According to Shahhosseini (2014), “There is a negative causal impact of capital adequacy requirements on managerial decisions in the U.S. banking system. Stress-tested banks reduce net loan charge-offs and keep problematic loans on their books to a greater extent than banks in a non-tested group to meet the capital ratio requirements. Managers increase the level of non-performing loans in the aftermath of stress tests announcement. Stress-tested banks with greater exposure to the housing market change the classification of loan losses to a greater extent than other banks”.

[79] The underlying idea is that if the “time to recover” is greater than the “time to survive”, the supply chain will not be able to match supply with demand.

challenging and not necessarily easily replicable across sectors. *Second*, at this stage we did not consider competition between companies that would result in a dynamic restructuring of the network at stake. Future work aims therefore at creating/deleting/replacing a link to see how it modifies resilience. The underlying idea is to examine to what extent a supply chain could be made more resilient by not making it less efficient, and more precisely how proactively mitigate risks rather than react to disruptions after the fact. *Lastly*, data could be complemented by patent data to control for technological dependencies and/or potential technological disruptions that could substitute to a critical input. In considering future research directions, we are cognisant of this, and our future research will focus on incorporating and analysing these further elements.

References

- Acemoglu, D. & V.M. Carvalho, A. Ozdaglar & A. Tahbaz-Salehi, (2012). The network origins of aggregate fluctuations. *Econometrica*, 80/5, pp. 1977-2016.
- Acemoglu, D.; Akcigit, U. & W. Kerr. (2016). Networks and the macroeconomy: An empirical exploration, *NBER Working Paper N°21344*. Available at Networks and the Macroeconomy: An Empirical Exploration (nber.org)
- Adenso-Diaz, B.; J. Mar-Ortiz & S. Lozano. (2018). Assessing supply chain robustness to link failure. *International Journal of Production Research*, 56/15, pp. 5104-5117.
- Amiti, M. & J. Konings. (2007). Trade liberalization, intermediate inputs, and productivity: Evidence from Indonesia. *American Economic Review*, 97(5), pp. 1611-38.
- Bacilieri, A., A. Borsos, P. Astudillo-Estevez & F. Lafond. (2023). Firm-level production networks: What do we (really) know?, *INET Oxford Working Paper* N° 2023-08. Available at No. 2023-08 - Firm-level production networks: what do we (really)… (ox.ac.uk)
- Bailey, D. & L. De Propis. (2014). Manufacturing reshoring and its limit: The UK automotive case. *Cambridge Journal of Regions, Economy and Society*, 7(3), pp. 379-395.
- Baldwin, R. & R. Freeman. (2022). Risks and global supply chains: What we know and what we need to know. *Annual Review of Economics*, 14, pp. 153-80.
- Barrot, J-N. & J. Sauvagnat. (2016). Input specificity and the propagation of idiosyncratic shocks in production networks, *Quarterly Journal of Economics*, Vol. 131/3, pp. 1541-1592, 2016.
- Boehm, C., A. Flaaen & N. Pandalai-Nayar. (2014). Input Linkages and the transmission of shocks: Firm level evidence from the 2011 Tohoku earthquake, *Review of Economics & Statistics*, Vol. 101/1, pp. 60-75.
- Bonneau, Ch. & M. Nakaa. (2020). Vulnérabilité des approvisionnements français et européens, *Trésor-ECO*, N°274, 2020. Available at https://www.tresor.economie.gouv.fr/Articles/2020/12/17/vulnerabilite-des-approvisionnements-francais-et-europeens
- Bruegel. (2022). Europe’s promised semiconductor subsidies need to be better targeted. *Blog post*. 17.10.2022. Available at https://www.bruegel.org/blog-post/europes-promised-semiconductor-subsidies-need-be-better-targeted
- Bundesverband WindEnergie (BWE). (2023). Praxisvorschläge zum Umgang mit Fledermäusen bei Windenergievorhaben. *Positionspapier*. Available at https://www.wind-energie.de/fileadmin/redaktion/dokumente/publikationen-oeffentlich/themen/01-mensch-und-umwelt/03-naturschutz/20230607_BWE_Positionspapier_Fledermausschutz.pdf
- Campbell, J.Y. & L. Viceira. (2005). The term structure of the risk-return tradeoff. *Working Paper NBER* N°11119. Available at The Term Structure of the Risk: Return Trade-Off on JSTOR
- Carvalho, V.M. (2010), Aggregate fluctuations in the network structure of intersectoral trade, *Working Paper*. Available at download;jsessionid=0CFA6EB016BCC0F5430B7C184819C117 (psu.edu)
- Carvalho, V.M. & X. Gabaix. (2013). The great diversification and its undoing, *American Economic Review*, 103, pp. 1697-1727.
- Carvalho, V.M. & A. Tahbaz-Salehi. (2019). Production networks: a primer. *Annual Review of Economics*, 11, pp. 635-63.
- Carbon Brief Analysis. (2022). Record-low price for UK offshore wind is nine times cheaper than gas. July 8, 2022. Available at https://www.carbonbrief.org/analysis-record-low-price-for-uk-offshore-wind-is-four-times-cheaper-than-gas/
- Costinot, A., J. Vogel & S. Wang, (2013). An elementary theory of global supply chain. *Review of Economic Studies*, 80/1, pp. 109-142.

- D'Aguanno, L., O. Davies, A. Dogan, R. Freeman, S. Lloyd, D. Reinhardt, R. Sajedi & R. Zymeck, (2021). Global value chains, olatility and safe openness: Is trade a double-edged sword?, *Bank of England Paper* N°46. Available at Global value chains, volatility and safe openness: is trade a double-edged sword? | Bank of England
- European Central Bank. (2023a). Global production and supply chain risks: Insights from a survey of leading companies. *ECB Economic Bulletin* N°7/23, Available at https://www.ecb.europa.eu/pub/economic-bulletin/focus/2023/html/ecb.ebbox202307_01~2a0bcf0b48.en.html
- European Central Bank. (2023b). Stress tests. Available at https://www.bankingsupervision.europa.eu/banking/tasks/stresstests/html/index.en.html
- European Commission. (2021). SCAN (Supply Chain alert Notification) monitoring system, DG GROWTH, *Single Market Economics Paper*, 21p., available at 'SCAN' (Supply Chain Alert Notification) monitoring system (europa.eu)
- European Commission. (2022). Detecting and analysing supply chain disruptions, DG GROWTH *Economic Paper Series*, Series 1, 24p., available at Detecting and Analysing Supply Chain Disruption - Single Market Economic Papers issue 1 (europa.eu)
- European Commission. (2023a). An enhanced methodology to monitor the EU's strategic dependencies and vulnerabilities,, Single Market Economy Papers. Working paper N° 2023/14. Available at An enhanced methodology to monitor the EU's strategic dependencies and vulnerabilities (europa.eu)
- European Commission, (2023b). Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions. European wind power action plan. Com (2023) 669 final.
- European Commission (2023c), An EU approach to enhance economic security. *Joint Communication*. Available at An EU approach to enhance economic security (europa.eu)
- Global Wind Energy Council (GWEC). (2022). Global wind report 2022. Available at https://gwec.net/global-wind-report-2022/
- Global Wind Energy Council (GWEC). (2023). Global wind report 2023. Available at GWR-2023_interactive.pdf (gwec.net)
- Grossman, G.M. & E. Rossi-Hansberg. (2008). Trading tasks: a simple theory of offshoring. *American Economic Review*, 98(5), pp. 1978-97.
- Grossman, G.M.; E. Helpman & H. Lhuillier. (2021). Supply chain resilience: Should policy promote diversification or reshoring? *NBER Working Paper* N° 29330.
- Global wind Energy Council (GWEC) (2022). Global Offshore Wind Report. Available at
- Halpern, L.; M. Koren & A. Szeidl. (2015). Imported inputs and productivity. *American Economic Review*. 105(12), pp. 3660-703.
- Heise, S. How Did China's COVID-19 Shutdown Affect U.S. Supply Chains?. (2020). Federal Reserve Bank of NY, 2020, available at https://libertystreeteconomics.newyorkfed.org/2020/05/how-did-chinas-covid-19-shutdown-affect-us-supply-chains/
- Horvath, M. (1998). Cyclicality and sectoral linages: aggregate fluctuations from independent sectoral shocks, *Review of Economic Dynamics*, 1, pp. 781-808.
- International Energy Agency (IEA). (2023). Monthly gas statistics. Available at https://www.iea.org/data-and-statistics/data-product/monthly-gas-statistics and https://www.iea.org/topics/russias-war-on-ukraine
- International Energy Agency (IEA). (2023). Critical minerals market review 2023. Report. Available at Critical Minerals Market Review 2023 – Analysis - IEA
- International Energy Agency (IEA). (2022). World energy outlook 2022. Available at https://www.iea.org/reports/world-energy-outlook-2022

- International Energy Agency (2020). World energy outlook 2020. Available at World Energy Outlook 2020 (windows.net)
- International Monetary Fund. (2023). Geoeconomic fragmentation and commodity markets. *IMF Working Paper*. October 3. Available at Geoeconomic Fragmentation and Commodity Markets (imf.org)
- International Monetary Fund. (2023). Geoeconomic fragmentation and the future of multilateralism. January 15. *Staff Discussion Note*/2023/001. Available at Geoeconomic Fragmentation and the Future of Multilateralism (imf.org)
- Jain, N., K. Girotra & N. Netessine. (2016). Recovery from supply interruptions: The role of sourcing strategies. *INSEAD Working Paper* N°2016/58/TOM.
- Johnson, R.C. 2018). Measuring global value chains, *Annual Review of Economics*, vol. 10, pp. 207-236.
- Jordaan, D. du P.S & J.F. Kirsten. (2019). Measuring the fragility of agribusiness value chains: a case study of the South African lamb chain. *International Food and Agribusiness Management Review*: 22 (1), pp. 137 - 154
- JRC. (2022). Wind energy in the European Union, Report, 205p. Available at Wind Energy in the European Union (europa.eu)
- Korniyeko, Y., M. Pinat & B. Dew. (2017). Assessing the fragility of global trade: The impact of localize supply shocks using network analysis, *IMF Working Paper* 17/30.
- Long, J.B. & Ch. I. Plosser. (1997). Real business cycles, *Journal of Political Economy*, 91, pp. 39-69.
- Lucas, R. E. (1977). Undertanding business cycles, *Carnegie-Rochester Conference Series on Public Policy*, 5, pp. 7-29. Available at Understanding business cycles - ScienceDirect
- Marshall, D.; P. Mcgrath & L. McCarthy. (2016). What's your strategy for supply chain disclosure? *MIT Sloan Management Review*.
- McKinsey. (2020). Why now is the time to stress-test your industrial supply chain, Article July 27, 2020. Available at Why now is the time to stress-test your industrial supply chain | McKinsey
- Meier, M. & E. Pinto. (2020). Covid 19 supply chain disruptions. *IDEAS Working Paper.* Available at dp239 (crctr224.de)
- Miroudot, S. (2020. Reshaping the policy debate on the implications of COVID 19 for global supply chains. *Journal of International Business Policy*, 3, pp. 430-442.
- OECD. (2023). Raw materials critical for the green transition: Production, International trade and export restrictions. *Working Paper* N°269, April. Available at OECD TRADE POLICY PAPER N°270 (oecd-ilibrary.org)
- OECD. (2021). Fostering economic resilience in a world of open and integrated markets: risks, vulnerabilities and areas for policy action. *Report* prepared for the 2021 UK presidency of the G7.
- OECD. (2020). Shocks, risks and global value chains: Insights from the OECD METRO model, June 29. Paris: OECD.
- OECD. (2023a). The structure of firm-level production networks and its lessons for industrial policy: Evidence from Estonia. *Unpublished Manuscript, DSTI/CIIE(2024)*.
- OECD. (2023b). The digital and green transitions across firm-level production networks: Evidence from Estonia, *Unpublished Manuscript, DSTI/CIIE(2024)*.
- Shahhosseini, M. (2014). The unintended consequences of bank stress tests. SSRN Paper. Available at https://papers.ssrn.com/sol3/papers.cfm?abstract_id=2951425
- Simchi-Levi D. & E. Simchi-Levi. (2020). We need a stress test for critical supply chains. *Harvard Business Review* April 28, 2020. Published on line: We Need a Stress Test for Critical Supply Chains (hbr.org)
- Tarullo, D.K., (2020). Are we seeing the demise of stress testing?, *Brookings Paper*, June 25. Available at https://www.brookings.edu/blog/up-front/2020/06/25/stress-testing/
- US Geological Survey. (2023. Mineral commodity summaries 2023. *Report*. Available at Mineral Commodity Summaries 2023 (usgs.gov)

- Wind Europe (2019), Wind energy is the cheapest source of electricity generation. Available at Economics | WindEurope
- Wind Europe (2022). Wind Europe position on non-price criteria in auctions. *Report* available at 20220413-WindEurope-Position-paper-non-price-criteria-in-auctions.pdf
- Wind Europe. (2023). Wind energy in Europe: 2022 statistics and the outlook for 2023-2027. Available at https://windeurope.org/intelligence-platform/product/wind-energy-in-europe-2022-statistics-and-the-outlook-for-2023-2027/
- Wiser, R.; J. Rand; J. Seel; Ph. Beiter; E. Baker; E. Lantz & P. Gilman. (2021). Expert elicitation survey predicts 37% to 49% declines in wind energy costs by 2050. *Nature Energy*, 6(5), pp. 555-65.
- World Bank. (2019). Global value chains: Trading for development. *World Development Report 2020*. Washington DC: World Bank.

Appendix A: convergence of the stress test with the non-nested model

Figure A1: Convergence of the stress test to a steady state with the non-nested model (Filter 1)

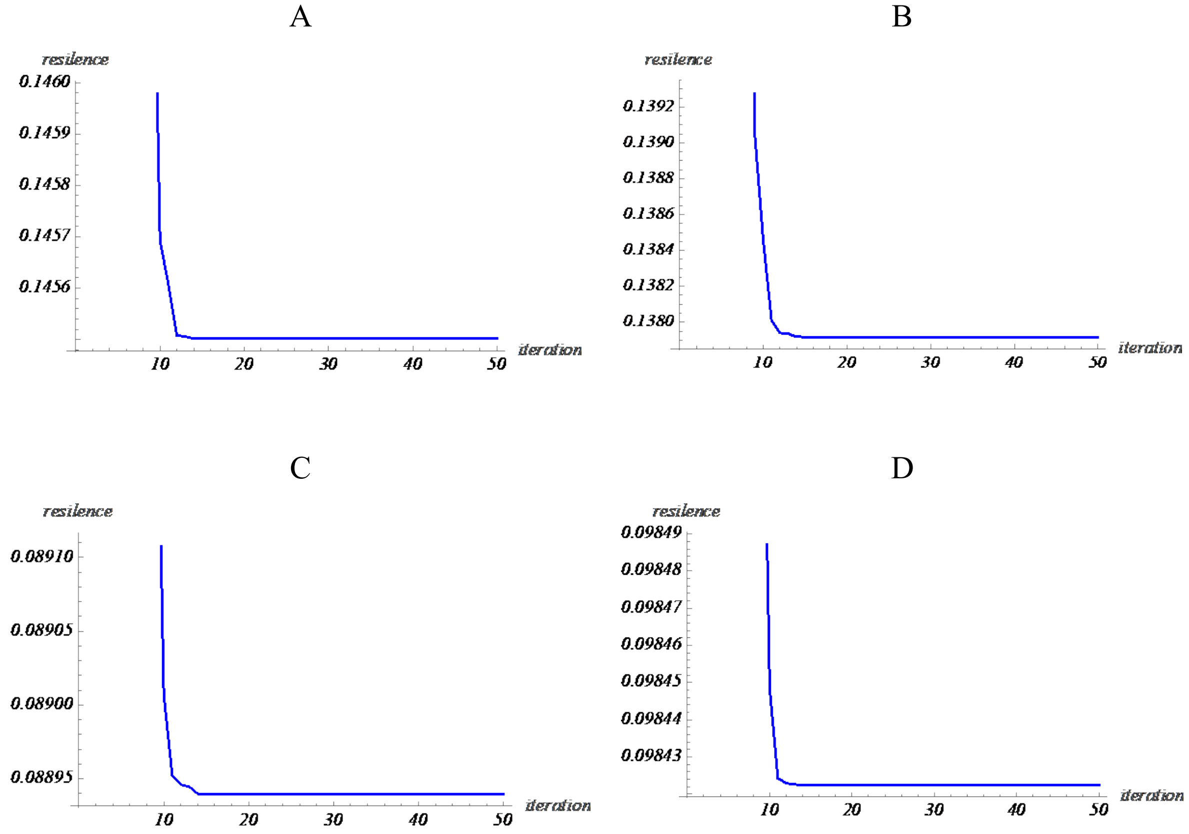


Figure A2: Convergence of the stress test to a steady state with the non-nested model (Filter 2)

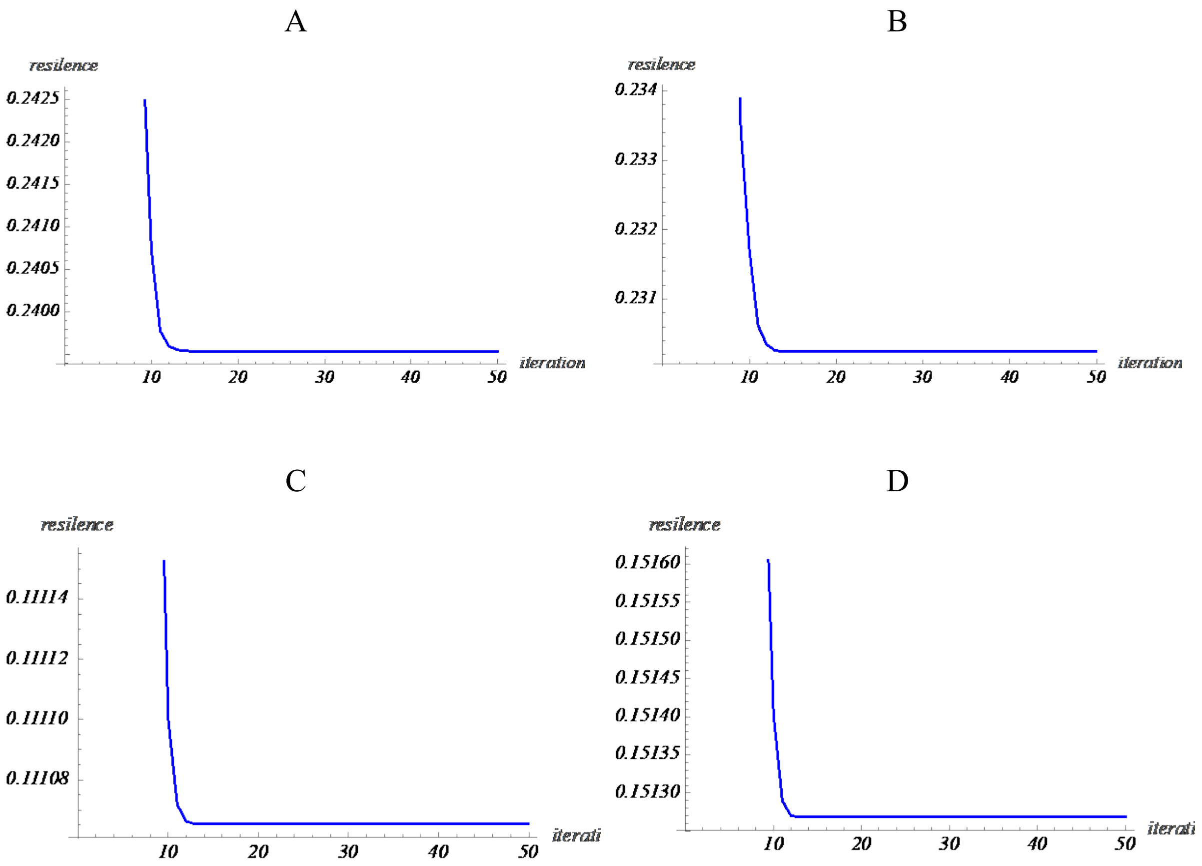


Figure A3: Convergence of the stress test to a steady state with the non-nested model (Filter 3)

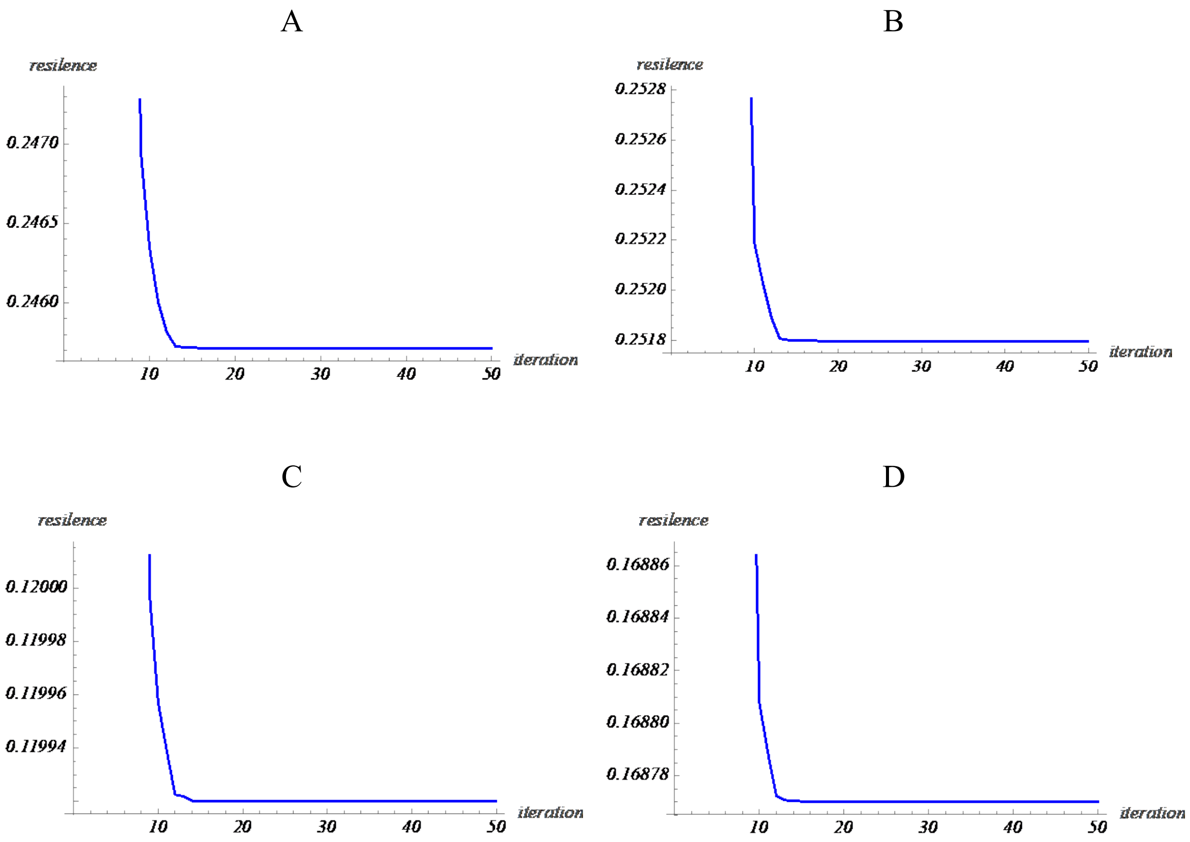
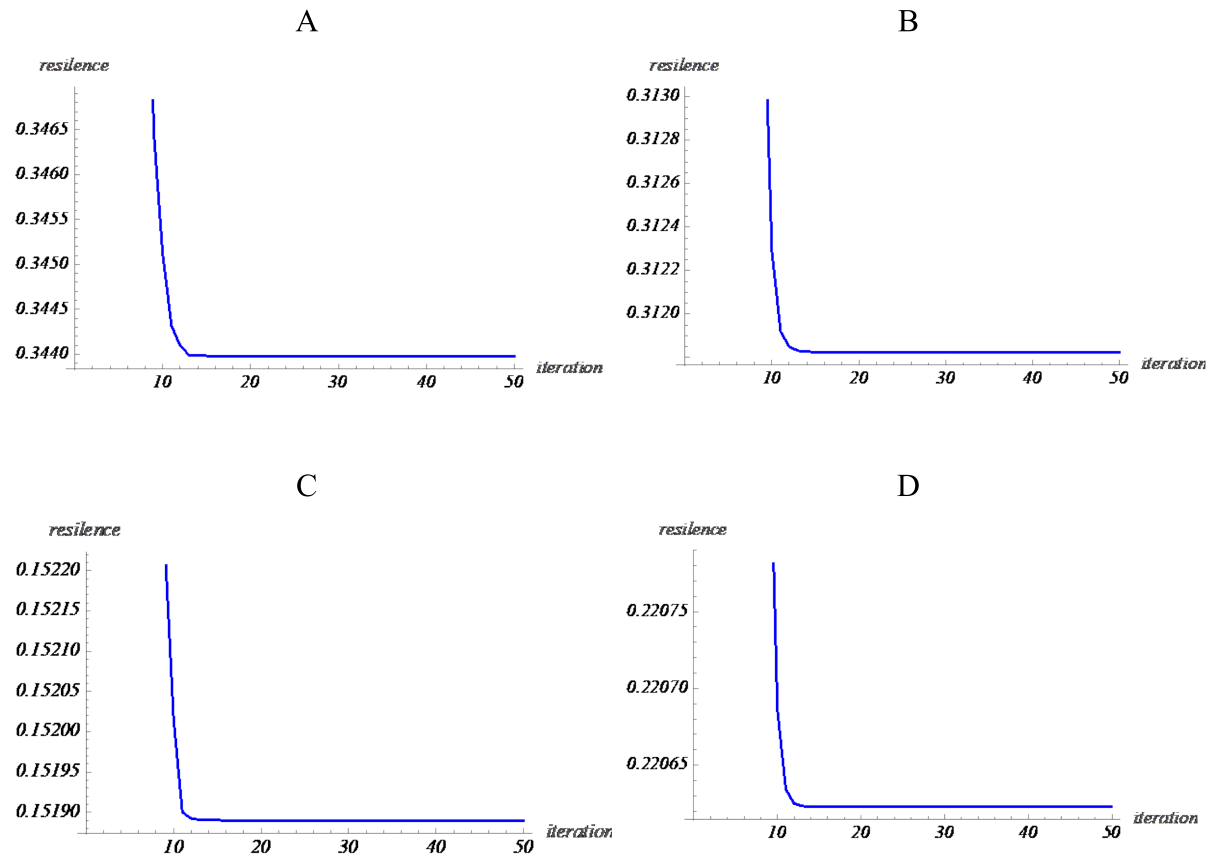
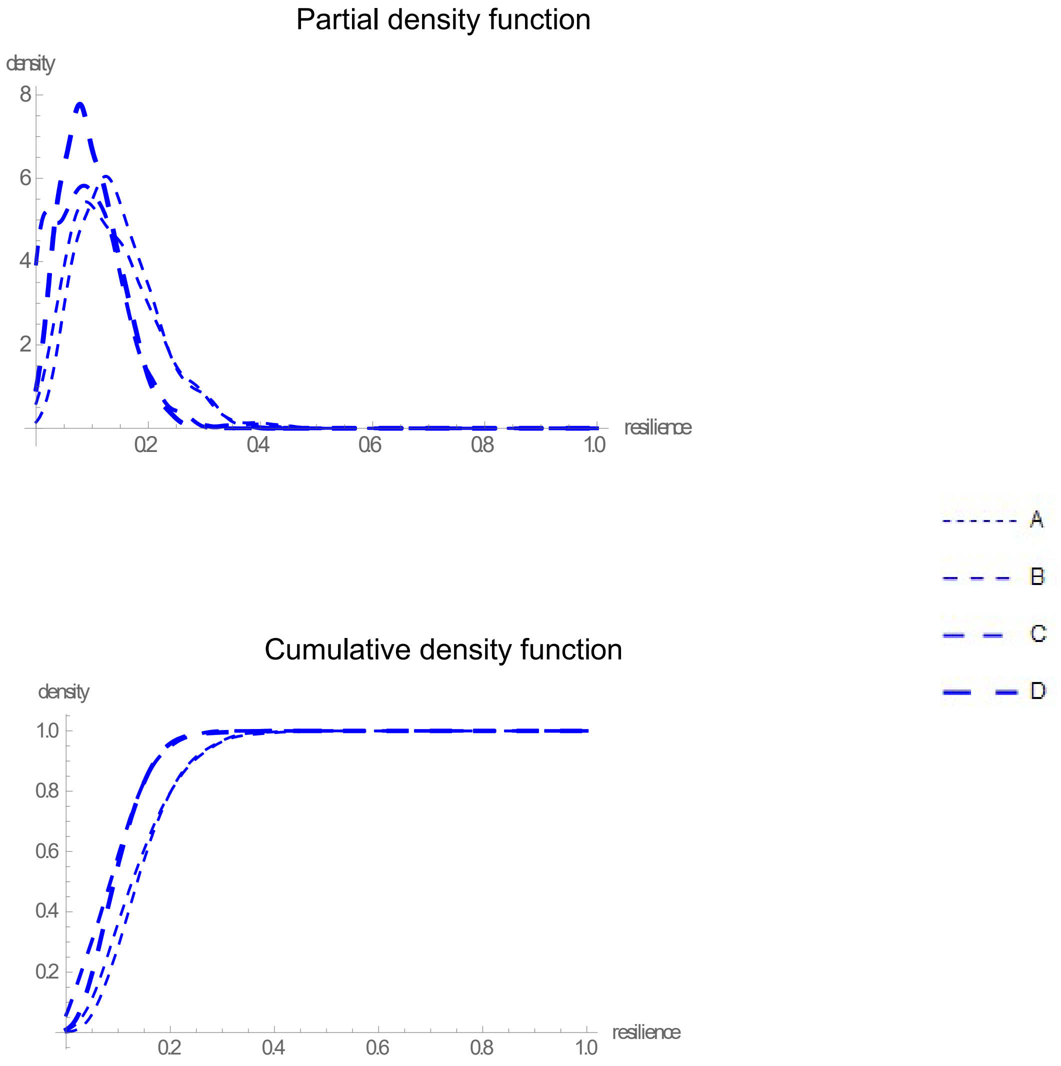


Figure A4: Convergence of the stress test to a steady state with the non-nested model (Filter 4)



Appendix B: comparison of the aggregate index of resilience with the non-nested model

Figure B1: Comparison of the distribution of the aggregate index of resilience at the final iteration of the stress test for the four wind turbine manufacturers (non-nested model, Filter 1)


Partial density function

Cumulative density function

Figure B2: Comparison of the distribution of the aggregate index of resilience at the final iteration of the stress test for the four wind turbine manufacturers (non-nested model, Filter 2)

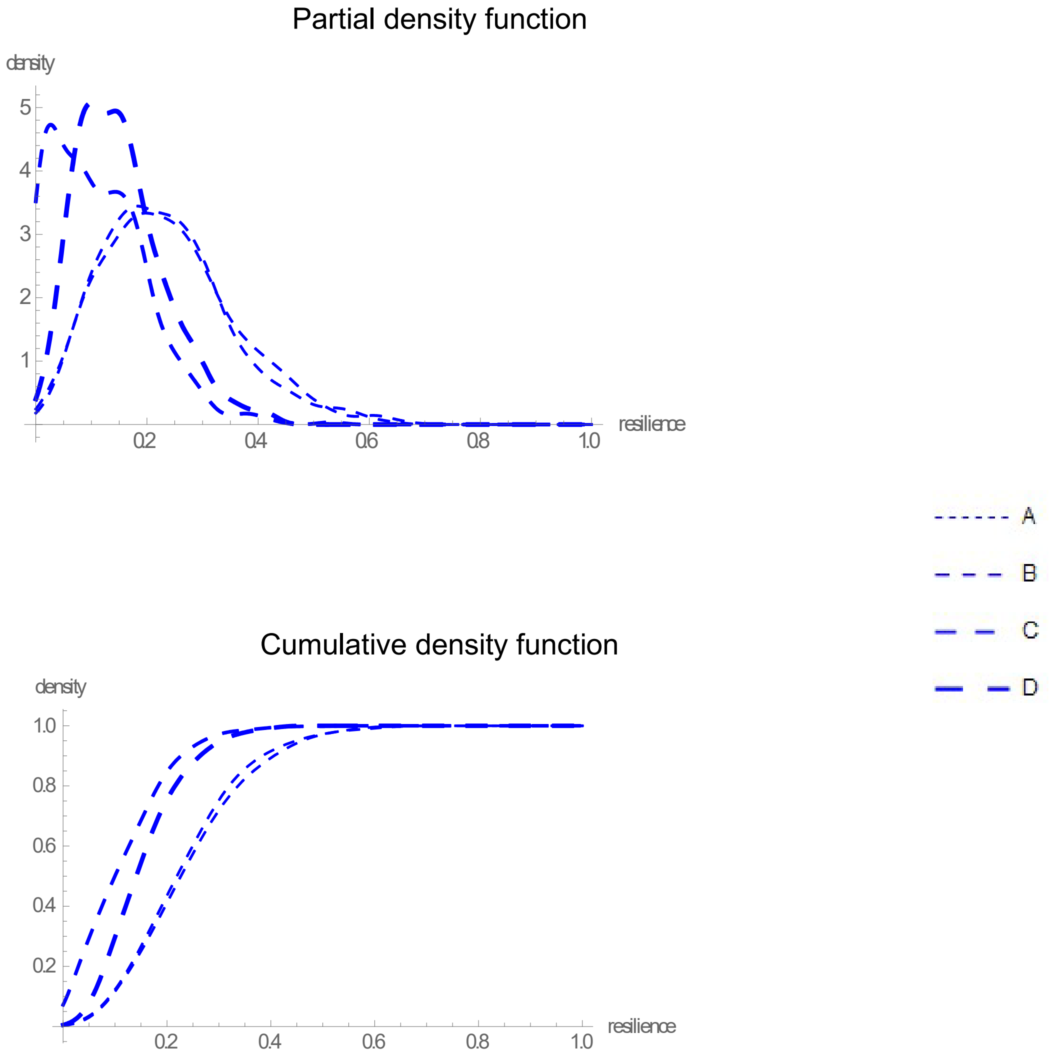
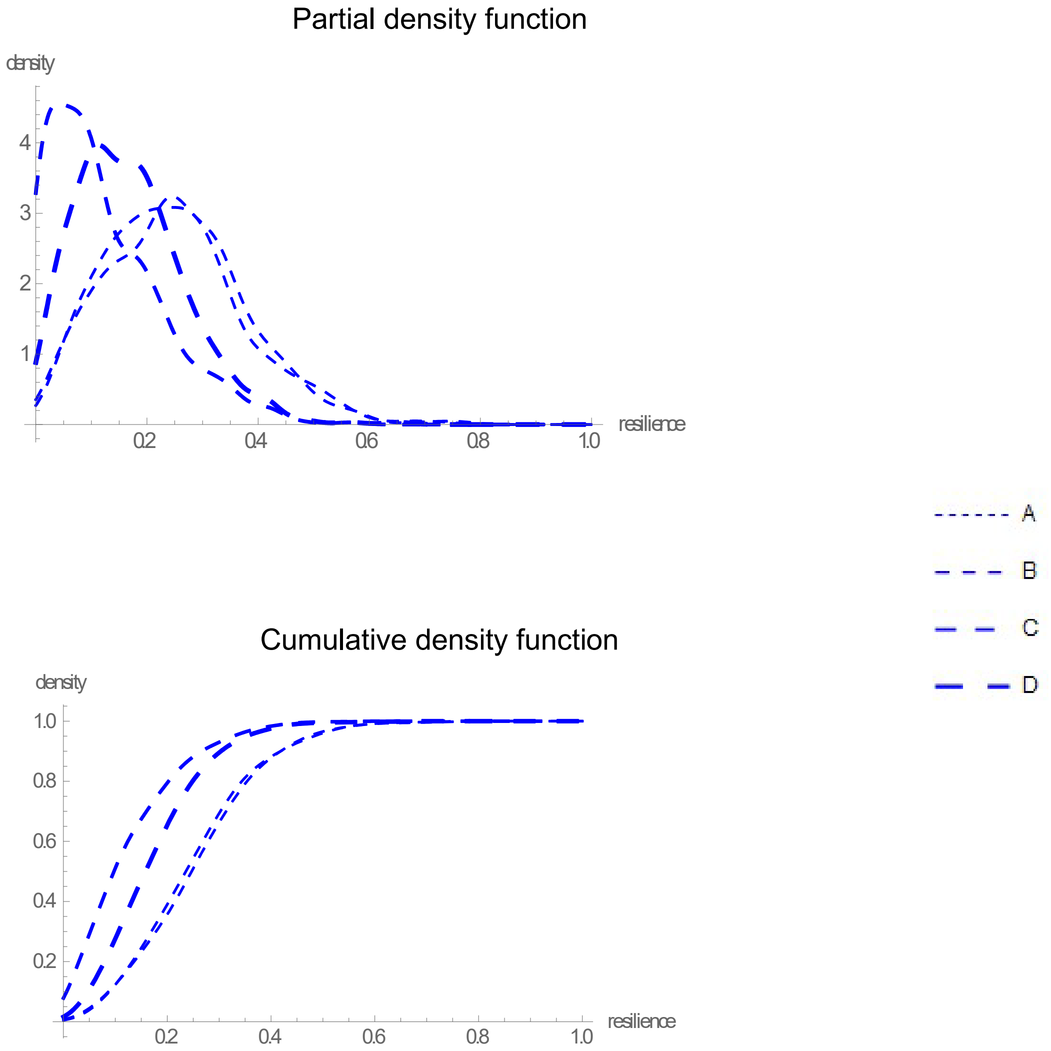


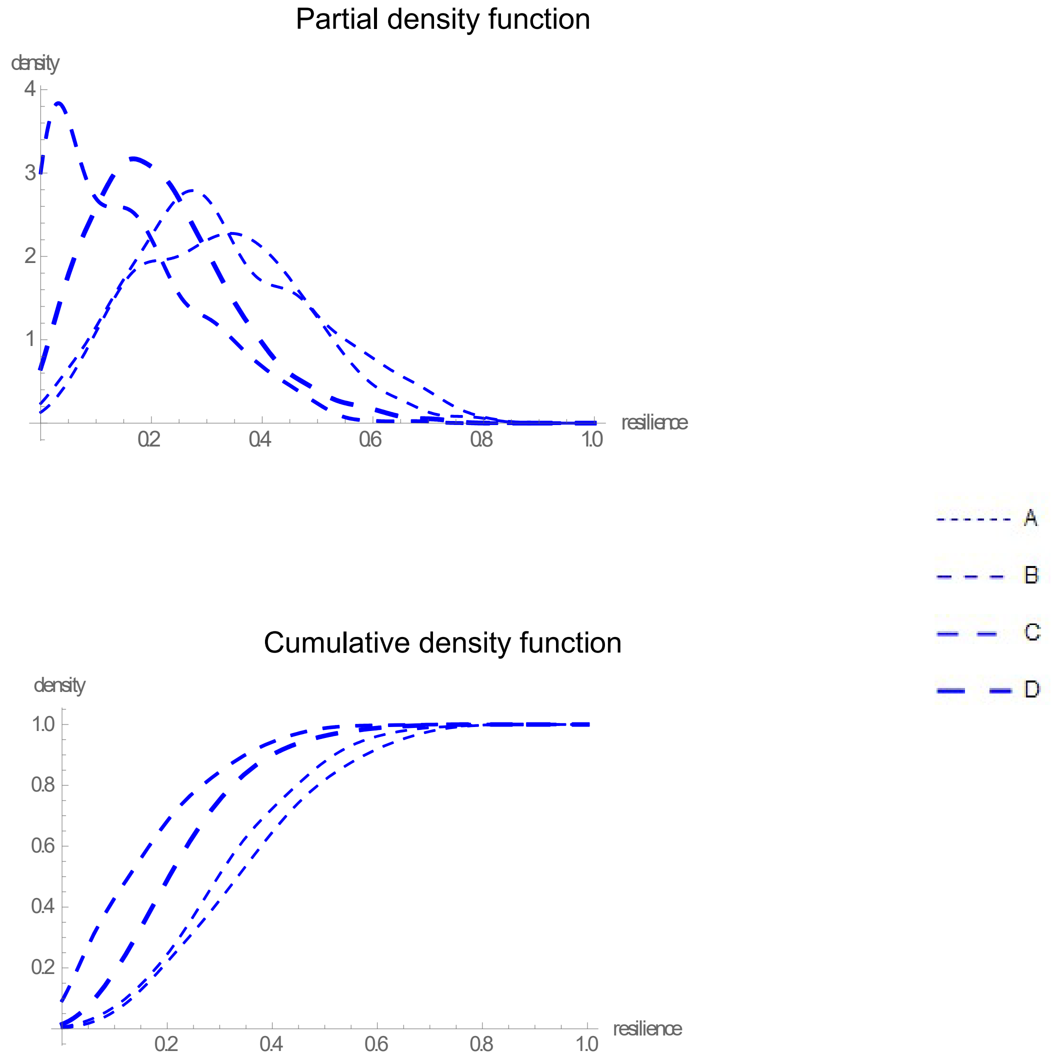
Figure B3: Comparison of the distribution of the aggregate index of resilience at the final iteration of the stress test for the four wind turbine manufacturers (non-nested model, Filter 3)



Partial density function

Cumulative density function

Figure B4: Comparison of the distribution of the aggregate index of resilience at the final iteration of the stress test for the four wind turbine manufacturers (non-nested model, Filter 4)



Partial density function

Cumulative density function

Appendix C: distribution of the aggregate index of resilience with the non-nested model

Figure C1: Distribution of the aggregate index of resilience at different iterations of the stress test (non-nested model, Filter 1)

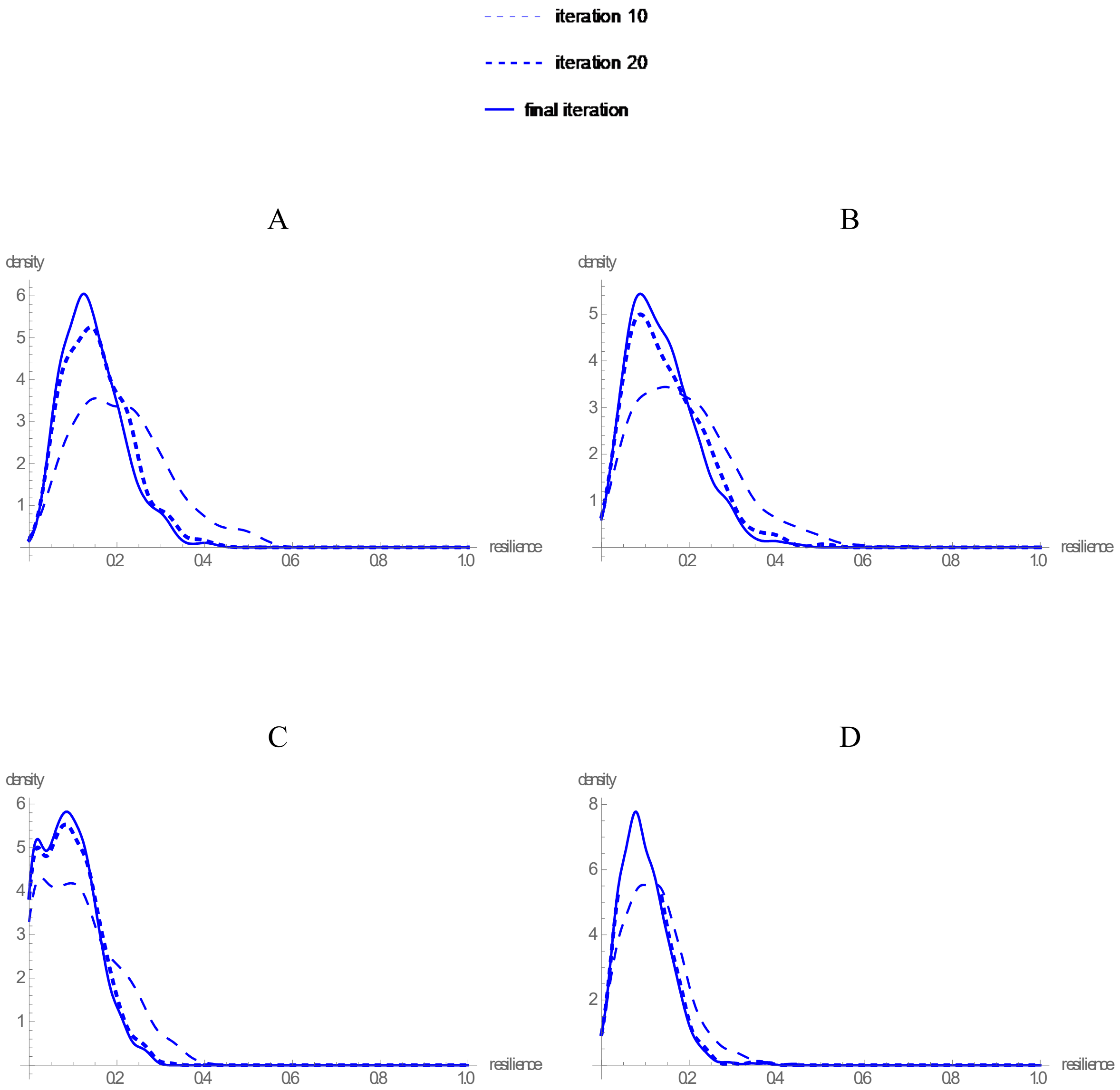


Figure C2: Distribution of the aggregate index of resilience at different iterations of the stress test (non-nested model, Filter 2)

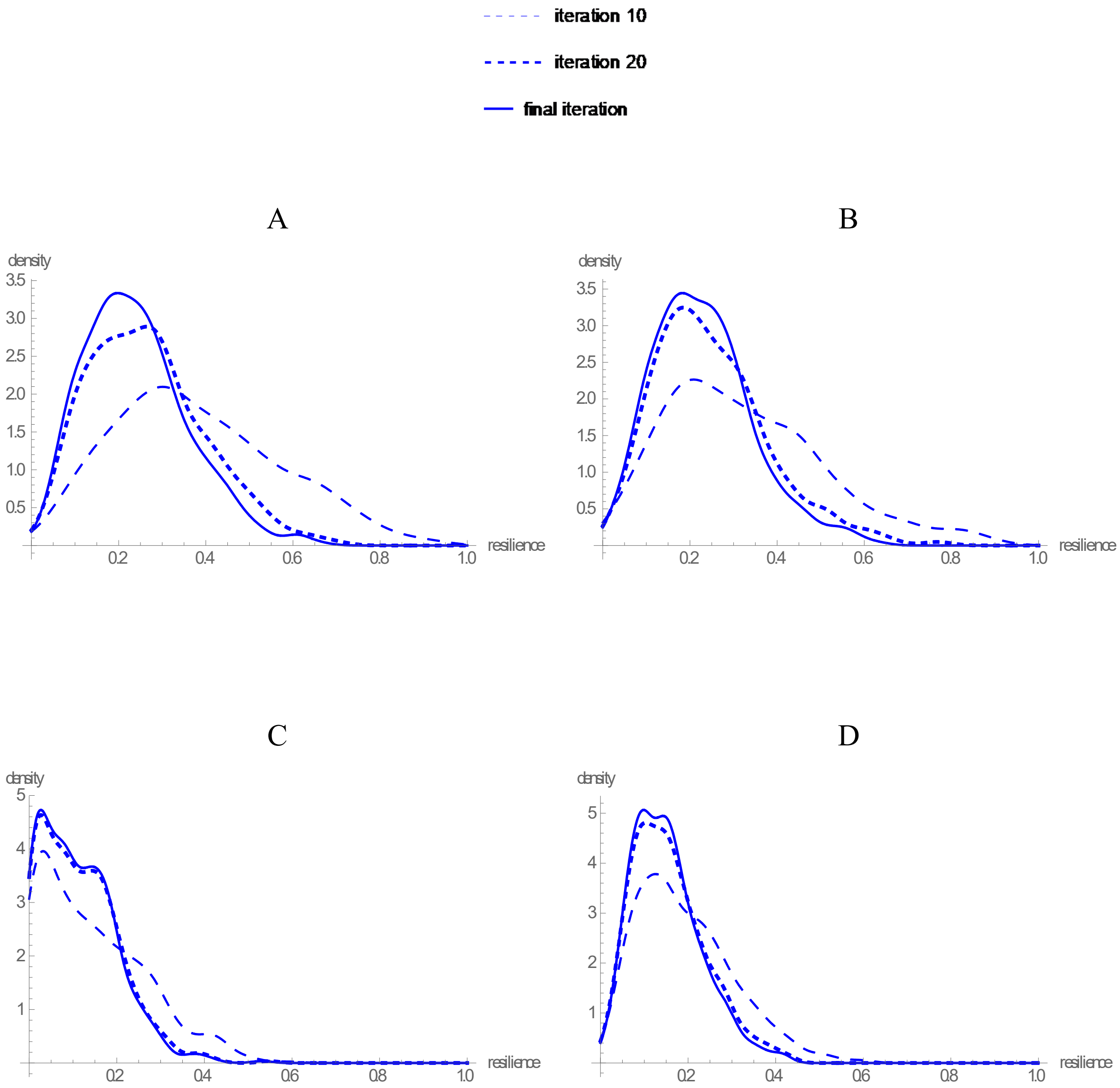


Figure C3: Distribution of the aggregate index of resilience at different iterations of the stress test (non-nested model, Filter 3)

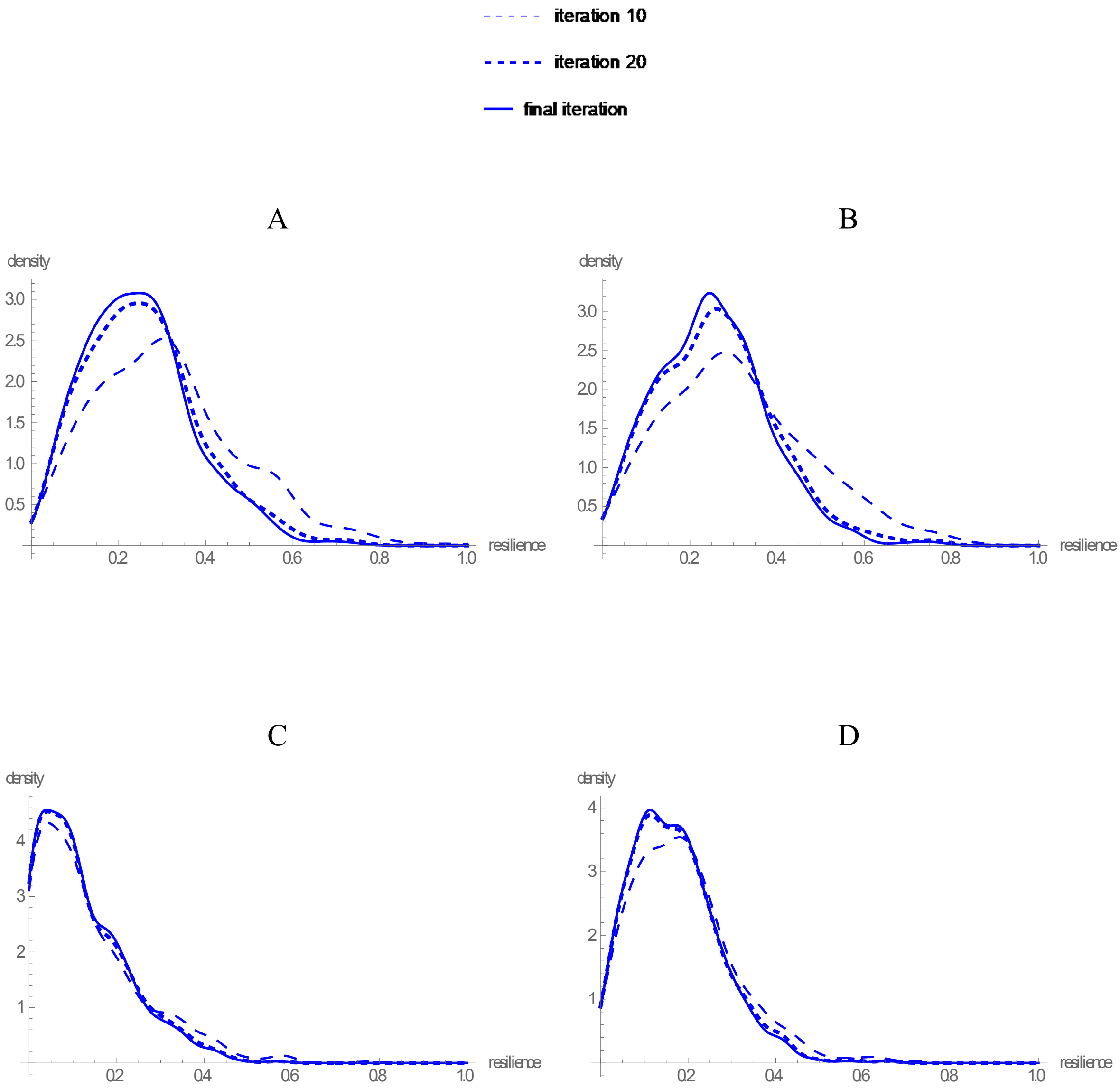
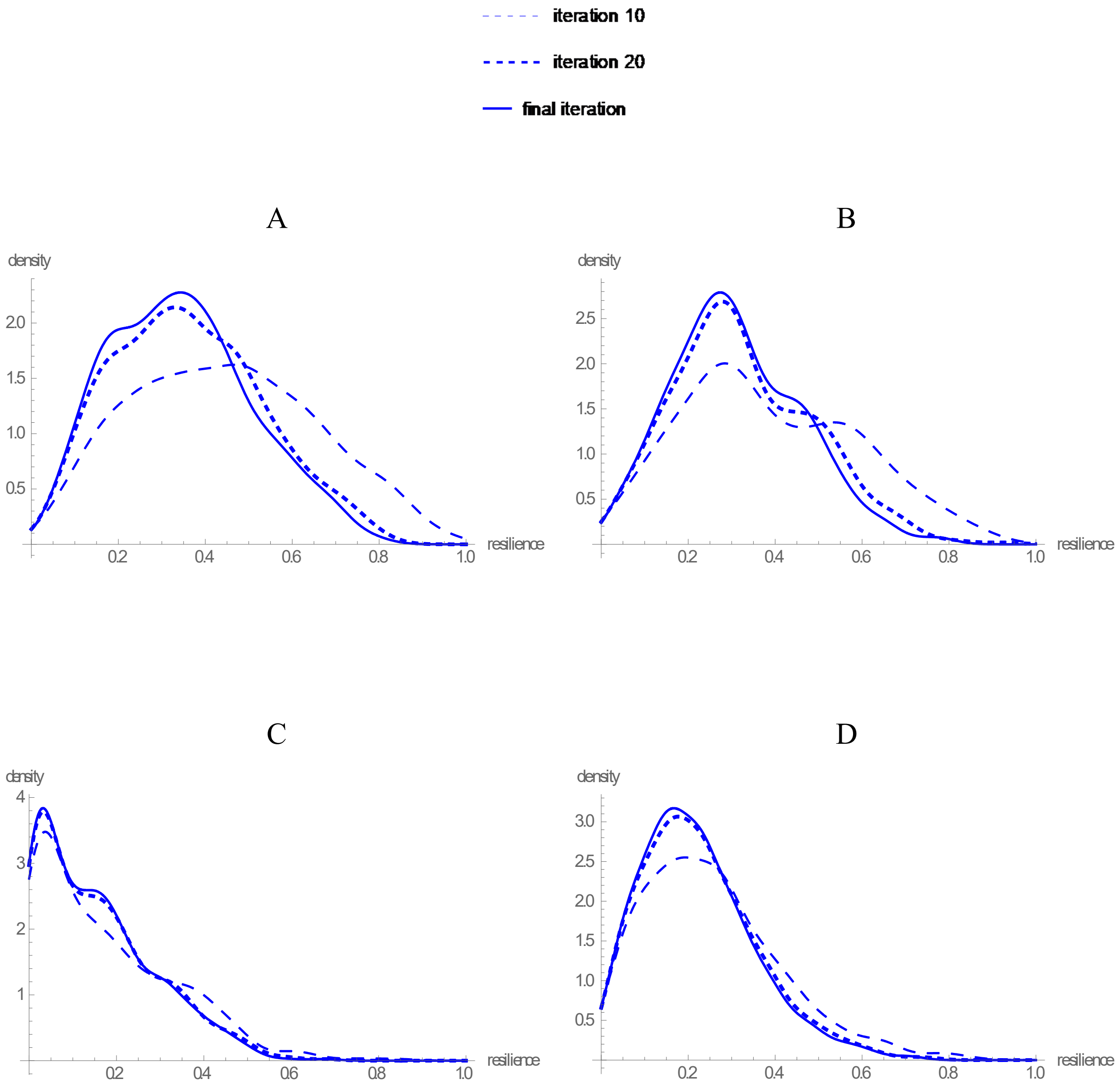


Figure C4: Distribution of the aggregate index of resilience at different iterations of the stress test (non-nested model, Filter 4)



GETTING IN TOUCH WITH THE EU

In person

All over the European Union there are hundreds of Europe Direct centres. You can find the address of the centre nearest you online (european-union.europa.eu/contact-eu/meet-us_en)

On the phone or in writing

Europe Direct is a service that answers your questions about the European Union. You can contact this service:

— by freephone: 00 800 6 7 8 9 10 11 (certain operators may charge for these calls),

— at the following standard number: +32 22999696,

— via the following form: european-union.europa.eu/contact-eu/write-us_en

FINDING INFORMATION ABOUT THE EU

Online

Information about the European Union in all the official languages of the EU is available on the Europa website (european-union.europa.eu)

EU publications

You can view or order EU publications at op.europa.eu/en/publications. Multiple copies of free publications can be obtained by contacting Europe Direct or your local documentation centre (european-union.europa.eu/contact-eu/meet-us_en).

EU law and related documents

For access to legal information from the EU, including all EU law since 1951 in all the official language versions, go to EUR-Lex (eur-lex.europa.eu)

EU open data

The portal data.europa.eu provides access to open datasets from the EU institutions, bodies and agencies. These can be downloaded and reused for free, for both commercial and non-commercial purposes. The portal also provides access to a wealth of datasets from European countries.

ET-01-24-002-EN-N

DOI: 10.2873/1355245
ISBN: 978-92-68-20580-8

Publications Office
of the European Union