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Abstract

This paper develops a new toolkit for analysing how global shocks affect the geographical and functional distribution of global value chains (GVCs) at the subnational level. Using the toolkit, which we call the shocks approach to indicator design, we derive a family of GVC indicators that distinguish between import and export-side GVC exposure, direct (face-value) and indirect (hidden exposure) linkages, and gross versus value-added GVC trade flows. Applying the indicators to multi-regional multi-country input-output data and analysing EU-UK and EU-China trade, we show that inferences about regional vulnerability depend critically on the type of exposure measured. The results highlight how global disruptions propagate unevenly across regions and provide a foundation for place-based policies that strengthen resilience through targeted diversification and smarter supply-chain monitoring.

Key words: Regional value chains, global value chains, value chain disruptions, input reliance, shocks, foreign exposure.

JEL classification: D57, F13, F14, F15, F60, R15.

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1 Introduction

As Comotti et al. (2020) and Crescenzi and Harman (2023) show, national indicators of globalization and supply-chain linkages mask deep sub-national asymmetries. High levels of spatial inequality in output, employment and growth are a persistent feature of most economies (Iammarino et al. 2019). In many countries, metropolitan regions prosper from globalization and automation while peripheral areas gain less or fall further behind (Capello et al. 2024b).

This spatial disparity matters profoundly. As research shows, persistent spatial disparities within nations can undermine both economic and social cohesion (Jones et al. 2019; Chan et al. 2024). In some high-income countries, these inequalities have also manifestly entered the realm of electoral politics, contributing to what some scholars call a "geography of discontent" (Bathelt et al. 2024; Clarke and Tilley 2019). The experience of living in "left behind" regions has fueled populist discontent, eroding trust in national institutions and driving political polarization that threatens the foundations of collective policy-making (Rodríguez-Pose et al. 2023).

Understanding the impact of global shocks is the first step in designing evidence-based and place-based policies that can mitigate the adverse spatial inequality effects of international economic integration and disintegration.

This issue has become more important than ever in recent years as trade policy instruments have increasingly been employed beyond their traditional role in protectionism, in what some have termed "weaponized interdependence" (Farrell and Newman 2019; Drezner et al. 2021; Bosone et al. 2024). For instance, tariffs implemented by the US in 2018 were followed by other countries introducing reciprocal measures to raise trade and investment barriers, often citing geo-economic and national objectives (York 2023; Bown and Kolb 2018). The trend reached new heights when the US government announced broad and high tariffs on most nations on 2 April 2025 (Baldwin 2025). The ripple effects of this continue to accumulate, ranging from export controls that China introduced on 4 April 2025 (MOFCOM 2025) to defensive duties to shield markets from exports that were deflected from the US (Evenett and Fritz 2025).

Scholars have responded to this clear need to examine regional effects. Empirical work linking international shocks to sub-national economic geography impacts is flourishing. The literature jumps off from multi-country input-output (IO) tables—which proliferated in the 2010s[1]—and ensuing GVC indicators that were developed for national level analysis (Johnson and Noguera 2012a; Koopman et al. 2012, 2014; Stehrer 2012; Antràs and Chor 2013, 2018; Timmer et al. 2013, 2014, among others).

These tables were extended to the regional level only recently. At the regional level, one of the most widely used multi-regional multi-country IO tables is the EUREGIO

[1]See, for example, the World Input-Output Database, WIOD (Timmer et al. 2015); OECD Inter-Country IO tables (OECD 2015); and EORA Database (Lenzen et al. 2013)

database (Thissen et al. 2018).[2] Published in 2018, this opened the door for researchers to study the geography of regional participation in, and exposure to, GVCs using IO tools.[3]

One of the early shocks analyzed with the new data and tools was Brexit. Most of these studies focus on Brexit's impact on final demand. Broadly speaking, they use regional-level multi-country IO databases to determine where a region's value added ends up in final demand. This is the basis of a first-order approximation of how much each region's GDP would vanish if foreign regions stopped buying the region's output. As standard in the IO literature, the results do not attempt to simulate a full general equilibrium adjustment to the shock.

Specifically, Brexit's regional fallout has been mapped with interregional IO tools that track the ultimate source of final demand for each region's value-added. Chen et al. (2018), for example, extend the EUREGIO database to year 2013 and show, via a value-added demand-side exposure index, an asymmetry between the exposure of UK and EU regions to a hypothetical shut down of two-way purchases. They find that UK regions, outside London in particular, face markedly higher GDP and labor-income risks than most EU regions, with Ireland being an exception. IJtsma and Los (2020) extend this to regional competitiveness under alternative Brexit regimes and also link UK regions' GVC embedding to export-related employment risks.

Complementing these demand-side IO perspectives, Tsekeris (2021) uses a network analysis built on interregional IO data and a hypothetical-extraction exercise to pinpoint which EU regions are structurally vulnerable to a UK Brexit shock, showing that London's disruption is strongest through services (tourism/finance) whereas the rest of the UK transmits impacts mainly through manufacturing, with especially large effects on highly internationalised regions such as Ireland and Luxembourg.

Starting with the regional GDP impact of international disruptions of final demand was natural, policy-relevant, and essential to thinking about policy responses. However, Brexit (and many other trade shocks) also operate on the supply side; high tariffs, boycotts, export controls, and various delays disrupt intermediate shipments. Beyond geopolitical shocks, the world is facing increasingly frequent system supply-chain shocks arising from extreme weather (climate change), cyberattacks, and outright attacks on shipping in places like the Red Sea.

1.1 This paper's contributions

The first contribution of our paper is to add a new methodological approach to characterize the complexities of GVCs' sub-national dimensions and thus address the question of how global shocks affect the geographical and functional distribution of GVCs at the sub-national level. To do this, we propose various new indicators. The main one which

[2]See Section 2 and Thissen et al. (2018) for further description.

[3]A variety of other data sources such as surveys, firm-level data, case studies, etc. have also been employed to conduct region-specific GVC analyses.

operates on the supply-side, based on an indicator we developed for analysis of supply shocks at the national level, is called Foreign Production Exposure: Import side, or *FPEM* for short (Baldwin et al. 2022). Using the new indicators, we conduct several empirical exercises that illustrate how the application of different indicators changes what conclusions might be drawn when analyzing the impact of global shocks on regional supply chain exposure. For instance, applying *FPEM* to the same Brexit scenarios explored in economic geography papers to date reveals how dependent regional production structures are on foreign intermediate inputs, offering a regional-level, supply-chain-vulnerability gauge to complement the regional-level demand-loss gauge in the existing literature. Specifically, conducting this exercise reveals stark differences in terms of which EU and UK regions could be hardest hit from the Brexit shock.

This addition of a supply-side indicator provides supplementary insights at the sub-national level, where regions differ sharply in trade patterns on the sales side (related to foreign final demand) and the sourcing side (related to their reliance on imported versus domestic inputs). One region, for example, may be mostly selling its value added locally but sourcing its intermediates internationally, while another may predominantly source locally but mostly export its value added. A further distinction in our indicators arises from the fact that several of them consider GVC trade on a gross trade flow basis rather than value-added trade flow basis. While this has its limitations, many types of international shocks—tariffs for example—apply to gross flows rather than just the local value added embedded in the gross trade flow.

To make this point differently, consider that many supply-chain linkages operate between gross production in one region and gross production in another. For example, in 2023 Houthi groups launched attacks on various commercial vessels in the Red Sea region, disrupting shipments to—amongst various locations—European manufacturers that source components from Asia to be embedded in local manufacturing production. As boats were re-routed, shipments were delayed, and bottlenecks occurred. The importance of these disruptions was related to gross exports from Asia to European regions, rather than the specific value-added content of the exports emanating from one country only.

To illustrate the impact that the gross versus value-added basis has, we simulate the impact of a disruption between EU regions and China. In doing so, our empirical analysis demonstrates how using different indicators for the same type of shock can lead to different policy inferences. Indeed, we show that all EU regions are more exposed to Chinese input sourcing on a gross basis than they are on a value-added basis. Further, our analysis reveals very different patterns for sourcing versus sales. Except for a few regions in southern Italy and Portugal, EU regions are much more exposed to China on the sourcing versus sales side, indicating that any disruption between the EU and China would have larger impacts on EU production overall.

We also note that some of our indicators—at the national level—have been used for policy analysis.[4] Eight of them have been included in the 2023 and 2025 updates of the OECD's database of supply chain indicators, Trade in Value Added (TiVA), and are now available for all countries and all TiVA sectors.[5] The indicators have also been subject to some empirical evaluation. For instance, Schwellnus et al. (2023a) conclude: "the new indicators of exposure to GVC risk developed by Baldwin and Freeman (2022) [which are derived in Baldwin et al. (2022)], and described in Schwellnus et al. (2023b), are accurate predictors of the impact of shocks to foreign suppliers and buyers on domestic production." Using an entirely different method, Imbs and Pauwels (2023) derive a supply chain indicator that is equivalent to one of ours and show that the indicator correlates tightly with the value-added response to foreign shocks. But, to the best of our knowledge, these indicators have not yet been used to address regional economic geography issues.

The second contribution of our paper is to offer a simple mathematical framework that provides a synthesis of indicators, which we call the 'shocks approach to indicator design'. The ensuing toolkit is intended to bring some order to the large portfolio of indicators that have been used, as well as providing an organizing framework for thinking about which indicators should be used for which policy or empirical questions. While we began developing the toolkit a few years ago (Baldwin and Freeman 2022; Baldwin et al. 2022), it has been extended in various places (Baldwin et al. 2023) and there is no one piece which brings together all the components. We believe that this toolkit would be a useful background resource for economic geography scholars (and trade economists more generally).

The plan of the paper is as follows. Section 2 reviews the existing literature on GVC indicators, integration, and shocks at the national and sub-national level, showcasing where our contribution fits in. Section 3 reviews basic methods for measuring supply chain exposure. Section 4 presents the shocks approach to indicator design toolkit, and develops a handful of indicators at the regional level. Section 5 presents several charts and stylized facts to illustrate what the different indicators can tell us. In doing so, we revisit some questions which have been explored in the economic geography literature to date and show how different indicators can lead to different inferences to the same policy question. Finally, Section 6 presents our concluding remarks.

[4]See Baldwin and Freeman (2020a,b, 2022); Baldwin et al. (2023); Baba et al. (2023); Crowe and Rawdanowicz (2023); Schwellnus et al. (2023a,b).

[5]See Gross Output Flows in Global Value Chains (`https://www.oecd.org/en/data/datasets/gross-output-flows-in-global-value-chains.html`) to download the indicators and accompanying technical guide

2 GVC indicators and analysis: From national to sub-national

In this section, we review some of the literature on GVC indicators, integration, and shocks at both the national and sub-national levels.

As mentioned above, the development of GVC indicators which account for the full network of trade linkages was accelerated by the widescale publication of multi-country IO tables at the country-level in the 2010s. The extensive literature on supply chain indicators that followed has been recently reviewed (Johnson 2018; Antràs 2020; Antràs and Chor 2022). Seminal contributions by Hummels et al. (2001), Johnson and Noguera (2012a), and Koopman et al. (2014) used the rich information available in multi-country IO tables to propose new ways to trace and decompose value-added trade flows across nations. These methods naturally led to the construction of novel indicators of GVC participation, among which backward and forward linkages (Hummels et al. 2001), the VAX ratio (Johnson and Noguera 2012a,b), and domestic value added embodied in foreign final demand (Stehrer 2012). The subsequent wave of literature (e.g. Bems et al. 2011; Timmer et al. 2013, 2014; Los et al. 2015; Johnson and Noguera 2017; Los and Timmer 2023, among others) added further nuance to the task of understanding countries' participation in complex supply networks through GVC trade. Further refinements on how to measure GVC participation and correct for issues like double counting have been proposed by De Backer and Miroudot (2013), Los et al. (2016), Miroudot and Ye (2018, 2022), Borin et al. (2021), and Borin and Mancini (2023).

Alongside the development of GVC participation indicators, a related literature proposed novel ways of measuring the length of value chains and countries' upstream and downstream position in them (Antràs et al. 2012; Fally 2012; Antràs and Chor 2013, 2018; Miller and Temurshoev 2017; Fally and Hillberry 2018). Recent work has also proposed new network concentration metrics (Inomata and Hanaka 2024).

Recent papers that focus on the derivation of supply chain indicators include Borin et al. (2021), Timmer et al. (2021), Borin and Mancini (2023), and Imbs and Pauwels (2023). Imbs and Pauwels (2023) use a macro model to derive the exact relationship between foreign shocks and domestic value added, and then show that the exact relationship in their model is approximated by a supply chain indicator that they call—drawing on their earlier work (Imbs and Pauwels 2020, 2022)—Higher Order Trade (HOT). HOT is equivalent to what we call Foreign Production Exposure: Export side ($FPEX$). Borin et al. (2021) present a novel method of measuring GVC participation using output and value-added trade linkages. Using their new measures, they show that output-based GVC integration decreases exposure to domestic shocks while increasing exposure to foreign shocks.

As new data sources have broken down national IO data to account for sub-national linkages, a new stream of research has ensued which extends country-level GVC indictors to the regional level and uses them to study the geography of regional participation in, and exposure to, GVCs.[6] For instance, the EUREGIO database (Thissen et al. 2018) brings the country-level World Input-Output Database (WIOD) IO tables to the regional level. The data are disaggregated into 14 industries, cover 249 NUTS-2 regions from 24 European countries, the UK, 15 other non-EU countries, and a rest of the world aggregate, span years 2000-2010, and add up exactly to the national WIOD tables, thus providing regional granularity while preserving global linkages.[7]

Mirroring the prevalence of value-added based GVC indicators at the national level, the indicators used in regional GVC studies primarily rely on value-added trade linkages. The aims of this research can be grouped into three broad categories: (i) understanding the patterns and drivers of regional participation in GVCs; (ii) exploring the regional costs and benefits to GVC involvement; and (iii) showcasing the potential regional effects of GVC exposure to shocks.

To provide a broad overview of the regional landscape of GVC participation, Almazán-Gómez et al. (2023) measure regional GVC participation as a region's share of exported value-added and highlight that GVC participation is highly concentrated not only domestically, but inter-regionally. Analysis in Giammetti et al. (2022) supports these findings. They show that EU regional production networks have proliferated since 2000, and while most of this has occurred at the EU level, production fragmentation outside the EU has developed faster. Michel et al. (2018) use firm-level data to construct export-heterogeneous national IO tables for Belgium, and integrate these into a global IO table to present important stylized facts about export-oriented Belgian manufacturing firms.

Looking at changing patterns in regional GVC participation over time, IJtsma and Los (2020) extend country-level indicators of GVC income and GVC jobs from Timmer et al. (2013) to the regional level and examine how important GVCs are for the generation of value added and employment in UK regions. They find that GVC activities became less important for all UK regions over the 2000-2010 period, likely due to the decline of the UK's manufacturing sector.

To further examine EU regional GVC patterns, Capello et al. (2024a) compute and combine two different value-added-based indicators and show that, even within single countries, regions vary greatly in their GVC roles, with competitive, resource-endowed regions more likely to secure favorable positions. Bolea et al. (2022) study how EU

[6]A range of papers have explored the geography of regional participation in, and exposure to, GVCs using different types of data sources (firm-level analyses, surveys, case studies, etc.) Here we review studies which use multi-regional multi-country IO data, given its ability to account for direct and indirect GVC links amongst and within regions.

[7]To ensure national consistency, EUREGIO combines regional accounts, employment data, sectoral statistics, trade data, and survey-based IO tables, where available. Importantly, the database was constructed by breaking down the national-level tables in the WIOD (Timmer et al. 2015) to the regional level. Thus, a key feature of the EUREGIO tables is that they add up exactly to the national WIOD IO tables. See Thissen et al. (2018) for full details. Chen et al. (2018) and Almazán-Gómez et al. (2023) extend the EUREGIO data to individual years 2013 and 2017, respectively.

regions' participation and position in GVCs are associated with regional characteristics such as urbanization, human capital, and regions' productive structures. Both prove to be significantly shaped by spatial spillovers from nearby regions' proximity and similarity in production structures, specialization, and GVC position.

Further considering regions' position (versus participation) in GVCs, Dietzenbacher (2002) and Midmore et al. (2006) use regional output and input multipliers[8]—the regional-level equivalent of country-level measures of downstreamness and upstreamness—to show that such linkages vary considerably by sector and region.[9] And, looking at a different facet of GVC participation, Hernández-Rodríguez et al. (2025) adapt country-level GVC measures of value-added exports and distribute this across occupational functions to construct measures of functional upgrading and downgrading in GVCs. They find that EU regions tend to functionally upgrade (becoming more specialized more complex GVC functions) in GVCs towards functions that are related to the ones in which they are already specialized. Using network analysis to look at regional GVC participation, Tsekeris (2021) defines a set of regional centrality measures and shows that regions from the most advanced countries in central and western Europe are most integrated in European GVCs. He also points to regional disparities within countries, with large metropolitan areas outperforming more rural zones.

Digging into the regional costs and benefits to GVC involvement, various papers have shown how GVC involvement can help regions recover from largescale crises. For instance, Zádor et al. (2024) show that higher value chain importance during the 2008 Global Financial Crisis led to a more robust recovery in the 2011-2018 period. Interestingly, this result is driven by regions' integration in GVCs with countries outside the EU, underscoring that the benefits of GVC involvement are especially bolstered by global (as opposed to regional) connections. Kitsos et al. (2023) examine how the share of a region's direct inter-industry intermediate input sales and supply transactions that are anchored locally affected a region's resistance to the 2008 Great Recession, measured by employment changes between pre- and post-crisis periods. They find that moderate shares enhance resistance, but excessive ones can hurt it, especially for manufacturing and financial and business services sectors.

Finally, various papers turn the discussion to regional GVC exposure and the impact of shocks. By and large, these papers exploit the Brexit shock, made possible by the fact that the EUREGIO database makes available disaggregate regional IO data for Europe and the UK. As discussed above, Chen et al. (2018) examine the potential exposure of UK and EU regions to a no-deal Brexit. They build a value-added based regional GVC exposure index to capture how much regional economic activity—both in terms of value-added

[8]In the IO literature, output and input multipliers are commonly known as backward and forward linkages, respectively (Miller and Blair 2009).

[9]Dietzenbacher (2002) conducts this analysis using regional input-output data from Eurostat for 6 EU countries and Midmore et al. (2006) spotlight this using regional Welsh input-output data for year 1995 and underscore the potential for sectoral linkages to drive regional economic impacts.

exports and labor income—in each UK and EU region depends on trade with regions in the respective country. Importantly, the authors also distinguish between direct versus total (i.e. direct and indirect) exposure to Brexit and show that total exposure levels are significantly higher than direct exposure levels. Their GVC exposure index is akin to what we call $FPEXV$, a value-added based indicator of export exposure. As described in the introduction, the authors also conclude that Brexit poses a much larger risk to UK regions than to EU regions, a prediction which is echoed by Tsekeris (2021) using network analysis. IJtsma and Los (2020) also examine the Brexit shock. Extending a country-level indicator proposed in Los and Timmer (2018)—geared at uncovering export-related risks of bilateral trade barriers to jobs—to the regional level they show that UK regions that depend relatively more on GVC activities with respect to their employment tend to be those for which the trade-related employment risks of Brexit are highest.

Thinking about broader types of economic unraveling, Giammetti et al. (2022) study the effect of various hypothetical de-globalization scenarios on value-added trade for EU regions. Similar in spirit to the methodology employed in Chen et al. (2018), they construct a value-added based regional GVC exposure index and then, for each scenario, 'switch off' the relevant trade links. Overall, their study shows both that the degree of exposure to de-globalization is similar in neighboring EU regions which extend beyond national borders and that de-globalization has the potential to generate winners and losers, with the losers being export-led economies that largely benefited from trade openness.

We view our contribution as complementary to the above literature in two main ways. First, our unified approach to designing indicators of supply chain exposure provides an organizing framework and toolkit for thinking through which types of indicators are appropriate according to the shock of concern. Through this framework, and extending our shocks approach to the regional level, we derive a family of indicators to address questions on supply chain disruption, and particularly those related to how global shocks propagate through space. Second, applying the indicators to various empirical cases, we highlight how regional analyses on GVC exposure and the impact of shocks might be tackled from multiple angles, and how alternative indicators can lead to different inferences to the same policy question.

3 Tools for measuring foreign exposure

We now turn our attention to the tools necessary for measuring GVC exposure. To fix ideas and introduce notation, we first present well-known elements of input-output analysis.[10]

At the regional level, the use-accounting identity states that a region-sector's gross

[10]A fuller discussion can be found in Baldwin et al. (2022), and in Miller and Blair (2009), Lenzen et al. (2013), OECD, WTO and World Bank Group (2014), Timmer et al. (2015), Borin and Mancini (2015, 2023), and Antràs and Chor (2022).

output is used as intermediate goods or final goods. In our notation, subscripts indicate the origin region ($i = 1, \ldots, R$), and the destination region ($j = 1, \ldots, R$); superscripts indicate the selling sector ($k = 1, \ldots, S$) and buying sector ($s = 1, \ldots, S$). In matrix notation, the use-accounting identity is:

$$\boldsymbol{X} = \boldsymbol{T}\,\boldsymbol{\iota} + \boldsymbol{F};\ \boldsymbol{X} = \begin{bmatrix} X_1 \\ \vdots \\ X_R \end{bmatrix}, \boldsymbol{F} = \begin{bmatrix} F_1 \\ \vdots \\ F_R \end{bmatrix}, \boldsymbol{T} = \begin{bmatrix} T_{11} & \ldots & T_{1R} \\ \vdots & \ddots & \vdots \\ T_{R1} & \ldots & T_{RR} \end{bmatrix} \tag{1}$$

where $\boldsymbol{X}$ is a (RSx1) vector of gross output with each element X_i a (Sx1) vector of stacked X_i^k values, $\boldsymbol{F}$ is a (RSx1) vector of final demand with each element F_i a (Sx1) vector of stacked $\sum_j^R F_{ij}^k$ values, and $\boldsymbol{T}$ is a (RSxRS) matrix of bilateral intermediate input transactions, with each element T_{ij} a (SxS) matrix of T_{ij}^{ks} values, and $\boldsymbol{\iota}$ is a (RSx1) column vector of ones.

Transforming $\boldsymbol{T}$ into input-output coefficients and the vector of gross outputs, the use-accounting identity can be rewritten as:

$$\boldsymbol{X} = \boldsymbol{A}\,\boldsymbol{X} + \boldsymbol{F};\ \boldsymbol{A} = \begin{bmatrix} a_{11} & \ldots & a_{1R} \\ \vdots & \ddots & \vdots \\ a_{R1} & \ldots & a_{RR} \end{bmatrix} \tag{2}$$

where $\boldsymbol{A}$ is a (RSxRS) matrix of input-output coefficients, where each a_{ij} is a (SxS) matrix with elements $a_{ij}^{ks} = {}^{T_{ij}^{ks}}/_{X_j^s}$, and $\boldsymbol{T}\,\boldsymbol{\iota} \equiv \boldsymbol{A}\,\boldsymbol{X}$. Importantly, the a_{ij}^{ks} are fixed, i.e., unresponsive to prices. Solving (2) for $\boldsymbol{X}$ yields the classic Leontief relationship:

$$\boldsymbol{X} = \boldsymbol{L}\,\boldsymbol{F},\ \text{where } \boldsymbol{L} \equiv (\boldsymbol{I} - \boldsymbol{A})^{-1} \tag{3}$$

where $\boldsymbol{I}$ is a (RSxRS) identity matrix and $\boldsymbol{L}$ is the Leontief inverse matrix. The elements of $\boldsymbol{L}$, denoted ℓ_{ij}^{ks}, give the gross production in every sector-region needed to produce final output in every sector-region, taking account of all direct and indirect linkages.

The matrix $\boldsymbol{A}$ captures the direct input-output links among country-sectors, i.e., the tier-1 suppliers, that can be observed in IO tables. $\boldsymbol{L}$ captures these direct links plus indirect purchases of inputs by all suppliers to all suppliers. As Miller and Blair (2009) and Antràs and Chor (2022) point out:

$$(\boldsymbol{I} - \boldsymbol{A})^{-1} = \boldsymbol{I} + \boldsymbol{A} + \boldsymbol{A}^2 + \boldsymbol{A}^3 + \ldots + \boldsymbol{A}^\infty \tag{4}$$

We use this to decompose linkages into the direct (face-value) and indirect (hidden-exposure) links among region-sectors. The face-value links are given by $\boldsymbol{I} + \boldsymbol{A}$, where $\boldsymbol{I}$ reflects the production location of one dollar of final goods and $\boldsymbol{A}$ reflects the tier-1 intermediates necessary to make it. The subsequent terms, $\boldsymbol{A}^2 + \boldsymbol{A}^3 + \ldots + \boldsymbol{A}^\infty$, are the indirect (hidden-exposure) links which capture the fact that inputs are used in inputs which are used in inputs, and so on without end. These links are 'hidden' in that they are not observed in the data; they must be calculated from IO tables. The sum of the direct and indirect links is what we call 'look-through' links.

The classic GVC measures focus on the value-added content of trade flows. Deriving these from gross trade flows, we employ a (RSx1) vector:

$$\widehat{\boldsymbol{V}} = \begin{bmatrix} \widehat{V}_1 \\ \vdots \\ \widehat{V}_R \end{bmatrix}$$

with each element $\widehat{V}_i$ a (Sx1) vector of value-added-to-gross-output ratios, $\widehat{V}_i^k = {}^{V_i^k}/{}_{X_i^k}$ which can be used to convert gross flows into value-added flows. Using (3), we get $\langle\widehat{\boldsymbol{V}}\rangle\boldsymbol{X} = \langle\widehat{\boldsymbol{V}}\rangle\boldsymbol{L}\,\boldsymbol{F}$, where $\langle\widehat{\boldsymbol{V}}\rangle$ denotes a diagonal matrix with the elements of $\widehat{\boldsymbol{V}}$ placed along the diagonal and all off-diagonal elements set to zero. This translates to:

$$\boldsymbol{V} = \boldsymbol{VL}\,\boldsymbol{F} \text{ where } \boldsymbol{V} = \begin{bmatrix} V_1 \\ \vdots \\ V_R \end{bmatrix} \text{ and } \boldsymbol{VL} \equiv \langle\widehat{\boldsymbol{V}}\rangle\boldsymbol{L} \tag{5}$$

Here the elements of $\boldsymbol{V}$ are (Sx1) vectors of value added, V_i^k, and the elements of $\boldsymbol{VL}$, denoted v_{ij}^{ks}, are the value-added equivalents of the ℓ_{ij}^{ks}. Likewise, we can convert $\boldsymbol{X} = \boldsymbol{A}\,\boldsymbol{X} + \boldsymbol{F}$ to a value-added basis: $\langle\widehat{\boldsymbol{V}}\rangle\boldsymbol{X} = \langle\widehat{\boldsymbol{V}}\rangle\boldsymbol{A}\,\boldsymbol{X} + \langle\widehat{\boldsymbol{V}}\rangle\boldsymbol{F}$.

The identities (2), (3), (4), and (5) are the foundation of our shocks approach to indicator design.[11]

4 The shocks approach to deriving supply chain indicators

This section presents our simple shocks approach to deriving supply chain indicators from first principles and then derives a family of indicators. We see the approach as a toolkit to be used for building a range of indicators to address various supply chain disruption questions.

Differentiating $\boldsymbol{X} = \boldsymbol{LF}$, the links between changes in gross output and changes in final output are:

$$\boldsymbol{dX} = \boldsymbol{L}\,\boldsymbol{dF} \tag{6}$$

There is no $\boldsymbol{dL}\,\boldsymbol{F}$ term in (6) since the ℓ_{ij}^{ks} are fixed by assumption. In words, (6) shows the change in gross production in every region-sector, $\boldsymbol{dX}$, necessary to accommodate a change in every region-sector net output, $\boldsymbol{dF}$. This establishes the fundamental linkages

[11]Appendix A.1 presents the expression of gross output identities from the cost accounting perspective. Appendix A.2 develops analogous GVC exposure indicators to those presented in section 4 below.

among production in every region-sector pair. When the sectors are in different regions, it shows the foreign production exposure, namely exposure of gross production in one region to final production in another, and vice versa.

Importantly, (6) is not a behavioral equation as it is derived from an accounting identity. As written, (6) seems to say that $\boldsymbol{dF}$ shocks are causing $\boldsymbol{dX}$, but we could equally think of $\boldsymbol{dX}$ shocks as causing $\boldsymbol{dF}$. Moreover, since IO frameworks reflect equilibrium outcomes, $\boldsymbol{X}$ and $\boldsymbol{F}$ represent both supply and demand for the relevant quantities. For example, $\boldsymbol{dF}$ can be viewed as a shock to final demand or a shock to final production.

Expression (6) is the general formula for supply chain linkages; to derive an indicator we specify the production shock and impacted sector of interest. To illustrate our first indicator with a concrete example without too much notation, we consider a simplified version of the general model that has only two regions (regions A and B) and two sectors (sectors 1 and 2). The shock we consider involves region B's net output in sector 1, namely dF_B^1. The impacted region-sector we are interested in is $2A$. Thus equation (6) simplifies to:

$$dX_A^2 = \ell_{AB}^{21} dF_B^1 \tag{7}$$

This gauges $1B$'s exposure to $2A$ in the sense that $1B$ can expand if and only if $2A$ also expands.

In early work (Baldwin and Freeman 2022), we pointed out that ℓ_{AB}^{21}, unnormalized, is an indicator of $1B$'s reliance on $2A$'s gross production; we called this Foreign Input Reliance (*FIR*).[12] When considering a more aggregate reliance, for example, the *FIR* of sector s in region j to inputs from region i, we summed across sectors in each exporting region:

$$FIR_{ij}^s = \sum_k^S \ell_{ij}^{ks} \tag{8}$$

When looking at region-pair aggregates, we weighted *FIR* by the importing sector's gross output to get: $FIR_{ij} = \sum_s^S \left(FIR_{ij}^s * \left(X_j^s / \sum_s^S X_j^s \right) \right)$.[13]

While *FIR* is helpful for understanding time trends in regions' foreign input reliance, it does not gauge the relative size of exposure. As such, the measure is not directly comparable across different sectors that produce intermediates in different proportions. This led us to normalize the fundamental linkage, ℓ_{ij}^{ks}, to facilitate comparisons across indicators and shocks. There is, however, no one normalizer that is appropriate for all

[12] In a sense, *FIR* is normalized since the sum of each column of $\boldsymbol{L}$ gives the value of intermediates necessary to make \$1 of the corresponding final good, so the normalization is by \$1. But since the inputs-to-final goods ratio varies across sectors *FIR* has limited applications.

[13] *FIR* at the country-pair-sector level is one of our indicators included in the 2023 and 2025 updates of the OECD TiVA database. They also include *FIR* at the country-pair-*macro*-sector level (e.g. total manufacturing, total services, etc., as well as the total economy), where the aggregation is done using gross output weights of the macro-sector: $FIR_{ij}^S = \sum_{s \in S} \left(FIR_{ij}^s * \left(X_j^s / \sum_{s \in S} X_j^s \right) \right)$ where S corresponds to the importing macro-sectors (see technical note entitled "Guide to OECD trade in Gross Output Indicators, 2023 edition" in Gross Output Flows in Global Value Chains download folder: `https://www.oecd.org/en/data/datasets/gross-output-flows-in-global-value-chains.html`).

situations. For example, Schwellnus et al. (2023b) use a version of *FIR* at the country level that is normalized by gross output. If we were interested in the sector's GDP, we could normalize ℓ_{ij}^{ks} by the sector's value added instead, although this would be an indicator whose numerator is measured in gross terms but whose denominator is measured in value-added terms.

4.1 Foreign production exposure based on gross trade: *FPEM* and *FPEX*

The first normalized indicator we derive is the Foreign Production Exposure: Import side (*FPEM*) indicator that is meant to capture a region-sector's exposure to foreign production shocks. To keep the discussion intuitive, we start with the two-region-two-sector example.

The dollar value of GVC linkages between $1B$ and $2A$ in (7) is ℓ_{AB}^{21}. To gauge how exposed buying sector 1 in region B is to $2A$, we normalize ℓ_{AB}^{21} by $1B$'s total purchases from all sectors and regions, namely: $TI_B^1 \equiv (\ell_{AB}^{11} + \ell_{AB}^{21} + \ell_{BB}^{11} + \ell_{BB}^{21})\, F_B^1$. Forming shares and proportional changes, we get: ${dX_A^2}/{TI_B^1} = 100 * \left(\ell_{AB}^{21} F_B^1 / TI_B^1\right) \left({dF_B^1}/{F_B^1}\right)$. Taking ${dF_B^1}/{F_B^1} = 1$ and turning the indicator into an index, *FPEM* in this example is $FPEM_{AB}^{21} = 100 * \left(\ell_{AB}^{21} / (\ell_{AB}^{11} + \ell_{AB}^{21} + \ell_{BB}^{11} + \ell_{BB}^{21})\right)$. In words, $FPEM_{AB}^{21}$ is $2A$'s share of $1B$'s total intermediate inputs, so it gauges the exposure of $1B$ to inputs from $2A$. Generalizing, the *FPEM* for sector s in region j to inputs from sector k in region i is:

$$FPEM_{ij}^{ks} = 100 * \frac{\ell_{ij}^{ks}}{\sum_i^R \sum_k^S \ell_{ij}^{ks}} \tag{9}$$

FPEM is bound between zero and 100 since if we summed over purchases across all selling regions and sectors (foreign and domestic) the numerator would equal the denominator.

Our approach allows for aggregation across multiple regions and sectors. For instance, the *FPEM* for importing sector s in region j to all inputs from each foreign region (either within or outside the same country) i is:

$$FPEM_{ij}^{s} = 100 * \frac{\sum_k^S \ell_{ij}^{ks}}{\sum_i^R \sum_k^S \ell_{ij}^{ks}} \tag{10}$$

where the aggregation takes place in the numerator across exporting sectors k. Aggregating to the bilateral region level, region-j's total exposure to production in foreign region i is:

$$FPEM_{ij} = 100 * \frac{\sum_k^S \sum_s^S \ell_{ij}^{ks} F_j^s}{\sum_i^R \sum_k^S \sum_s^S \ell_{ij}^{ks} F_j^s} \tag{11}$$

However, in doing this aggregation we cannot cancel the F_j^s as we did in (9) and (10). Note that $FPEM_{ij}$ measures the exposure of gross production in region i, X_i, to shocks to final demand in region j, F_j, but the shock to final demand could be a supply shock or a demand shock.

Given the two-way nature of (7), there is a close analogy to *FPEM* on the selling side. By definition, ℓ^{21}_{AB} is the link between gross production in $2A$ and final output in $1B$. *FPEM* looked at this as $1B$'s exposure to $2A$ on the sourcing side, but equally it is $2A$'s exposure to $1B$ on the sales side. The normalizer for *FPEM*, however, is not appropriate for gauging export-side exposure. Since we want to gauge sector $2A$'s exposure of sales to sector $1B$, we normalize by $2A$'s total sales to all region-sectors. Thus, *FPEX* for exporting sector k in region i to importing sector s in region j is:

$$FPEX^{ks}_{ij} = 100 * \frac{\ell^{ks}_{ij} F^s_j}{\sum^R_j \sum^S_s \ell^{ks}_{ij} F^s_j} \tag{12}$$

Note that the F^s_j terms do not cancel as they did in (9) as we are now summing across buying regions and sectors in the denominator. Also, note that the denominator equals to the gross output of the selling region-sector X^k_i. The aggregation of *FPEX* follows the *FPEM* procedure. *FPEX* for sector k in region i to all sectors in region j, and at the region-pair level are, respectively:

$$FPEX^k_{ij} = 100 * \frac{\sum^S_s \ell^{ks}_{ij} F^s_j}{\sum^R_j \sum^S_s \ell^{ks}_{ij} F^s_j}; \; FPEX_{ij} = 100 * \frac{\sum^S_k \sum^S_s \ell^{ks}_{ij} F^s_j}{\sum^S_k \sum^R_j \sum^S_s \ell^{ks}_{ij} F^s_j} \tag{13}$$

FPEM and *FPEX* are included at the country-level in the 2023 and 2025 updates of the OECD TiVA database.

Two points on *FPEM* and *FPEX* are noteworthy. First, both the direct and indirect components of the input trade include accumulated gross production from third regions. Second, since the indicators are based on gross trade, they necessarily ‘double count’ trade flows. This is a feature, not a bug, of the indicators looking at disruptions because supply shocks typically disrupt the entire, i.e. accumulated, value of a shipment, rather than just the value added in the disrupted region.

There are situations where value-added trade flows are more appropriate, so we turn to the derivation of such measures.

4.2 Foreign production exposure on a value-added basis

Loosely speaking, we can think of gross production as important since it reflects total business turnover. As such, *FPEM* and *FPEX* are indicators of the exposure of a region's total business turnover to foreign shocks; *FPEM* gauges exposure on the sourcing side while *FPEX* gauges exposure on the selling side.

Likewise, we can think of value added as important since it is roughly proportional to employment. Since there can be cases where the key question is exposure of a sector's employment to foreign shocks, or a sector's exposure to foreign employment shocks, there can be instances where we want to consider value-added trade linkages rather than gross trade linkages. In these scenarios, we start with the derivative of the value-added identity, (5), $\boldsymbol{dV} = \boldsymbol{VL}\,\boldsymbol{dF}$.

In the simple case, we get, for example, $dV_A^2 = v_{AB}^{21}\,dF_B^1$ in our simplified two-sectors-two-regions case. Given (5) is an identity, we can think of v_{AB}^{21} as either the sales of $2A$ to $1B$ on a value-added basis, or sector $1B$'s purchases of value added from sector $2A$. In either case, v_{AB}^{21} shows the impact of a small change in $1B$'s final output on value added in $2A$, or vice versa. By analogy with *FPEM*, the natural normalizer for the import-side exposure of $1B$ to $2A$ is $1B$'s value-added inputs from all sectors and regions. This gives: $FPEMV_{AB}^{21} = 100 * \left(v_{AB}^{21}/\left(v_{AB}^{11} + v_{AB}^{21} + v_{BB}^{11} + v_{BB}^{21}\right)\right)$. Here the suffix V refers to the fact that the flows are evaluated on a value-added basis rather than a gross basis.

Generalizing, an indicator of the exposure of final output in sector s in region j to value added in sector k in region i is:

$$FPEMV_{ij}^{ks} = 100 * \frac{v_{ij}^{ks}}{\sum_i^R \sum_k^S v_{ij}^{ks}} \tag{14}$$

This is the value-added analogue of (9) in that it shows the exposure of region j's sector s to value added in region i's sector k. In words, $FPEMV_{ij}^{ks}$ reflects the exposure of final output in sector s in region j to value added in sector k in region i. This indicator could be appropriate when the key question is exposure of an importing sector's final output to foreign employment shocks.

On the export side, the value-added analogue of (12) is:

$$FPEXV_{ij}^{ks} = 100 * \frac{v_{ij}^{ks} F_j^s}{\sum_j^R \sum_s^S v_{ij}^{ks} F_j^s} \tag{15}$$

In words, $FPEXV_{ij}^{ks}$ reflects the exposure of the value added of exporting sector k in region i to final demand in importing sector s in region j. This indicator could be appropriate when the key question is exposure of an exporting sector's employment to foreign final production/demand shocks. In the regional economic geography literature, value added based measures along the lines of $FPEXV$ have been used in a range of studies to explore both regional patterns of GVC integration and regional exposure to GVC shocks, including employment risks to GVC shocks (Chen et al. 2018; IJtsma and Los 2020; Bolea et al. 2022; Almazán-Gómez et al. 2023; Zádor et al. 2024).

Before turning to our decomposition of look-through linkages into face-value and hidden exposure components, we compare the above indicators with the well-known backward linkage (BL) measure from Hummels et al. (2001). The BL indicator is similar in spirit to $FPEMV$ in that it focuses on imported value-added trade flows but differs in two ways. First, it is export-based rather than production-based. In the simple case, $FPEMV_{AB}^{21}$ shows the exposure of $1B$'s *final production* to value added in $2A$, while BL_{AB}^{21} shows the exposure of $1B$'s *exports* to value added in $2A$. Second, BL is normalized by gross exports, so it has a value-added measure in the numerator and a gross measure in the denominator whereas *FPEMV* has value-added measures in both.[14]

4.3 Hidden exposure: Face-value versus look-through indicators

Equation (4) shows that $\boldsymbol{L}$ captures both direct and indirect trade links. As discussed in Baldwin et al. (2023), this insight allows us to decompose *FPEM* and *FPEX* into observed (direct) links and indirect links. We refer to direct links as 'face-value' exposure as these links are directly observable in the data. We refer to indirect links as 'hidden exposure' because they are not observable directly in the IO data. Otherwise put, these links are hidden in the higher order terms $\boldsymbol{A}^2 + \boldsymbol{A}^3 + \ldots + \boldsymbol{A}^\infty$ in equation (4). We refer to the sum of face value and hidden exposure as 'look-through' exposure. We chose this term because the look-through concept pierces the veil of the network of inputs feeding into inputs.

In this terminology, *FPEM* is a look-through measure, which we can decompose into its face-value and hidden exposure components:

$$FPEM_{ij}^{ks} = 100 * \left(\frac{\mathbb{1}[(i,k)=(j,s)] + a_{ij}^{ks}}{\sum_i^R \sum_k^S \ell_{ij}^{ks}} + \frac{\sum_{m=2}^{\infty} a_{ij}^{ks,m}}{\sum_i^R \sum_k^S \ell_{ij}^{ks}} \right) \tag{16}$$

where $a_{ij}^{ks,m}$ is a component of the $\boldsymbol{A}$ matrix raised to the power of m and $\mathbb{1}[i=j]$ is the indicator function that equals one when the region and sector coincide $(i,k)=(j,s)$. In the decomposition on the right-hand side, the first and second terms in the parentheses are face-value and hidden exposure, respectively. This decomposition applies to *FPEX*, as well as their value-added analogues *FPEMV* and *FPEXV*.[15]

4.4 Indicators based on observed trade flows: Tier-1 supplier exposure

Using the shocks approach, we can equally design more traditional indicators that focus solely on directly imported intermediate goods.[16] From (2), $\boldsymbol{X} = \boldsymbol{A}\,\boldsymbol{X} + \boldsymbol{F}$, where $\boldsymbol{A}\,\boldsymbol{X}$ is all the direct, i.e., tier-1 inputs, needed to produce $\boldsymbol{X}$. If we focus only on imported inputs, this expression gives us some indication of how important directly imported foreign (i.e. from a different region within the same country, or a different region outside of the same country) intermediates are to the production of domestic gross output. Although the directly imported intermediates do not identify the true region of origin (only that last stage in the GVC), it may be useful to design indicators based on this identity. For instance, the shocks under consideration may involve disruption of directly imported

[14] For a more technical discussion, see Baldwin et al. (2022).

[15] The decomposition of *FPEM* and *FPEX* into face-value and hidden exposure components is included in the 2023 and 2025 updates of the OECD TiVA database.

[16] See Baldwin et al. (2022) for details.

inputs—not all direct and indirect foreign production. For example, when COVID shut down some countries' manufacturing sectors, the entire supply chain was interrupted so measures like *FPEM* were appropriate. However, when it came to the Houthi attack example in the introduction, the disruption was limited to European regions' direct imports from Asia.

Given the calculations above, the derivation of the relevant indicators is simple. In essence, the ℓ_{ij}^{ks} in *FPEM* and *FPEX* are replaced by the corresponding elements of $\boldsymbol{A}$, i.e., a_{ij}^{ks}, to get:

$$OFPEM_{ij}^{ks} = 100 * \frac{a_{ij}^{ks}\, X_j^s}{\sum_i^R \sum_k^S a_{ij}^{ks}\, X_j^s} \tag{17}$$

where the prefix O stands for observed. This simplifies to $OFPEM_{ij}^{ks} = 100 * \left(T_{ij}^{ks} / \sum_i^R \sum_k^S T_{ij}^{ks} \right)$ and hence (17) is the ratio of observed imported inputs to observed total inputs ('observed' means it ascribes the full value of the inputs to the proximate sector-region source). Similarly, the observed equivalent of *FPEX* is:

$$OFPEX_{ij}^{ks} = 100 * \frac{a_{ij}^{ks}\, X_j^s}{X_i^k} = 100 * \frac{T_{ij}^{ks}}{X_i^k} \tag{18}$$

4.5 Meet the extended family: GVC indicators derived and derivable

Here we present an organizing framework for thinking about how the indicators fit together (Table 1). The two essential elements of an indicator are a trade flow in the numerator (exports or imports on a gross or value-added-basis), and a normalizer in the denominator. In our approach, the numerator is always a trade linkage that comes from the differentiation of an IO equation: $\boldsymbol{X} = \boldsymbol{L}\,\boldsymbol{F}, \boldsymbol{X} = \boldsymbol{A}\,\boldsymbol{X} + \boldsymbol{F}$, $\boldsymbol{V} = \boldsymbol{V}\boldsymbol{L}\,\boldsymbol{F}$, or $\boldsymbol{X} = \boldsymbol{G}\,\boldsymbol{V}$ (see appendix A.1 for the derivation of the Ghosh identity, $\boldsymbol{X} = \boldsymbol{G}\,\boldsymbol{V}$, where $\boldsymbol{G}$ is the Ghosh inverse matrix). In the indicators we derive here, we think of the foreign shocks coming from the right-hand side, and the domestic impact affecting the left-hand side, but as mentioned, that is merely an interpretation of an identity. The trade flow in the numerator will be direct and indirect trade when using $\boldsymbol{X} = \boldsymbol{L}\,\boldsymbol{F}, \boldsymbol{V} = \boldsymbol{V}\boldsymbol{L}\,\boldsymbol{F}$, or $\boldsymbol{X} = \boldsymbol{G}\,\boldsymbol{V}$, and direct only when using $\boldsymbol{X} = \boldsymbol{A}\,\boldsymbol{X} + \boldsymbol{F}$.

The choice of the numerator—the normalizer of the trade flow—is not directly dictated by the differentiation, but it should be consistent with the relevant expression. For instance, an indicator based on, say $dX_A^2 = \ell_{AB}^{21} dF_B^1$, could have the impacted sector's gross output as the normalizer by writing ${}^{dX_A^2}/_{X_A^2} = 100 * \left({}^{\ell_{AB}^{21} F_B^1}/_{X_A^2} \right) \left({}^{dF_B^1}/_{F_B^1} \right)$. Many normalizers are possible. Six are listed in the table although we derive the indicators for only a small set of them. The empty cells show indicators we did not generate but which could be generated should the need arise. The final two rows show the face-value versus hidden exposure distinction we developed for some look-through indicators but could be generated for others.

Table 1: Shocks-approach indicators

	Use accounting								Cost accounting	
	Gross trade				Value added trade				Gross trade	
Identity	$\boldsymbol{dX} = \boldsymbol{L}\,\boldsymbol{dF}$		$\boldsymbol{dX} = \boldsymbol{A}\,\boldsymbol{dX}$		$\boldsymbol{dV} = \boldsymbol{VL}\,\boldsymbol{dF}$		$\boldsymbol{dV} = \langle\widehat{\boldsymbol{V}}\rangle \boldsymbol{A}\,\boldsymbol{dX}$		$\boldsymbol{dX} = \boldsymbol{G}\,\boldsymbol{dV}$	
Shock	Foreign $\boldsymbol{dF}$		Foreign $\boldsymbol{dX}$		Foreign $\boldsymbol{dF}$		Foreign $\boldsymbol{dX}$		Foreign $\boldsymbol{dV}$	
Impact	Domestic $\boldsymbol{dX}$		Domestic $\boldsymbol{dX}$		Domestic $\boldsymbol{dV}$		Domestic $\boldsymbol{dV}$		Domestic $\boldsymbol{dX}$	
Link	ℓ_{ij}^{ks}		a_{ij}^{ks}		v_{ij}^{ks}		$\widehat{V}_i^k a_{ij}^{ks}$		g_{ji}^{sk}	
Numerator (trade links)	Direct & indirect		Direct		Direct & indirect		Direct		Direct & indirect	
Evaluation	Imports	Exports	Imports	Exports	Imports	Exports	Imports	Exports	Imports	Exports
Normalizers:										
Total inputs	***FPEM***									***FVEX***
Total gross output		***FPEX***		***OFPEX***					***FVEM***	
Total direct inputs			***OFPEM***							
Total inputs (VA basis)					***FPEMV***					
Total value added						***FPEXV***		***OFPEXV***		
Total direct (VA basis)							***OFPEMV***			
No normalization	***FIR***									***FMR***
Decomposition:										
Face-value	***FPEMfv***	***FPEXfv***			***FPEMVfv***	***FPEXVfv***			***FVEMfv***	***FVEXfv***
Hidden exposure	***FPEMhe***	***FPEXhe***			***FPEMVhe***	***FPEXVhe***			***FVEMhe***	***FVEXhe***

Source: Authors' elaboration.

Notes: The indicators derived in this paper are shown in bold; those that are not directly derived but are simple extensions of other indicators are shown in light grey; the empty cells are indicators that could be derived by analysts interested in particular supply chain disruption questions, shocks, and linkages. More columns could be added under the cost accounting identity in parallel with those for the use accounting identity.

The naming convention uses *FPE* for foreign production exposure with the suffixes M and X reflecting the trade flow direction (import- and export-side, respectively). The suffix V is for indicators with value-added trade flows. The prefix O denotes trade flows that are observed (i.e., direct) only. The suffixes *fv* and *he* designate the face value and hidden exposure components. The last two columns work with the Ghosh identity (see appendix A.2) where the shock involves foreign value added and the domestic impact involves gross output. Here *FVE* stands for foreign value-added exposure. Our early indicators, *FIR* and *FMR*, were not normalized; the abbreviations stand for Foreign Input Reliance (*FIR*), and Foreign Market Reliance (*FMR*). We could have included more columns under the Ghosh identity in parallel with those for the Leontief identity, for instance how domestic value added responds to shocks to foreign value added, but omitted them for reasons of space.

5 Applications of the new indicators

In this section, we apply some of the GVC exposure indicators presented above to policy-relevant questions to illustrate their use. We generated the indicators using the EUREGIO-2017 database (Almazán-Gómez et al. 2023).[17] To extend the EUREGIO database to year 2017, the authors start from the EUREGIO-2013 table (developed in Chen et al. 2018) and, using Eurostat's FIGARO[18] multi-regional IO tables as the national benchmark, apply bi-proportional adjustment methods to distribute national data down to the regional level, constructing consistent interregional IO accounts for 296 NUTS-2 European, UK and EFTA regions and 64 sectors in 2017. In doing so, they also re-map all regions to the updated NUTS-2 (Rev. 2016) classification. Beyond European, UK and EFTA regions, the dataset also includes country-sector level information for 16 nations outside the EU including a rest of world aggregate (see Almazán-Gómez et al. 2023 for details).

To keep the analysis that follows focused, we concentrate solely on manufacturing. Thus, when looking at import exposure, all figures show manufacturing's intermediate purchases from all manufacturing sectors. Analogously, when looking at export exposure, we examine manufacturing's input sales to all manufacturing sectors.[19]

Our first application revisits one of the principal Brexit exercises from Chen et al. (2018) and looks at the exposure of regions in European countries to potential disruptions to GVC trade with the UK. Specifically, in line with Chen et al. (2018), the left panel of Figure 1 shows the share of each European (and EFTA) regions' value added which is

[17] The EUREGIO-2017 table from Almazán-Gómez et al. (2023) was developed in the context of the ESPON-IRIE project (ESPON-IRIE 2022; link to project resources: `https://gis-portal.espon.eu/arcgis/apps/sites/#/irie-hub`.

[18] FIGARO stands for Full International and Global Accounts for Research in Input-Output Analysis.

[19] Note that other aggregations, such as manufacturing's intermediate purchases from all sectors (goods and services, for example), can easily be constructed following the methodology outlined in Section 4.

sent to the UK. Using the terminology from Section 4.2, this is the *FPEXV* indicator. As presented in Chen et al. (2018), this indicator can also be interpreted as the share of each regions' value added which is attributed to final demand in the UK. Hence, this can be seen as a demand-side indicator.

In line with results in Chen et al. (2018), we see that *FPEXV* is largest for various regions in Germany, with wide regional variation within the country. For instance, German regions like Koblenz—which is known for the production of automotive and auto-supplier components like shock absorbers and brakes, as well as metal products like screws—exhibit much higher levels of *FPEXV* (shaded in dark blue) than German regions like Oberbayern (shaded in yellow) which produces agricultural and food items. We also see large regional exposures to the UK in some parts of Belgium, the Netherlands, Sweden, Finland, the boot of Italy, and, to a lesser extent, France and Spain.[20]

The right panel of Figure 1 switches the focus in two ways. First, noting that Brexit (and other shocks) operate on the supply, in addition to the demand, side, we examine the exposure of regions within EU (and EFTA) countries to input purchases from the UK. Second, noting that many supply-chain linkages operate between gross production in one region and gross production in another, we spotlight regional import side GVC exposure in gross (rather than value added) terms. Using the terminology from Section 4.2, this is the *FPEM* indicator.

Immediately, we notice very different patterns in terms of regional exposure to UK manufacturing inputs. Notably, the most exposed regions are now located in Eastern Europe (especially Hungary and Czech Republic), Belgium, and Ireland. In many regards, this makes sense; within Eastern Europe, the most exposed Hungarian and Czech regions are auto-part producers.[21] In Western Europe, the Belgian regions most exposed to UK inputs[22] are also heavy producers of manufacturing parts which are used as components for chemicals and petrochemicals, automotive parts, pharma and biotech, aerospace, steel and metals, and agri-food and textiles industries. Finally, it is not surprising that Ireland appears as particularly exposed to UK inputs both because of its role in the production of manufacturing parts (e.g. for pharmaceutical products, medical devices, electronics/ICT hardware, among others) and its geographical proximity to the UK.

Overall, two main messages can be drawn from Figure 1. First, inferences about regional exposure (in this case to UK manufacturing inputs) differ depending on the

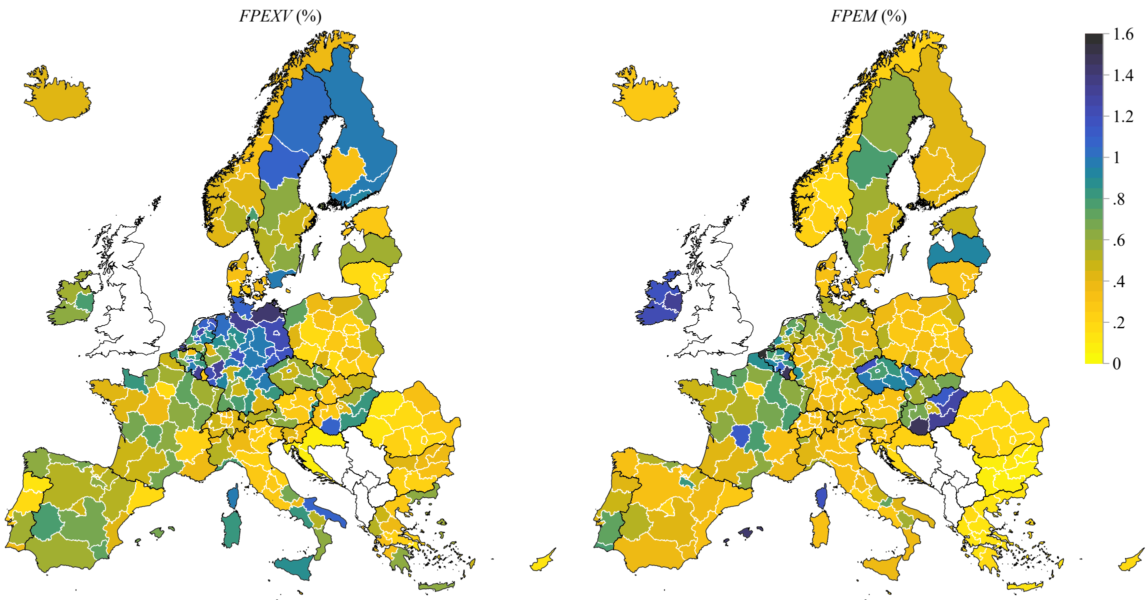
[20]While overall patterns align with those reported in Chen et al. (2018), magnitudes are smaller across the board. This is explained by two factors: differences in the sectoral composition of sales and purchases considered (Chen et al. 2018 consider all sectors whereas we consider just manufacturing to manufacturing); and differences in sample year and dataset.

[21]In Hungary, for example, Dél-Alföld is home to a Mercedes-Benz plant, BMW has a large presence in Észak-Alföld and the region has an active auto part production scene, and Észak-Magyarország is home to one of Bosch's largest electronics plants worldwide. Similarly, the most exposed Czech regions (Severozápad, Moravskoslezsko, Jihozápad, Střední Morava, Praha, Jihovýchod, and Severovýchod) are all home to significant auto parts production.

[22]These include West-Vlaanderen, Province of Luxembourg, Namur, Limburg, Hainaut, Brabant Wallon, Antwerp, and Liège.

shock considered and the type of exposure considered: demand versus supply, and value-added versus gross. We see that, by and large, considering demand versus supply side shocks paints a very different picture of regional exposures. Second, these exposures are particularly marked when thinking about disruptions to the total value of shipments, not just value-added.

Figure 1: Demand-side (*FPEXV*) versus supply-side (*FPEM*) Brexit exposure



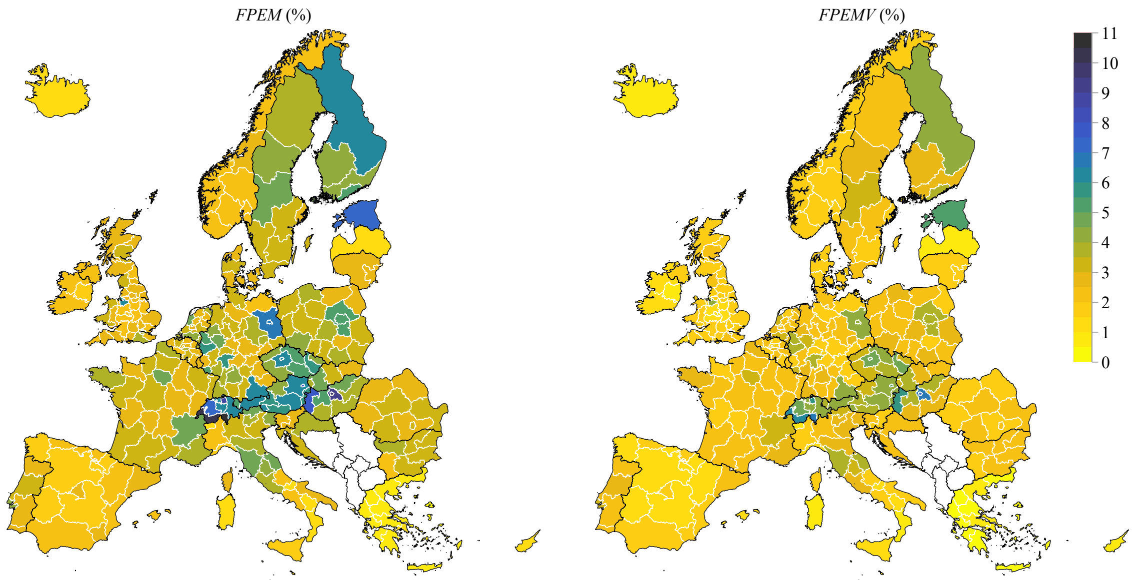
Source: Authors' elaboration based on EUREGIO-2017 IO database (Almazán-Gómez et al. 2023).
Notes: This figure shows the exposure of regions' manufacturing sector to the UK's manufacturing sector. Values for the UK are not shown as the exercise does not consider UK exposure to itself. *FPEXV* stands for Foreign Production Exposure: Export side where the suffix *V* refers to the fact that the flows are evaluated on a value-added (rather than gross) basis. *FPEM* stands for Foreign Production Exposure: Import side. For expositional purposes we do not plot the following remote regions: Canarias, Guadeloupe, Martinique, Guyane, La Réunion, Mayotte, Região Autónoma dos Açores, Região Autónoma da Madeira.

In their analysis, Chen et al. (2018) also spotlight that UK regions, outside London in particular, face markedly higher exposure to most EU regions than vice-versa. Our analysis also confirms this and shows even starker differences in regional exposures for *FPEM* versus *FPEXV* (Appendix Figure B.1).

Having uncovered large differences between GVC exposure on the export versus import side, our second application sticks to import side exposure and highlights the difference between gross and value-added indicators. In doing so, we turn the focus to regional exposure to the world's top manufacturer, China (World Bank 2020), where production of intermediate manufactured goods has advanced even more rapidly than its production of final goods. Simply put, China has become widely known as the "OPEC of industrial inputs" (Baldwin 2022).

As such, Figure 2 plots regional manufacturing sector exposures to Chinese manufacturing inputs using the *FPEM* and *FPEMV* indicators (left and right panels, respectively). Three main messages stand out. First, for every single region, exposure to China is systematically higher on a gross versus value added basis, but patterns are similar across the two indicators. In other words, despite China's prominent role in supply chain trade, the value-added content of its input production is relatively low. Importantly, this suggests that it's worthwhile considering GVC exposure in gross terms, as disruptions affect gross flows, not just value-added. Second, within country borders, there tends to be large regional heterogeneity, pointing to the fact that the effects of GVC disruptions are likely to be felt differently depending on the region in question. This is particularly true for Hungarian regions in Eastern Europe, but also for regions in Western European countries including Switzerland, Italy, and Germany. Third, as can be seen by the dark-shaded regions, the most exposed regions to Chinese inputs tend to be concentrated in Eastern European countries and Austria, all of which are heavy auto parts producers, as well as in Switzerland, where pharma and chemicals are highly reliant on Chinese intermediates, and in Finland and Sweden, where machinery, electronics, and green technology industries source significant inputs from China.

Figure 2: Regional exposure to Chinese manufacturing inputs – *FPEM* and *FPEMV*



Source: Authors' elaboration based on EUREGIO-2017 IO database (Almazán-Gómez et al. 2023).
Notes: This figure shows the exposure of regions' manufacturing sector to China's manufacturing sector. *FPEM* stands for Foreign Production Exposure: Import side and the suffix *V* refers to the fact that the flows are evaluated on a value-added (rather than gross) basis. For expositional purposes we do not plot the following remote regions: Canarias, Guadeloupe, Martinique, Guyane, La Réunion, Mayotte, Região Autónoma dos Açores, Região Autónoma da Madeira.

Noting that regions may differ in their reliance on imported inputs for production versus their reliance on input sales to international partners, Appendix Figure B.2 compares sourcing versus sales side exposure to Chinese manufacturing using the *FPEM* and *FPEX* indicators. The main takeaway is that, aside for a handful of regions, European regions are much more exposed to China on the sourcing versus sales side. This asymmetry indicates that any disruption between the EU and China would have larger impacts on EU production overall.

Turning our attention to differences across indicators we next examine the share of all

296 regions in the EUREGIO-2017 database for which the top partner is a specific country (Figure 3). On the import side (*OFPEM*, *FPEM* and *FPEMV*) the figure shows the share of regions for which the top input supplier is China, the US, Germany, or other. On the export side (*OFPEX*, *FPEX* and *FPEXV*) the figure shows the share of regions for which the top destination of intermediate production is one of these countries. This exercise shows how different indicators provide different answers to the same question: *To which foreign supplier or destination of intermediates is a particular region's manufacturing sector most exposed?*

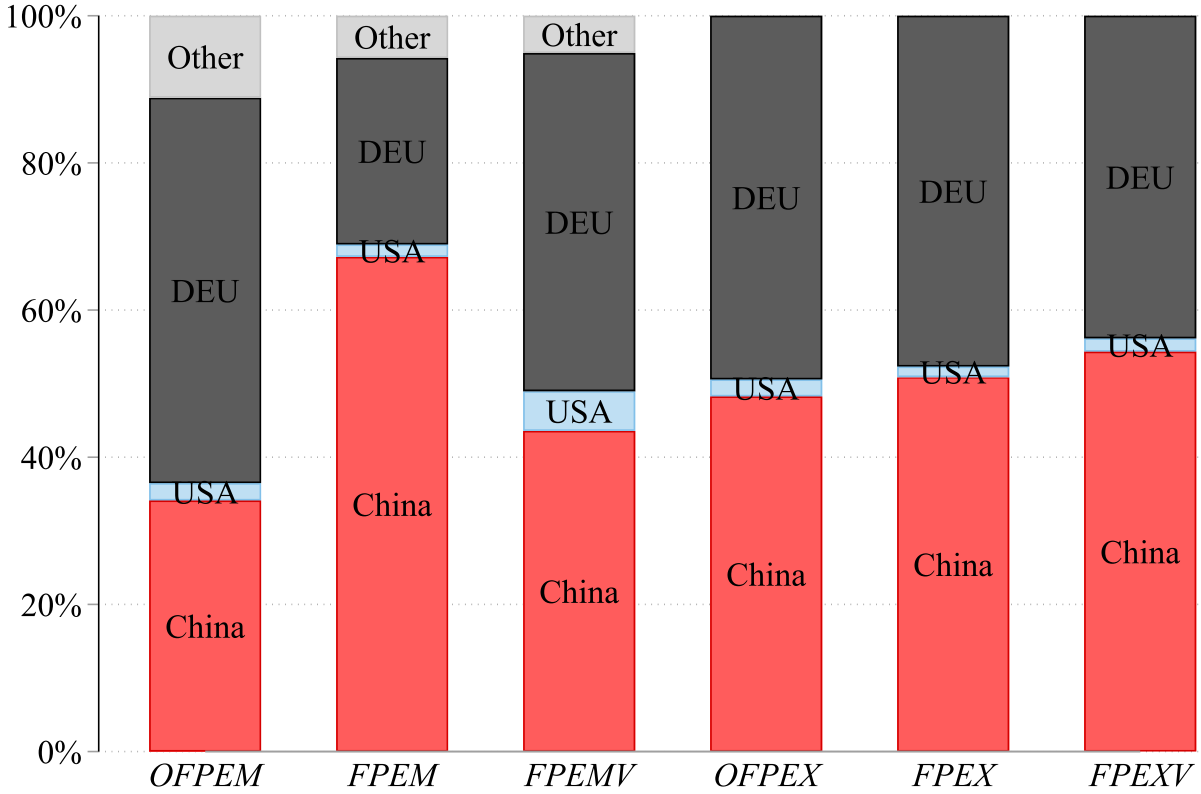
Looking at the first three stacked bars reveals stark differences in the top input supplier depending on the indicator used. For instance, when considering direct GVC links only (*OFPEM*), Germany comes out as the top input supplier to just over half the 296 regions considered. In contrast, China is the top input supplier to 67 percent of regions when considering all (direct and indirect) GVC links on a gross basis (*FPEM*), and 44 percent of regions when considering all GVC links on a value-added basis (*FPEMV*, with the US also taking a larger role). What can we conclude? First, looking at direct trade links only masks the importance of input trade which flows through other countries. Otherwise put, answering the question *'Who is your top supplier?'* with the *OFPEM* indicator would give a very different answer than would the *FPEM* or *FPEMV* indicator. Second, echoing one of the main messages which emerged from Figure 2, the differences in the height of the stacked bars across *FPEM* and *FPEMV* hints that the value-added content of Chinese inputs is relatively lower than inputs which are sourced from the US and Germany.[23]

In contrast, patterns across the last three stacked bars look much more similar; the share of regions for which the top destination of intermediate production is more or less evenly split between China and Germany. In short, this paints a picture of regional value chain activity which is more localized on the export side (within 'Factory Europe') than on the import side. The fact that the share of regions for which the top destination of intermediate production is China is higher for *FPEXV* versus *FPEX* also underscores an asymmetry in the composition in export patterns: while European regional imports of Chinese intermediates may contain low Chinese value added, European regional exports of intermediates to China are relatively high in value added.

Importantly, on both the import side and export side, the fact that the indicators give different answers to the same question is not an indictment of any indicator; it is a 'buyer beware' warning and a call for careful thinking when selecting indicators. For example, *OFPEM* focuses on direct trade links, while *FPEM* focuses on look-through links between production sectors. If the shock of concern is only to bilateral trade—a bilateral tariff, or embargo, for example—then *OFPEM* may be more appropriate. If the shock is to a whole sector, region, or nation—a complete decoupling of European manufacturing from China, for example—then *FPEM* may be more appropriate.

[23] This is evidenced by the fact that the height of the China bar is higher for the *FPEM* verus *FPEMV* indicator.

Figure 3: Share of 296 EU, EFTA, and UK regions for which top partner is China, US, Germany or other

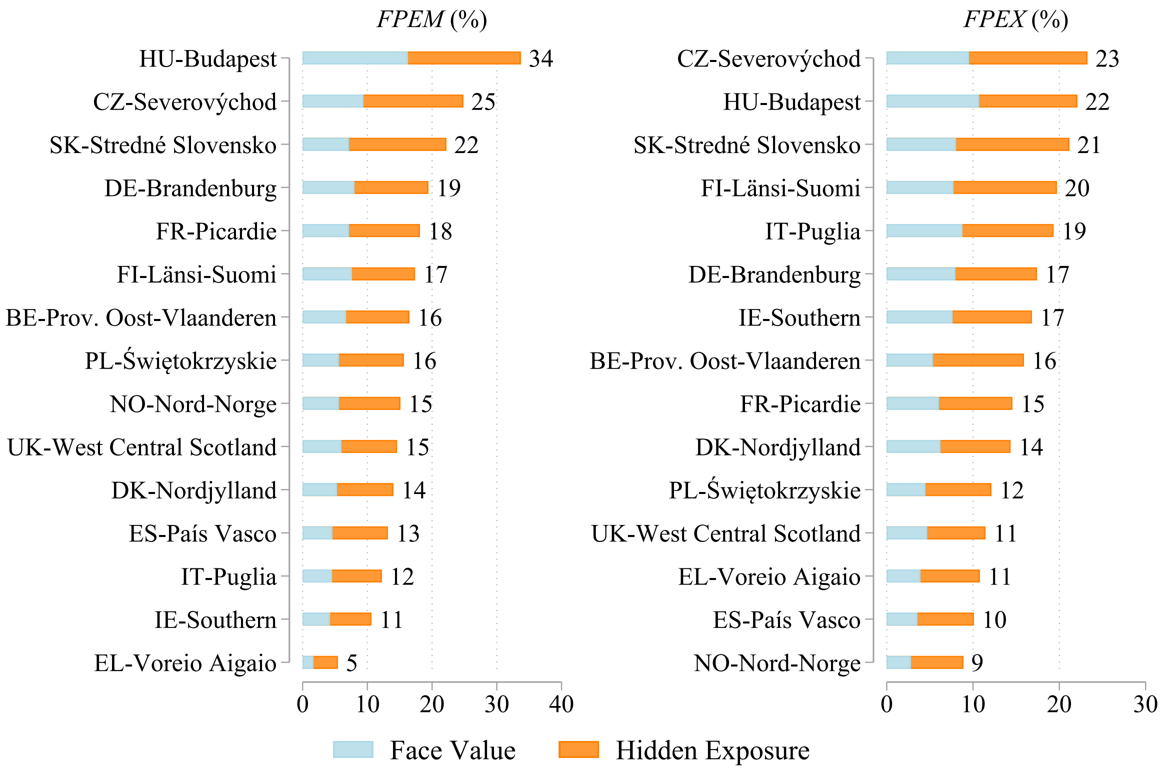


Source: Authors' elaboration based on EUREGIO-2017 IO database (Almazán-Gómez et al. 2023). Notes: On the import side (*OFPEM*, *FPEM* and *FPEMV*) this figure shows the share of regions for which the top input supplier is China, the US, Germany, or other. On the export side (*OFPEX*, *FPEX* and *FPEXV*) this figure shows the share of regions for which the top destination of intermediate production is China, the US, Germany, or other.

Finally, Figure 4 decomposes international exposure (i.e. to regions outside a given country border) on an import (*FPEM*) and export (*FPEX*) basis into face-value and hidden-exposure links for 15 select regions. To ensure that the figure included a wide variation of regional exposures, we selected regions by first ranking the *FPEM* variable in descending order, and then choosing 15 regions which are of roughly equal distance in the ranking from each other. Thus, in our dataset, Budapest (in Hungary) has the highest *FPEM* and Voreio Aigaio (in Greece) has the lowest. Also commonly referred to in the literature as direct and indirect exposure (see, for example, Antràs and Chor 2022, Chen et al. 2018), the face value and hidden exposure components tell us the share of exposure which is observed versus 'hidden' in the sense that it is not directly observed in the data. For instance, the FR-Picardie bar of the FPEM panel says that 18% of Picardie's total manufacturing inputs are sourced from the manufacturing sector in regions outside France. Of that, roughly 7 percentage points are sourced directly (face-value exposure), while roughly 12 percentage points are sourced indirectly (hidden exposure).

The numbers are striking. On both the import and export side, hidden exposure links account for at least half—and in most cases more than two-thirds—of regions' total international exposure. Put differently, the ratio of total (look-through) to face-value exposure is between two and three, meaning that look-through exposure is two to three times higher than face-value statistics suggest. Zooming in on regional differences, we observe, unsurprisingly, that, by and large, regions with the highest overall exposure are located in the countries which are heavily involved in input production (Hungary, Slovakia, Germany, Belgium) whereas regions with the lowest overall exposures are more remote and have less prominent manufacturing industries (Greece, Norway, Spain, etc.).

Figure 4: Selected regions' international exposure: Face-value versus hidden exposure



Source: Authors' elaboration based on EUREGIO-2017 IO database (Almazán-Gómez et al. 2023). Notes: This figure shows the import side (*FPEM*) and export side (*FPEX*) international exposure, i.e. to regions outside a given country's border, of select regions. The horizontal length of each bar corresponds to each region's look-through exposure. Within each horizontal bar, the stacked bars for face-value (*FV*) and hidden exposure (*HE*) decompose look-through exposure into *FV* versus *HE* components.

6 Conclusion

This paper set out to shed light on the complexities of GVCs' sub-national dimensions and to raise relevant considerations about how to measure the way in which global shocks and disruptions propagate spatially, affecting the geographical and functional distribution of GVCs at the sub-national level. To do so, we make two primary contributions, one theoretical and one empirical.

Our main theoretical contribution is to extend what we have called, in prior unpublished work, the 'shocks approach to indicator design' (Baldwin et al. 2022) to the regional level. Importantly, while we began developing this approach a few years ago, it has been advanced in various places (Baldwin et al. 2023) and there is no one piece which pulls all the components together into a single, unified mathematical framework. Our aim in doing so here is to provide researchers and policymakers with an organizing framework and toolkit for thinking about which indicators should be used for which policy or empirical questions, in particular those related to how global disruptions propagate unevenly across regions within and across nations. The framework brings together several strands of work on value chains, trade exposure, and regional interdependence into a single, comparable system. It highlights three distinctions that are often treated separately but matter greatly for understanding exposure.

The first is between direct and indirect regional value chain exposure to global shocks, which we call face-value and hidden exposure, respectively. Because of its complexity, GVC trade can be difficult to track as standard bilateral trade data only show the final cross-border stage of transactions, not the whole production chain. The face-value versus hidden exposure distinction centers on the differences between observed linkages that are visible from bilateral trade data and those that require IO calculations to determine the ultimate source of inputs, or the ultimate destination of outputs, as they travel indirectly through GVC networks.

The second is between import-side and export-side exposure, namely whether a region's vulnerability stems more from its suppliers or from its customers. This is important because regions' trade patterns—both within and across nations—may differ significantly on the sourcing- versus sales-side. One region may source most of its inputs internationally and sell locally, while another may source most of its inputs locally and sell internationally. As such, the indicators we develop in this paper help gauge the connections between foreign shocks and regional economic activity.

The third is between gross and value-added linkages. This focuses on whether shocks affect the total transaction value of flows or just the domestic value which is created along the way. Thinking systematically across these three dimensions helps explain why regions that appear sheltered from disruption under one measure can look highly vulnerable under another. Taken together, these distinctions form a simple but versatile toolkit for constructing value chain indicators that are transparent, comparable, and grounded in a clear economic logic.

Our main empirical contribution lies in conducting a set of empirical exercises that illustrate how the various indicators can change what inferences might be drawn compared to when the 'classic' GVC indicators are used to analyze the impact of global shocks on regional supply chain trade patterns. Revisiting the case of Brexit, regions that looked most exposed on the demand side were not the same ones which appeared most exposed on the supply side. Simply put, this showcases that regional vulnerability depends as much on where inputs come from as on where output is sold. In the China case, measuring trade on a gross rather than a value-added basis revealed much higher exposure across almost all regions, underscoring Europe's dependence on imported Chinese intermediates for production. Together, these findings show how different indicators can change which regions appear most at risk, and why exposure should be viewed as multidimensional rather than a single number.

These results carry clear policy lessons. First, choosing appropriate indicators requires careful reflection upon the questions for which the indicators are intended. Second, regional resilience strategies need to look beyond headline trade flows and consider the hidden dependencies buried in multi-tier supply networks. Policymakers should distinguish between participation in global value chains and dependence on them, especially on the sourcing side. The toolkit we develop can help identify where supply-chain risks are concentrated and guide efforts to diversify inputs, target regional support, or design stress tests for critical industries. In short, it provides an evidence base for building resilience rather than simply reacting to shocks.

Like any static input–output (IO) framework, our approach captures exposure patterns but not behavioral adjustments or price responses that follow a shock. The results therefore reflect structural vulnerability, not full equilibrium outcomes. Imposed by the fact that IO tables assume fixed prices and Leontief technology, prices are taken as fixed even though the substitution of sources and inputs is critical to gauging the impact of any given supply chain disruption. In line with the vast IO literature, it is thus best to think of the exposure indicators as first-order approximations. Data limitations also matter. Regional (and country-level) IO tables remain infrequent, provide greater detail for advanced economies, and leave some important services sectors (e.g. digital linkages) underrepresented. Future work could extend the indicators to newer datasets, integrate them into dynamic or network-based models, and link supply-chain exposure to climate, cyber, or infrastructure risks. The broader goal is to build a consistent geography of resilience in an interdependent world.

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Appendix

A Deriving foreign value-added exposure indicators

A.1 Tools for measuring value-added exposure

The main text presents the expression of gross output from the use accounting perspective. This can equally be seen from the cost accounting perspective, which looks at the cost components of gross output. Using the notation presented in the main text, the cost accounting identity is: $\boldsymbol{X} = \boldsymbol{T}'\,\boldsymbol{\iota} + \boldsymbol{V}$ where the $'$ symbol denotes the transpose.

Transforming $\boldsymbol{T}'$ into allocation coefficients and the vector of gross output, the cost accounting identity can be rewritten as:

$$\boldsymbol{X} = \boldsymbol{B}'\,\boldsymbol{X} + \boldsymbol{V};\ \boldsymbol{B}' = \begin{bmatrix} b_{11} & \dots & b_{R1} \\ \vdots & \ddots & \vdots \\ b_{1R} & \dots & b_{RR} \end{bmatrix} \tag{A.1}$$

where $\boldsymbol{B}'$ is a $(RS\text{x}RS)$ matrix of allocation coefficients, where each b_{ji} is a $(S\text{x}S)$ matrix with elements $b_{ji}^{sk} = {}^{T_{ji}^{sk}}/_{X_i^k}$ and $\boldsymbol{T}'\,\boldsymbol{\iota} \equiv \boldsymbol{B}'\,\boldsymbol{X}$. Solving (A.1) for $\boldsymbol{X}$ yields:

$$\boldsymbol{X} = \boldsymbol{G}\,\boldsymbol{V},\ \text{where } \boldsymbol{G} \equiv (\boldsymbol{I} - \boldsymbol{B}')^{-1} \tag{A.2}$$

where $\boldsymbol{I}$ is a $(RS\text{x}RS)$ identity matrix and $\boldsymbol{G}$ is the Ghosh inverse matrix. The elements of $\boldsymbol{G}$, denoted g_{ji}^{sk} tell us the gross production in every sector that is needed to produce a given vector of value added in every sector, taking account of all direct and indirect linkages. As with the Leontief inverse $\boldsymbol{L}$, note that $\boldsymbol{G}$ is also part of an infinite sequence:

$$(\boldsymbol{I} - \boldsymbol{B}')^{-1} = \boldsymbol{I} + \boldsymbol{B}' + \boldsymbol{B}'^{2} + \boldsymbol{B}'^{3} + \ldots + \boldsymbol{B}'^{\infty} \tag{A.3}$$

A.2 Ghosh-based indicators: Foreign exposure based on value added

The cost accounting identity can be used to derive measures of supply chain exposure akin to those presented in the main text using the use accounting identity.

We call the analogous measure to *FIR* Foreign Market Reliance (*FMR*).[1] As presented

[1] *FMR* at the country-pair-sector level is included in the 2023 and 2025 updates of the OECD TiVA database. They also include *FMR* at the country-pair-*macro*-sector level (e.g. total manufacturing, total services, etc., as well as the total economy), where the aggregation is done using gross output weights of the macro-sector: $FMR_{ji}^{K} = \sum_{k\in K}\left(FMR_{ji}^{k} * \left({}^{X_i^k}/_{\sum_{k\in K} X_i^k}\right)\right)$ where K corresponds to the exporting macro-sectors (see technical note entitled "Guide to OECD trade in Gross Output Indicators, 2023 edition" in Gross Output Flows in Global Value Chains download folder: `https://www.oecd.org/en/data/datasets/gross-output-flows-in-global-value-chains.html`).

in Baldwin and Freeman (2022) at the country-pair-sector level, and here denoted for the region-pair-sector level, the *FMR* of sector k in region i selling to region j is:

$$FMR_{ji}^{k} = \sum_{s}^{S} g_{ji}^{sk} \tag{A.4}$$

The shocks approach is also easily applied to looking at linkages between the value added of every sector in every region and the gross production in every sector using $\boldsymbol{X} = \boldsymbol{G}\boldsymbol{V}$.

We introduce two additional measures: Foreign Value Added Exposure: Import side (*FVEM*) and Export side (*FVEX*). These are the value-added versions of *FPEM* and *FPEX*, and capture a region's exposure to value added that is embedded in inputs sourced from foreign trade partners (on the import side) and sent to foreign trade partners (on the export side) through direct and indirect links. They are different from *FPEMV* and *FPEXV* in that they consider the links between value added and gross output (due to $\boldsymbol{X} = \boldsymbol{G}\boldsymbol{V}$) versus final demand and value added (due to $\boldsymbol{V} = \boldsymbol{VL}\boldsymbol{F}$).

As such, *FVEM* is defined as:

$$FVEM_{ji}^{sk} = 100 * \frac{g_{ji}^{sk} V_i^k}{\sum_i^R \sum_k^S g_{ji}^{sk} V_i^k} \tag{A.5}$$

Importantly, note that the subscripts mirror those in $\boldsymbol{L}$ because $\boldsymbol{G}$ is defined using the transpose of $\boldsymbol{B}$ given that we use the cost accounting identity. In other words, the denominator corresponds to the total gross output of sector s in region j, X_j^s.

When considering export-side exposure we normalize by the total intermediate inputs sold by the exporting region-sector, now defined on a Ghosh basis:

$$FVEX_{ji}^{sk} = 100 * \frac{g_{ji}^{sk} V_i^k}{\sum_j^R \sum_s^S g_{ji}^{sk} V_i^k} \tag{A.6}$$

Both *FVEM* and *FVEX* range from zero to 100. It is straightforward to see that the aggregations presented in the main text carry through. Moreover, we can also split the Ghosh-based indicators into face value and hidden exposure components, due to equation (A.3). For example, the decomposition of *FVEM* is:

$$FVEM_{ji}^{sk} = 100 * \left(\frac{\left(\mathbb{1}\left[(i,k) = (j,s)\right] + b_{ji}^{sk}\right) V_i^k}{\sum_i^R \sum_k^S g_{ji}^{sk} V_i^k} + \frac{\left(\sum_{m=2}^{\infty} b_{ji}^{sk,m}\right) V_i^k}{\sum_i^R \sum_k^S g_{ji}^{sk} V_i^k} \right) \tag{A.7}$$

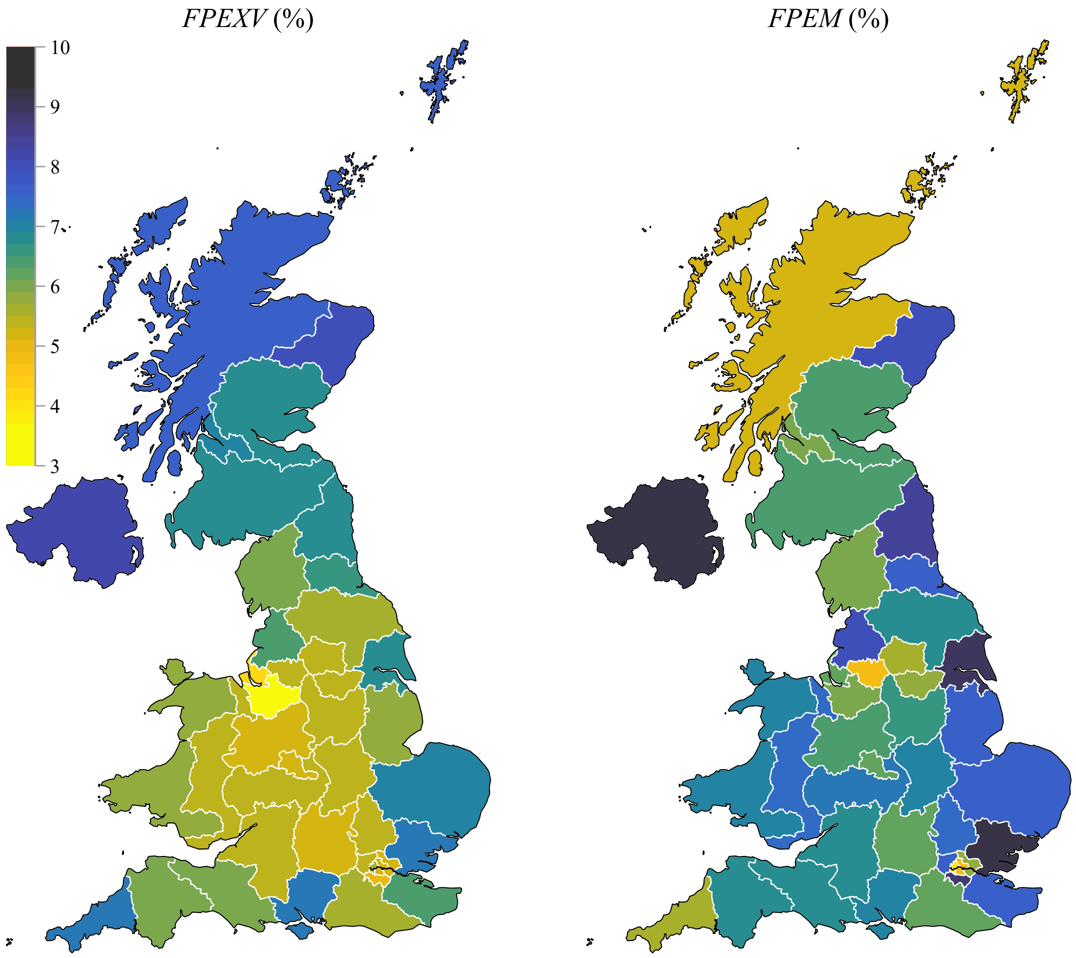
where $b_{ji}^{sk,m}$ is a component of the $\boldsymbol{B'}$ matrix raised to the power of m and $\mathbb{1}[i = j]$ is the indicator function that equals one when the region and sector coincide $(i,k) = (j,s)$. In the decomposition on the right-hand side, the first and second terms in the parentheses are face-value and hidden exposure, respectively.

B Regional GVC exposure

This appendix presents additional charts and figures referred to in the main text.

Using the same data source and computation methods described in the main text, Figure B.1 shows the exposure of UK regions to the EU. This is the flip side of the policy experiment from Figure 1, which showed EU regions' exposure to the UK. Three observations are noteworthy. First, compared to Figure 1, UK regions are more exposed EU GVCs than vice versa, and this holds irrespective of the type of exposure considered (sourcing versus sales) or the basis upon which GVC trade is calculated (value added versus gross). Second, UK regions outside of London face the highest exposure to the EU, with differences particularly marked on the sourcing (i.e. import) side. Finally, with the exception of the northernmost region in Scotland, import exposure to the EU (on a gross basis, right panel) is larger than export exposure (on a value added basis, left panel).

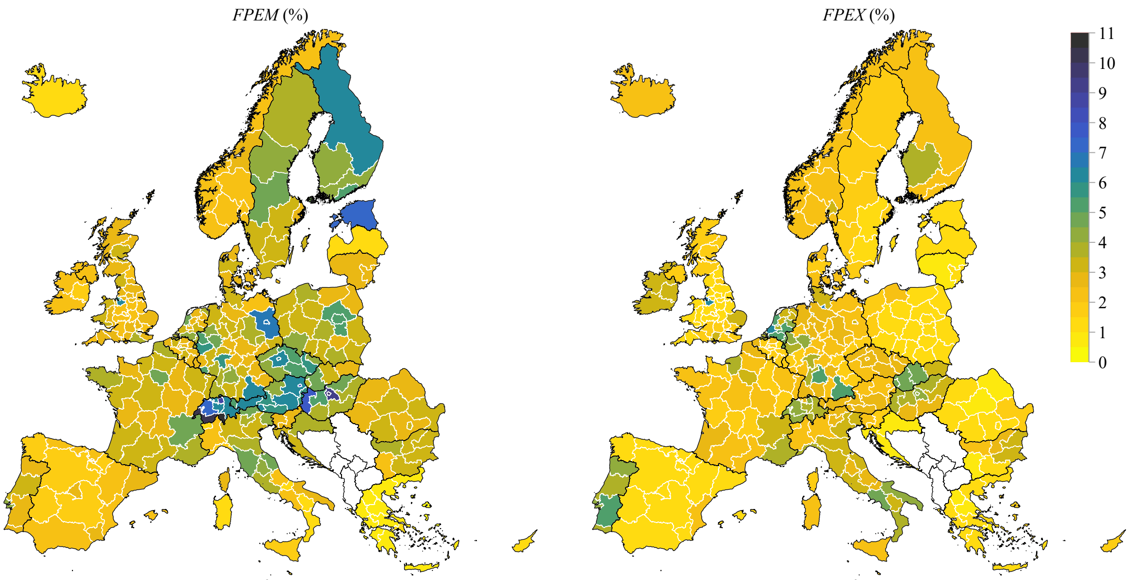
Figure B.1: Exposure of UK regions to the EU



Source: Authors' elaboration based on EUREGIO-2017 IO database (Almazán-Gómez et al. 2023).
Notes: This figure shows the exposure of UK regions' manufacturing sector to the EU's manufacturing sector. *FPEXV* stands for Foreign Production Exposure: Export side where the suffix *V* refers to the fact that the flows are evaluated on a value-added (rather than gross) basis. *FPEM* stands for Foreign Production Exposure: Import side. For expositional purposes we do not plot the following remote regions: Canarias, Guadeloupe, Martinique, Guyane, La Réunion, Mayotte, Região Autónoma dos Açores, Região Autónoma da Madeira.

Figure B.2 revisits the exposure of European regions to Chinese manufacturing inputs, now comparing gross exposure on the import side ($FPEM$) to the export side ($FPEX$). The main takeaway is that very different patterns for sourcing versus sales exist across regions. Except for a few regions in southern Italy and Portugal, EU regions are much more exposed to China on the sourcing versus sales side, indicating that any disruption between the EU and China would have larger impacts on EU production overall.

Figure B.2: Exposure of EU, EFTA, and UK regions to China – *FPEM* and *FPEX*



Source: Authors' elaboration based on EUREGIO-2017 IO database (Almazán-Gómez et al. 2023).
Note: This figure shows the exposure of regions' manufacturing sector to China's manufacturing sector. *FPEM* stands for Foreign Production Exposure: Import side and *FPEX* stands for Foreign Production Exposure: Export side. For expositional purposes we do not plot the following remote regions: Canarias, Guadeloupe, Martinique, Guyane, La Réunion, Mayotte, Região Autónoma dos Açores, Região Autónoma da Madeira.