# How Global Are Local Value Chains?*

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July 2026

**Abstract**

This paper examines how foreign input-cost shocks transmit through domestic supply chains, shaping local economic vulnerabilities. Using detailed firm-to-firm domestic and foreign transaction data, we quantify the direct and indirect exposure of Italian labor markets to imports from China and from other extra-EU source markets. We assess the importance of firms' domestic and foreign sourcing linkages for overall exposure and highlight the critical role of wholesalers and top importing firms within the domestic network in shaping tail risks. Marked local disparities in exposure reveal that aggregate import statistics conceal substantial and uneven regional vulnerabilities.

*Keywords:* global value chains, local labor markets, trade shocks, firm-to-firm linkages, geoeconomic fragmentation, production network.
*JEL codes:* F14, R12, L14, F61, R15

*We thank Andrea Benecchi and Giulio Papini for their help in constructing the data underlying the analysis. We thank the participants at the ECB Trade Experts Network workshop and European Commission ECFIN Research Seminar, James Faulconbridge (editor) and three anonymous referees for their helpful comments and suggestions. The views expressed in this paper are those of the authors and do not necessarily reflect those of Banca d'Italia. All remaining errors are our own.

# 1 Introduction

Decades of economic integration have fostered global value chains (GVCs) linking regions, sectors, and firms across borders (Henderson et al., 2002; Coe et al., 2004; Coe, Dicken and Hess, 2008; Coe and Yeung, 2019; Yeung and Coe, 2015; World Bank, 2019). Recent disruptive events, such as the COVID-19 pandemic and the Russian invasion of Ukraine, have revealed significant vulnerabilities in global production networks (Baldwin and Freeman, 2022; Gopinath et al., 2025), while escalating geopolitical tensions and renewed protectionism are reshaping the geography of production (Curran, Nadvi and Campling, 2019). Although the impact of such changes may appear moderate at the national level, their local effects can be substantial (Magerman and Palazzolo, 2024), depending on how sub-national networks are integrated into global production (Coe et al., 2004). This is especially true where activity is concentrated in specific sectors, technologies, or foreign markets (Ellison and Glaeser, 1997, 1999; Boschma and Iammarino, 2009), and where domestic supply linkages spread shocks beyond what direct import data suggest (Giroud and Mueller, 2019; Lafrogne-Joussier, Martin and Mejean, 2022). Understanding GVC integration at a granular, sub-national level is therefore crucial for assessing local vulnerabilities and resilience.

In this paper, we map the domestic and foreign sourcing networks of Italian firms and quantify the direct and indirect exposure of Italian Local Labor Markets (LLMs) to input shocks originating in extra-EU countries. Within this broader analysis, we devote particular attention to China, reflecting both its quantitative importance and its policy relevance. Between 2015 and 2025, China's share of extra-EU imports increased from 18.0% to 22.3% in the EU and from about 16% to around 22% in Italy, making it by far Italy's largest extra-EU supplier. This exposure is especially relevant amid growing concerns about critical dependencies and intensifying competition from Chinese producers, including in technologically advanced industries and sectors in which Europe has traditionally enjoyed a comparative advantage, such as automotive production (European Commission, 2023; Aprigliano et al., 2026). Comparing China with other extra-EU origins therefore allows us to assess whether these risks have a distinctive local footprint or instead reflect Italy's broader pattern of non-EU sourcing.

Micro-level data on firms and their supply relationships are essential to this exercise (Calvó López and Golub, 2023). We use Italian firm-level transaction data for 2022. Mandatory business-to-business electronic invoices are combined with firm-level imports from Intrastat and customs declarations. This allows us to observe not only which firms import but also which domestic firms buy from them and how these links connect local economies across space. The resulting production network consists of about 1.8 million firms, roughly four times more than in other papers using comparable data (see Bacilieri et al., 2026, for a survey).

Following Dhyne et al. (2021), our exposure measure captures the share of a firm's cost base exposed to inputs from a foreign market, directly through its own imports and indirectly through domestic suppliers. We microfound the measure as the first-order elasticity of unit cost to a proportional increase in the cost of inputs sourced from that market. We then aggregate firm exposure to the LLM-level using total costs as weights, so that LLM exposure is the elasticity of the local cost base. These are ex-ante network indicators based on benchmark expenditure shares. They show where foreign input-cost shocks enter the economy and how they propagate before firms adjust, rather than measuring realized effects on output, welfare, or employment.

The move from firms to LLMs is central. LLMs are functional labor-market areas based on commuting flows and are therefore the relevant scale for local specialization, agglomeration, and potential adjustment; they are not closed units, however, and trade intensively with each other. While LLMs identify the *geography of incidence*—the local cost base potentially affected—the firm network identifies the *geography of transmission*. This distinction allows us to separate vulnerability generated by direct imports, local production links, and connections to suppliers elsewhere in Italy.

This framing is the paper's main economic-geography contribution. Standard measures of local trade exposure map national shocks to places based on their sectoral composition (Autor, Dorn and Hanson, 2013; Acemoglu et al., 2016). We instead trace shocks through products, firms, and production networks before linking them to places. This more granular approach reveals both the firms through which import exposure enters the economy and the network links through which it spreads across workers and local production systems. As a result, we uncover the internal allocation and transmission of cost sensitivity within local economies—patterns that remain hidden when exposure is measured using aggregate statistics.

Domestic linkages are quantitatively important. National cost-weighted exposure to China equals 3.3% of total costs and exposure to other extra-EU imports 8.2%; in both cases, the indirect component transmitted through domestic suppliers exceeds the direct component, and it does so in about nine out of ten local labor markets. Chinese exposure displays a pronounced upper tail, with total exposure in the most exposed LLMs several times the national average.

Direct exposure is concentrated in the Center-North, whereas many LLMs in the Center-South and the islands have limited direct imports but high indirect exposure. For both source groups, nearly three quarters of indirect exposure is transmitted through suppliers in non-contiguous LLMs. Local linkages matter, but exposure is propagated mainly through national production connecting major hubs with specialized and peripheral systems. This matters for place-based policy because the firms and products initially affected by a shock are not necessarily located where its effects are ultimately felt. The findings align with work on shock propagation through domestic networks (Huneeus, 2018; Dhyne et al., 2021; Pichler et al., 2023) and on local adjustment under specialization and limited mobility (Topalova, 2010; Kovak, 2013; Autor, Dorn and Hanson, 2016; Caliendo, Dvorkin and Parro, 2019; Helm, 2020).

LLMs highly exposed to Chinese inputs tend also to be more exposed to other extra-EU imports, but the upper tails overlap only partially. China is embedded in Italy's broader geography of non-EU sourcing, yet is not simply a scaled-down version of it. This comparison is important for policy interpretation: an intervention aimed only at China-specific dependence would miss local vulnerabilities tied to other origins, while a generic extra-EU indicator would conceal places in which Chinese inputs are unusually important. Source-specific exposure must therefore be evaluated within the common domestic network that distributes it.

A subset of products, sectors, and firms mediate this exposure. Metals and mineral products generate the largest total exposure, followed by agrifood, chemicals, machinery, and other manufacturing inputs. AI-enabling and green products also generate non-negligible exposure with distinct geographies: AI-enabling exposure concentrates in the Center-North, while green-product exposure is more diffuse. Strategic input dependence is therefore territorial as well as national and sectoral.

Specific groups of firms shape the level and spatial distribution of exposure to foreign input-cost shocks. Wholesale trade accounts for roughly one third to two fifths of indirect exposure, depending on the source group, while retailers play a minor role. The top 100 importers account for a substantial share of total exposure, although sizable indirect exposure remains after neutralizing them. Among the most exposed LLMs, total exposure can exceed 30% of local costs and is often anchored by a dominant importer, selected wholesale intermediaries, or a narrow product set, consistent with the "rivet effect" in the regional-resilience literature (Martin and Sunley, 2015).

Finally, we clarify the relationship between firm-level exposure measures and sector–region input–output (IO) approaches. Firm-level data matter because they reveal which firms within a cell are directly exposed and which of those firms actually supply domestic buyers. A conceptual example, a controlled simulation, and a comparison based on the actual data show that aggregation to sector–region cells can either understate or overstate the actual indirect exposure, especially for the least and most exposed regions, depending on whether the exposed firms are central or peripheral suppliers. The bias therefore reflects the interaction between firm-level exposure and network position, even when aggregate direct exposure is preserved.

**Related Literature.** This paper contributes to four strands of the literature.

First, it contributes to work on how international shocks are transmitted within domestic economies. Earlier studies typically relied on industry- and region-level input-output linkages (Javorcik, 2004; Acemoglu et al., 2012, 2016; Helm, 2020), whose key limitation is the assumption that firms within a sector-region cell are representative in their input mix and network position (Koopman, Wang and Wei, 2012; Kee and Tang, 2016; De Gortari, 2019; Bems and Kikkawa, 2021). Firm-to-firm transaction data have enabled major advances in measuring shock transmission (Barrot and Sauvagnat, 2016; Huneeus, 2018; Boehm, Flaaen and Pandalai-Nayar, 2019; Carvalho et al., 2021; Alfaro-Urena, Manelici and Vasquez, 2022; Santamaria, Ventura and Yeşilbayraktar, 2023; Demir et al., 2024; Corsetti, Demir and Javorcik, 2025; Chen et al., 2026). Using administrative data on domestic transactions and firm-level imports, we measure the exposure of Italian LLMs without imposing proportionality within sector–region cells. Our main contribution to this literature is to show that exposure is highly concentrated: large importers and wholesale intermediaries with many links within and across LLMs account for a disproportionate share of aggregate exposure.

Second, by showing how inter-firm and inter-sectoral links shape heterogeneous local exposure, the paper contributes to the economic-geography literature on regional resilience (Martin, 2012; Diodato and Weterings, 2014; Giannakis and Bruggeman, 2017; Giannakis, Bruggeman and Mamuneas, 2024). Martin and Sunley (n.d.) argue that resilience measures should move from aggregate regional indicators toward a micro-level perspective in which regional outcomes emerge from the decisions and links of individual actors. We follow this agenda by showing that local vulnerability depends not only on imports within a place, but also on connections between local firms and suppliers elsewhere. The resulting measures can also serve as building blocks for constructing exposure shares in shift-share designs for causal analysis (Goldsmith-Pinkham, Sorkin and Swift, 2020; Borusyak, Hull and Jaravel, 2022).

Third, the paper speaks to research on spatial concentration and exposure to international shocks. Economic activity clusters in productive regions through agglomeration and firm selection (Combes et al., 2012; Behrens, Duranton and Robert-Nicoud, 2014; Gaubert, 2018; Davis and Dingel, 2020; De la Roca, Ottaviano and Puga, 2023), and this concentration can amplify exposure to global shocks (Coşar and Fajgelbaum, 2016; Redding, 2022; Bakker et al., 2024). Our findings add that foreign-input exposure diffuses beyond directly exposed hubs through firm-level production links, reaching specialized and peripheral LLMs connected to them through domestic supply chains.

Finally, the paper contributes to work on geoeconomic fragmentation and GVC reorganization, which largely evaluates risks at the aggregate cross-country level (see Baldwin and Freeman, 2022, for a survey). Baldwin, Freeman and Theodorakopoulos (2023) show that face-value imports can understate reliance on a source market because foreign inputs arrive embodied in third-country imports. We document a complementary within-country dimension: holding import content fixed, direct statistics conceal which local economies bear the cost sensitivity and the domestic channels through which it reaches them. What is hidden in our setting is not additional import content, but where cost sensitivity is incident and through which domestic channels it travels. By comparing China with the rest of extra-EU sourcing and by separating broad product groups, strategic categories, importers, and supplier locations, the paper also shows that fragmentation risks have source-specific and product-specific territorial footprints that national averages cannot recover.

The paper unfolds as follows. Section 2 describes the data and coverage; Section 3 presents the exposure measures and LLM aggregation; Section 4 reports the geographic, product, and firm-level evidence; Section 5 examines sector–region aggregation bias; and Section 6 concludes.

# 2 Data

Our empirical analysis draws on Italian administrative data for 2022, covering domestic and international transactions. Firms are identified through VAT numbers or fiscal codes, which allow different datasets to be merged unambiguously.[1] The dataset combines electronic invoicing for domestic transactions, customs and Intrastat declarations for foreign trade, firm registry data, employment records, and financial statements.

The first source, *FATTEL*, records domestic business-to-business transactions through electronic invoices. Since 2019, e-invoicing has been mandatory for private entities resident or established in Italy, subject to limited exemptions. Invoices are submitted through the Revenue Agency's Exchange System and identify the VAT numbers of buyer and

[1] The treatment of multiplant firms, VAT groups, cleaning, and preparation is described in Appendix A. We use 2022 because it is the most recent available year.

seller and the transaction value. The available data are aggregated annually.

The second source covers trade in goods. Intra-EU transactions are reported through Intrastat, while extra-EU trade is recorded in customs declarations. Both identify the Italian firm's VAT number, partner country, product classification, and transaction value.[2] Records are matched to firms after adjustments for VAT groups, allowing flows reported under different legal entities to be consolidated. Finally, *CERVED* provides reclassified balance sheets for about 700,000 limited companies, while INPS (Italy's National Social Security Institute) provides employment information, and Infocamere (the digital platform of the Italian Chambers of Commerce) provides firm registry data.

The dataset combines revenues, employment, assets, legal form, sector, location, domestic links, and foreign trade.[3] The production network contains nearly 1.8 million firms and 79 million directed links (Table 1), substantially more than most comparable firm-network datasets (see Bacilieri et al., 2026, for a survey). We observe 74,334 importing firms and EUR 422.7 billion in foreign purchases. Of these, 59,914 import from extra-EU countries for EUR 148.5 billion, and 31,009 import from China for EUR 46.3 billion.

Table 1 illustrates that the Italian production network is granular and skewed. The median buyer sources from 16 domestic suppliers, compared with 157 at the 95th percentile. Median total input purchases are EUR 67 thousand, while the 95th percentile reaches EUR 3.9 million. The median importer purchases EUR 200 thousand abroad, compared with almost EUR 18 million at the 95th percentile. A small set of highly connected and high-value firms can therefore play a disproportionate role in shock transmission.

The network is spatially extensive. About one quarter of domestic links and transaction value are within the same LLM; neighboring LLMs account for 13.9% of links and 9.3% of value; and non-neighboring LLMs account for 60.4% and 65.3%, respectively. Foreign-input exposure can thus propagate far beyond the locations of direct importers.

China is the largest extra-EU source market in the matched data by a wide margin, with more than three times the import value of the United States, the second-largest origin. It accounts for roughly one third of the import value among extra-EU origins above the EUR 1 billion threshold. The remaining sourcing base is diversified across Türkiye, Switzerland, India, the United Kingdom, Brazil, Korea, Japan, Vietnam, Russia, Taiwan, and other markets. This asymmetry motivates treating China separately while using the rest of extra-EU imports as a broad comparison group. The complete ranking is reported in Table B.1.

[2] Intrastat reporting thresholds vary by year and flow. For imports, monthly reporting is required if purchases exceed EUR 350,000 in any of the previous four quarters; for exports, the threshold is EUR 50,000.

[3] After cleaning and matching, about 3% of FATTEL transaction value is lost.

**Table 1:** Descriptive statistics of the firm-to-firm production network

| *Panel A: Sample coverage and aggregate flows* | # | Value (EUR bn) |
|---|---|---|
| Firm nodes | 1.8 million | |
| Domestic firm-to-firm links | 79.0 million | 3,142.8 |
| Importers | 74,334 | 422.7 |
| Extra-EU importers | 59,914 | 148.5 |
| Importers from China | 31,009 | 46.3 |

| *Panel B: Firm-level network distributions* | P5 | P10 | P25 | P50 | P75 | P90 | P95 | Mean |
|---|---|---|---|---|---|---|---|---|
| Domestic suppliers per buyer | 1 | 1 | 3 | 16 | 50 | 105 | 157 | 45 |
| Total input purchases | 0 | 0 | 5 | 67 | 396 | 1,622 | 3,860 | 2,454 |
| Domestic purchases | 0 | 0 | 3 | 39 | 261 | 1,156 | 2,804 | 1,781 |
| Import value per importer | 2 | 4 | 19 | 200 | 1,769 | 7,587 | 17,636 | 5,687 |
| Extra-EU import value per importer | 2 | 3 | 13 | 81 | 551 | 2,854 | 7,390 | 2,478 |
| China import value per importer | 2 | 4 | 14 | 89 | 524 | 2,413 | 5,642 | 1,493 |

| *Panel C: Spatial structure of domestic firm-to-firm links* | Link share (%) | Value share (%) |
|---|---|---|
| Same LLM | 25.7 | 25.4 |
| Neighboring LLMs | 13.9 | 9.3 |
| Non-neighboring LLMs | 60.4 | 65.3 |

*Notes*: The table reports descriptive statistics for the firm-to-firm production network in 2022. Panel A reports the number of nodes or directed links and the corresponding flow values in EUR billions. Domestic firm-to-firm links are directed from buyers to suppliers. Import-related rows exclude imports of mineral fuels, mineral oils and products of their distillation, bituminous substances, and mineral waxes, corresponding to Chapter 27 of the Harmonized System. Extra-EU importers are firms importing from non-EU source countries, and China importers are firms importing from China. Panel B reports selected percentiles and means of firm-level distributions. Value variables are expressed in thousands of euros and are computed conditional on positive values. For Panel C only, each firm is assigned to its main local labor market based on the largest employment share and reports the distribution of domestic firm-to-firm links across same-LLM, neighboring-LLM, and non-neighboring-LLM pairs. The exposure calculations allocate multiplant firms across LLMs using their municipal employment distribution, as described in the text and Appendix A.

Municipalities are mapped to 610 Local Labor Markets (LLMs, *Sistemi Locali del Lavoro*) defined by ISTAT (the Italian National Institute of Statistics) from commuting flows. LLMs are mutually exclusive and contiguous functional areas, although they do not necessarily follow administrative boundaries. Single-plant firms are assigned to the LLM containing their municipality. For multiplant firms, transactions and costs are allocated across plants using the municipal distribution of employment, while VAT-group transactions are consolidated at the group level.[4]

While domestic supply chains and firm-level exposures are reconstructed for the full set of firms observed in the integrated transaction dataset, territorial analyses require information on the municipal distribution of employment. The LLM-level sample therefore excludes sole proprietorships, which cannot be separately identified in the FATTEL data, and non-market activities, which are not covered by the Chambers of Commerce registers used to geolocate employment. We also exclude financial firms because of their specific role in the economy and the limited comparability of their cost structure with that of non-financial firms. The resulting sample accounts for more than 80% of the aggregate cost base observed in the combined domestic-transactions and foreign-trade dataset.

The geography of the data reflects Italy's North–South divide but is not uniform. Northern LLMs generally have firms with larger costs and denser links, while selected southern areas contain sizable industrial clusters. Transaction flows are also hierarchical. Firms trade intensively within LLMs and with nearby markets, but major cities—including Turin, Milan, Venice, Trieste, Bologna, Florence, Rome, Naples, and Bari—act as regional and national hubs (Di Giacinto et al., 2014). Sicily and Sardinia are more internally connected and less integrated with distant areas than the mainland. These patterns motivate the distinction between same-LLM, neighboring, and non-neighboring transmission. The map of median firm costs and the LLM-to-LLM transaction heatmap are reported in Figures B.1 and B.2, respectively, in Appendix B.1.

Several coverage caveats are relevant for interpretation. The foreign-trade data cover goods rather than services, and the e-invoice data do not always separate intermediate inputs from investment purchases. Labor costs are estimated when balance sheets are unavailable, and turnover and cost corrections are required in sectors such as trade and transport. These adjustments and their likely implications for exposure are documented in Appendix A.

[4]For the descriptive link counts in Panel C of Table 1, each firm is instead assigned to its main LLM, defined by its largest employment share.

# 3 Measures of exposure

Building on Dhyne et al. (2021), we measure the foreign-input exposure embodied in firms' direct imports and in purchases from domestic suppliers. We first derive the firm-level indicator as a cost-side elasticity and then aggregate it to LLMs. The complete derivation is collected in Appendix C.[5]

The measures are ex-ante indicators evaluated at the observed production network and benchmark expenditure shares. They describe how a foreign input-cost shock would enter firms' costs and propagate through domestic links before adjustment. They do not contain information on ex-post price and quantity responses, input substitution, supplier switching, or general-equilibrium effects. In applications, they could also serve as exposure shares in shift-share designs (Goldsmith-Pinkham, Sorkin and Swift, 2020; Borusyak, Hull and Jaravel, 2022).

## 3.1 Microfoundation of the firm-level exposure measure

Consider a firm $j$ that combines primary factors, imported inputs, and intermediate inputs purchased from a set of domestic suppliers $i \in \mathcal{S}_j$, where $\mathcal{S}_j$ denotes the set of domestic firms supplying intermediates to $j$. Let the unit cost function of firm $j$ be

$$c_j = c_j\Big(W_j, P_F, \{p_i\}_{i \in \mathcal{S}_j}\Big)\,, \tag{1}$$

where $W_j$ is the price of primary factors, $P_F$ is the price index of inputs sourced from foreign market $F$, and $p_i$ is the price of the domestic input purchased from firm $i$.[6] We assume that the cost function is differentiable and homogeneous of degree one in input prices.

By Shephard's lemma,

$$d \log c_j = s_{vj} d \log W_j + s_{Fj} d \log P_F + \sum_{i \in \mathcal{S}_j} s_{ij} d \log p_i, \tag{2}$$

where $s_{vj}$, $s_{Fj}$, and $s_{ij}$ are the shares of total costs spent on primary factors, imports from $F$, and purchases from supplier $i$. The denominator includes labor, foreign inputs, and domestic intermediates. Because Equation (2) is an envelope condition, benchmark expenditure shares are sufficient statistics for the local first-order cost effect even when firms

[5]For exposition, firms are treated as single-plant entities. The empirical treatment of multiplant firms is described in Appendix A.

[6]Prices of inputs from other foreign markets are held fixed and included in $W_j$.

can substitute across inputs.

Let the foreign shock satisfy $d\log P_F = d\log\tau$ and define firm exposure as

$$s_{Fj}^{T} \equiv \frac{\partial \log c_j}{\partial \log \tau}. \tag{3}$$

We hold primary-factor prices fixed. If firms are price takers or charge constant markups, changes in supplier prices reflect changes in supplier unit costs:

$$d\log p_i = d\log c_i. \tag{4}$$

Then, from Equation (2), we obtain

$$s_{Fj}^{T} = s_{Fj} + \sum_{i\in\mathcal{S}_j} s_{ij} s_{Fi}^{T}. \tag{5}$$

Total exposure is therefore the firm's direct import share plus the exposure embodied in its domestic suppliers. The first indirect round is $\sum_i s_{ij} s_{Fi}$; the second applies the same logic to each supplier's suppliers; and subsequent rounds follow progressively more distant paths. This decomposition clarifies why a firm can be exposed to a foreign input-cost shock even when it does not import from $F$ or use the affected input directly. A domestic supplier may itself depend on that input, or may buy from another supplier that does.[7]

Let $\mathbf{s}_F^T$ and $\mathbf{s}_F$ collect total and direct exposure, and let $\mathbf{S}$ be the firm-to-firm cost-share matrix. Then

$$\mathbf{s}_F^T = \mathbf{s}_F + \mathbf{S}\mathbf{s}_F^T, \qquad \mathbf{s}_F^T = (\mathbf{I}-\mathbf{S})^{-1}\mathbf{s}_F, \tag{6}$$

provided the spectral radius of $\mathbf{S}$ is below one.[8]

This propagation mechanism does not rely on a Leontief or Cobb-Douglas production function. The first-order result only requires differentiable unit costs and complete pass-through from costs to prices; substitution elasticities matter beyond this local approximation (Hulten, 1978; Baqaee and Farhi, 2019). Constant returns are assumed only to define a unit cost function that does not depend on production scale. If pass-through is incomplete, cost shocks propagate less strongly. More general markup adjustments may amplify or dampen transmission depending on firms' pricing responses.

Appendix C.5 discusses the local nature of the elasticity and the adjustment margins excluded from the ex-ante exercise.

[7]The complete higher-order expansion is reported in Appendix C.2.

[8]In practice, the system is solved by fixed-point iteration because direct inversion is infeasible at this scale.

## 3.2 Aggregation to local labor markets

We use LLMs as the spatial unit of incidence. Because they are defined by commuting flows, LLMs capture the scale at which local specialization, agglomeration, and labor-market adjustment are likely to matter. Aggregating to LLMs allows us to ask whether exposure is concentrated in particular production systems, whether it is associated with hub-like or specialized areas, and where adjustment pressures may affect a common labor market.[9] As discussed in Section 2, LLM-level aggregates are computed on the subset of firms whose employment can be allocated across municipalities, which accounts for more than 80% of the aggregate cost base. Supplier links reaching firms in an LLM may nevertheless originate locally, in neighboring LLMs, or elsewhere in the country.

Let $\mathcal{F}_\ell$ be the set of firms in LLM $\ell$, $C_i$ firm $i$'s total costs, and $C_\ell = \sum_{i \in \mathcal{F}_\ell} C_i$ the local gross cost base. Defining LLM exposure as $\partial \log C_\ell / \partial \log \tau$ yields

$$S^T_{F\ell} = \sum_{i \in \mathcal{F}_\ell} \omega^C_{i\ell} s^T_{Fi}, \qquad \omega^C_{i\ell} = \frac{C_i}{\sum_{i' \in \mathcal{F}_\ell} C_{i'}}. \tag{7}$$

Total-cost weights therefore follow from the cost-side object being measured. To see the aggregation directly, note that $d \log C_\ell = \sum_i (C_i/C_\ell) d \log C_i$ and, with quantities fixed in the ex-ante exercise, $d \log C_i = d \log c_i$. Dividing by the foreign shock gives Equation (7). Larger firms receive greater weight because they account for a larger share of the local cost base. Employment and labor-cost weights are useful robustness checks, but they answer different questions: they characterize exposure in worker- or wage-weighted firm distributions rather than the elasticity of gross local costs.

After solving the firm network, we partition LLM exposure into direct imports and indirect exposure transmitted through suppliers in the same, neighboring, and remaining LLMs:

$$S^T_{F\ell} = S^D_{F\ell} + S^{\text{same}}_{F\ell} + S^{\text{neighbor}}_{F\ell} + S^{\text{other}}_{F\ell}. \tag{8}$$

All terms use the same total-cost weights, so the decomposition changes only the assigned geographic channel, not the exposure object. The same-LLM term captures transmission within a local production system, where specialization and agglomeration are most directly relevant. The neighboring term captures integration across adjacent labor

[9] LLMs are a natural spatial scale for studying specialization, agglomeration, and adjustment to shocks (for a review, see Moretti, 2011), especially when workers and firms are imperfectly mobile across sectors and places (Topalova, 2010; Kovak, 2013; Autor, Dorn and Hanson, 2013, 2016; Caliendo, Dvorkin and Parro, 2019; Helm, 2020). This spatial unit also connects the analysis to the regional-resilience literature, which views local outcomes as the result of interactions among firms, workers, sectors, and production links (Martin, 2012; Diodato and Weterings, 2014; Martin and Sunley, 2015).

markets, while the residual term identifies longer-distance dependencies and hierarchical links between hubs, specialized districts, and peripheral areas. The explicit formulas are in Appendix C.4.

### 3.3 Relation to aggregate import statistics

Cost-weighted direct exposure captures the value of imports from $F$ relative to the aggregate gross cost base of firms. Cost-weighted total exposure is larger because an imported input shock affects not only the importing firm, but also the domestic firms that use its output as an intermediate input. The same imported input is therefore transmitted through multiple stages of the domestic production network. This does not represent additional import content being counted twice; it reflects the fact that the gross costs of several firms respond to the same foreign input shock. In this sense, total exposure is a gross-cost elasticity, similar in spirit to Domar weights in growth accounting, rather than a measure of additional imported inputs (Hulten, 1978). We therefore interpret the difference between direct and total exposure as domestic transmission through production linkages, not as hidden imports. Appendix E formalizes this distinction.

## 4 Results

We use Equation (5) to quantify the direct and indirect exposure of Italian firms to foreign input-cost shocks. We focus on imports from China and compare them with imports from other extra-EU countries, excluding China. China is the largest individual extra-EU source market in the data and is central to policy debates on strategic dependence; for Italy, it is particularly important in electronic appliances and machinery (Panon et al., 2026).

As explained in Section 3.2, results are reported at the LLM level using total-cost weights. We nevertheless allow the supplier relationships to transmit exposure across LLMs. A local economy can be vulnerable because it imports directly, because it is linked to exposed suppliers in the same production system, or because it purchases from hubs and specialized firms elsewhere. The results below trace each of these channels separately.

## 4.1 Direct and indirect exposure

Table 2 reports average import exposure by extra-EU source market. China accounts for 3.3 percentage points of total exposure, compared with 8.2 points for all other extra-EU markets combined. Put differently, China alone accounts for almost 30% of total extra-EU exposure, and its exposure equals roughly 40% of that generated by all other extra-EU origins combined. Its role is not limited to direct importers: indirect exposure to China is 2.0 percentage points, compared with 1.3 points of direct exposure. For extra-EU imports excluding China, the corresponding components are 5.3 and 2.9 points.

The last column of Table 2 shows that indirect exposure exceeds direct exposure in the vast majority of LLMs. The share is above 89% for each reported source and reaches 94.3% for extra-EU imports excluding China and 89.8% for China. The same pattern appears for individual origins such as the United States, Türkiye, Switzerland, India, Brazil, and the United Kingdom. Foreign dependence is therefore embedded not only in firms' own sourcing decisions, but also in domestic supplier relationships. First-round links account for an important part of this transmission, but the gap between first-round and total indirect exposure indicates that deeper network layers are also quantitatively relevant.

Figure 1 and Table 3 describe the distribution across LLMs. Direct exposure is highly concentrated: for many local economies it is close to zero, especially at the bottom of the distribution. Indirect exposure is instead positive even at very low percentiles, so LLMs with little or no direct importing can still be exposed through domestic links.

The difference between the two source groups is mainly one of levels. At the median, total exposure is 7.9% of costs for extra-EU imports excluding China and 3.0% for China. Median indirect exposure is 6.1% and 2.3%, respectively. Yet Chinese exposure also has a pronounced upper tail. The 99th percentile of total exposure is 13.2% for China, compared with 19.4% for the broader extra-EU group; direct exposure reaches 9.9% and 12.4%, respectively. Thus, national averages conceal a small set of highly exposed LLMs.

The shape of the distributions also distinguishes the two components. Direct exposure is compressed near zero and then rises steeply in the right tail, reflecting the concentration of importing activity. Indirect exposure has a higher floor and a narrower distribution because domestic suppliers spread foreign dependence across many buyers. Total exposure combines both features: a broad baseline generated by the network and an upper tail anchored by direct importers. Places with similar direct shares can occupy different positions in the total distribution, and some LLMs with little direct trade move into the upper tail once domestic links are included. Foreign-input dependence is transmitted not only through direct imports, but also through purchases from firms that embody that dependence in their own cost structure. The indirect component is not confined to first-round

**Table 2:** Average import exposure by source market

| Source market | Exposure share (%) Direct | First-round indirect | Total indirect | Total exposure | Share of LLMs with Indirect > Direct (%) |
|---|---|---|---|---|---|
| Extra-EU imports | 4.2 | 2.3 | 7.3 | 11.5 | 93.9 |
| China | 1.3 | 0.7 | 2.0 | 3.3 | 89.8 |
| United States | 0.4 | 0.1 | 0.5 | 0.8 | 91.5 |
| Türkiye | 0.2 | 0.2 | 0.5 | 0.8 | 93.6 |
| Switzerland | 0.2 | 0.1 | 0.2 | 0.5 | 93.3 |
| India | 0.2 | 0.1 | 0.3 | 0.5 | 93.8 |
| Brazil | 0.1 | 0.1 | 0.3 | 0.5 | 94.6 |
| United Kingdom | 0.2 | 0.1 | 0.3 | 0.4 | 95.4 |
| Republic of Korea | 0.1 | 0.1 | 0.3 | 0.4 | 94.6 |
| Japan | 0.1 | 0.1 | 0.2 | 0.3 | 94.4 |
| Vietnam | 0.1 | 0.1 | 0.2 | 0.3 | 91.8 |
| *Extra-EU imports excluding China* | *2.9* | *1.6* | *5.3* | *8.2* | *94.3* |

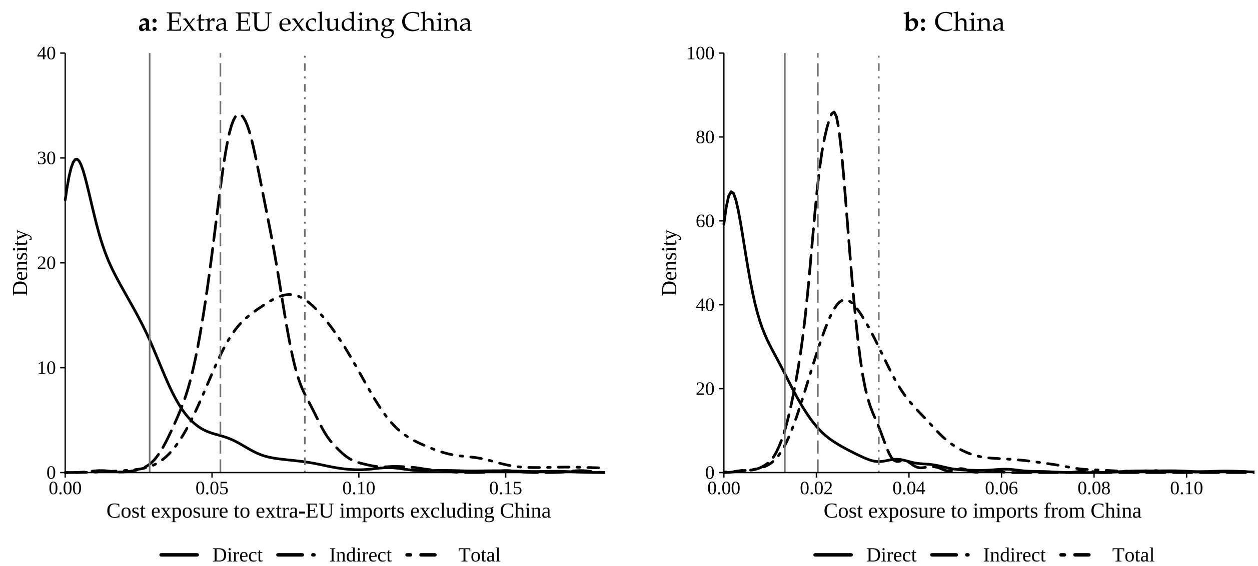
*Notes*: The table reports weighted average firm-level import exposure by source market, expressed as percentage shares of total costs, as in Equation (5). Exposure measures are ex-ante, network-based indicators constructed from pre-shock expenditure shares. Direct exposure captures the share of total costs accounted for by direct imports from the source market. First-round indirect exposure captures foreign-input exposure embodied in purchases from direct domestic suppliers. Total indirect exposure includes the first round and all higher-order rounds transmitted through the domestic firm-to-firm production network. Total exposure equals direct exposure plus total indirect exposure. The last column reports the share of local labor markets for which LLM-level total indirect exposure exceeds LLM-level direct exposure, expressed as a percentage of the number of LLMs with valid exposure measures. LLM-level exposure is computed as the firm-level cost-weighted average within each LLM, using firm total costs as weights. Extra-EU imports are decomposed into exposure to China and exposure to all extra-EU markets excluding China. The selected countries represent the top-10 extra-EU source markets for Italian firms in 2022, excluding imports of mineral fuels, mineral oils and products of their distillation, bituminous substances, and mineral waxes, corresponding to Chapter 27 of the Harmonized System.

**Table 3:** Distribution of LLM import exposure by source market and exposure measure

| Source market | Exposure | P1 | P5 | P10 | P25 | P50 | P75 | P90 | P95 | P99 |
|---|---|---|---|---|---|---|---|---|---|---|
| China | Direct | 0.0 | 0.0 | 0.0 | 0.1 | 0.5 | 1.3 | 2.5 | 3.8 | 9.9 |
| | Indirect | 1.2 | 1.5 | 1.7 | 2.0 | 2.3 | 2.6 | 3.0 | 3.3 | 4.6 |
| | Total | 1.4 | 1.8 | 1.9 | 2.4 | 3.0 | 3.8 | 5.1 | 6.5 | 13.2 |
| Extra-EU excluding China | Direct | 0.0 | 0.0 | 0.0 | 0.3 | 1.3 | 2.8 | 4.9 | 6.4 | 12.4 |
| | Indirect | 3.4 | 4.3 | 4.7 | 5.4 | 6.1 | 7.0 | 7.8 | 8.5 | 11.2 |
| | Total | 4.0 | 4.8 | 5.3 | 6.3 | 7.9 | 9.4 | 11.3 | 13.7 | 19.4 |

*Notes*: The table reports distributional moments of local labor market import exposure by source market and exposure measure. Each observation is a local labor market. For each source market and exposure measure, local labor market exposure is computed as the firm-level cost-weighted average of import exposure, using firm total costs as weights. Values are expressed as percentage shares of total costs, as in Equation (5). Direct exposure captures the share of total costs accounted for by direct imports from the source market. Indirect exposure captures foreign-input exposure transmitted through the domestic firm-to-firm production network, including both the first round and all higher-order rounds. Total exposure equals direct exposure plus indirect exposure.

**Figure 1:** Distribution of LLM exposure to extra-EU imports excluding China and to imports from China.




*Notes*: The figure reports kernel density estimates of local labor market (LLM) import exposure by source market. The left panel refers to extra-EU markets excluding China; the right panel refers to China. Each observation is a local labor market. Local labor market exposure is computed as the firm-level weighted average of import exposure, using firm total costs as weights, and is expressed as a share of total costs, as in Equations (5) and (7). Direct exposure captures the share of total costs accounted for by direct imports from the source market. Indirect exposure captures foreign-input exposure transmitted through the domestic firm-to-firm production network, including both the first round and all higher-order rounds. Total exposure equals direct exposure plus indirect exposure. Vertical dashed lines denote national firm-level cost-weighted averages. Kernel densities are estimated separately for each exposure measure using a Gaussian kernel.

suppliers: higher-order exposure remains sizable across the LLM distribution, including among places with limited direct imports. This is the production-network mechanism emphasized by Baqaee (2018); Huneeus (2018); Dhyne et al. (2021, 2022); Ferrari (2023).

Three additional checks help interpret these distributions. First, high-exposure LLMs have a non-negligible employment footprint: the most exposed quintile accounts for 21.9% of national employment for China and 18.9% for extra-EU imports excluding China, while the top twenty LLMs account for 1.7% and 2.2%, respectively (Table B.2). Second, the rankings are not an artifact of total-cost weights. Labor-cost- and employment-weighted exposure remain strongly correlated with the baseline, although these alternatives measure exposure in a worker-weighted firm distribution rather than the elasticity of the local cost base (Table B.3). Third, direct exposure rises sharply with the local employment share of large firms, consistent with fixed costs of global sourcing (Antras, Fort and Tintelnot, 2017), whereas indirect exposure is essentially flat (Figure B.5). Domestic links reach firms of all sizes and therefore weaken the relationship between total exposure and local firm-size composition. The full direct, first-round, and higher-order decomposition is reported in Figure B.3. These supplementary results are in Appendix B.2.

## 4.2 Geographical aggregation and transmission

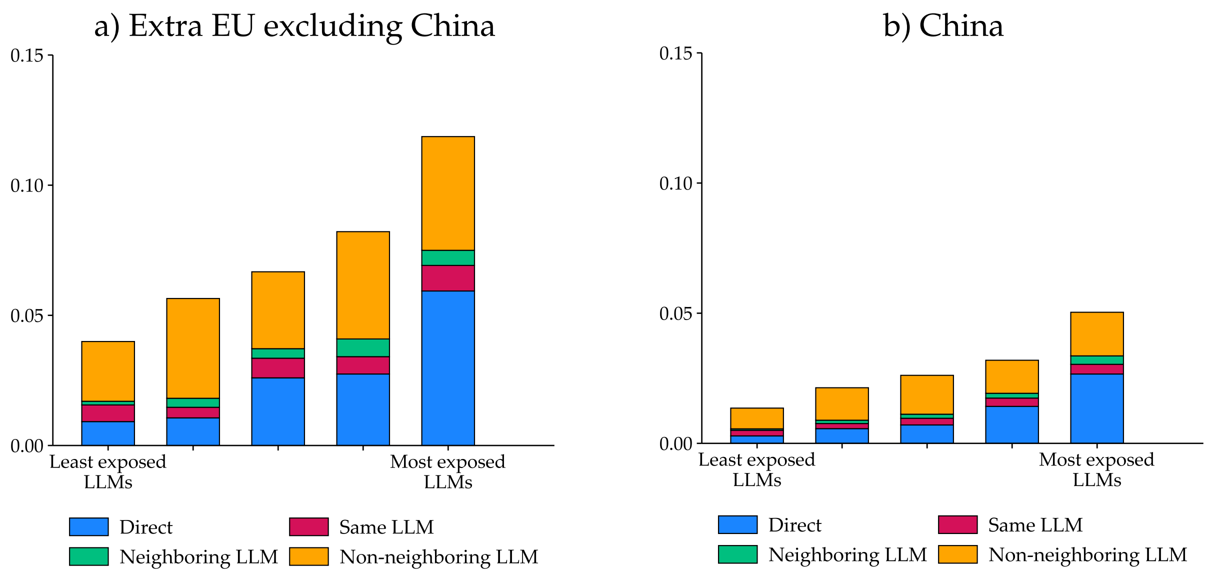
Figure 2 decomposes exposure across quintiles of the LLM distribution following Equation (8). It separates direct imports from indirect exposure transmitted through suppliers in the same LLM, neighboring LLMs, and non-neighboring LLMs. The left panel reports extra-EU imports excluding China and the right panel imports from China.

Two patterns stand out. First, exposure is highly uneven. For extra-EU imports excluding China, total exposure rises from about 4.0% of costs in the bottom quintile to 11.9% in the top quintile. For China, the corresponding increase is from about 1.4% to 5.0%. The broader extra-EU group is larger in level, but both distributions have steep spatial gradients.

Second, the composition of indirect exposure is strikingly similar. For China, 16.5% originates within the same LLM, 10.3% from neighboring LLMs, and 73.2% from non-contiguous LLMs. For extra-EU imports excluding China, the shares are 15.9%, 9.6%, and 74.5%. Nearly three quarters of indirect exposure is therefore mediated by firms in non-contiguous LLMs for both source groups.

This evidence shows that foreign-input vulnerability is not confined to local production systems or adjacent areas. It is propagated through spatially dispersed domestic links that connect distant labor markets. Direct imports identify the entry points of for-

**Figure 2:** Decomposition of LLM import exposure by proximity of partner LLMs across total exposure quintiles




*Notes*: The figure decomposes local labor market import exposure by source market and by the geographic proximity of domestic partner LLMs in the firm-to-firm production network. The left panel refers to extra-EU markets excluding China; the right panel refers to China. LLMs are ranked within each source market according to total import exposure and grouped into five quintiles, from least exposed to most exposed. For each quintile, bars report cost-weighted averages of LLM-level exposure components, using total firm costs in the LLM as weights. LLM-level exposure components are computed from firm-level ex-ante exposure measures (Equations (5), (7) and (8)). Direct exposure captures the share of total costs accounted for by direct imports from the source market. Same LLM, Neighboring LLM, and Non-neighboring LLM capture indirect exposure transmitted through domestic firm-to-firm links to partner firms located, respectively, in the same LLM, in geographically adjacent LLMs, and in non-adjacent LLMs. Adjacency is defined using contiguity between LLM polygons.

eign dependence, LLMs identify the cost bases potentially affected, and the firm network identifies the channels between them. The full LLM distribution in Figure B.4 confirms the importance of the non-neighboring component.

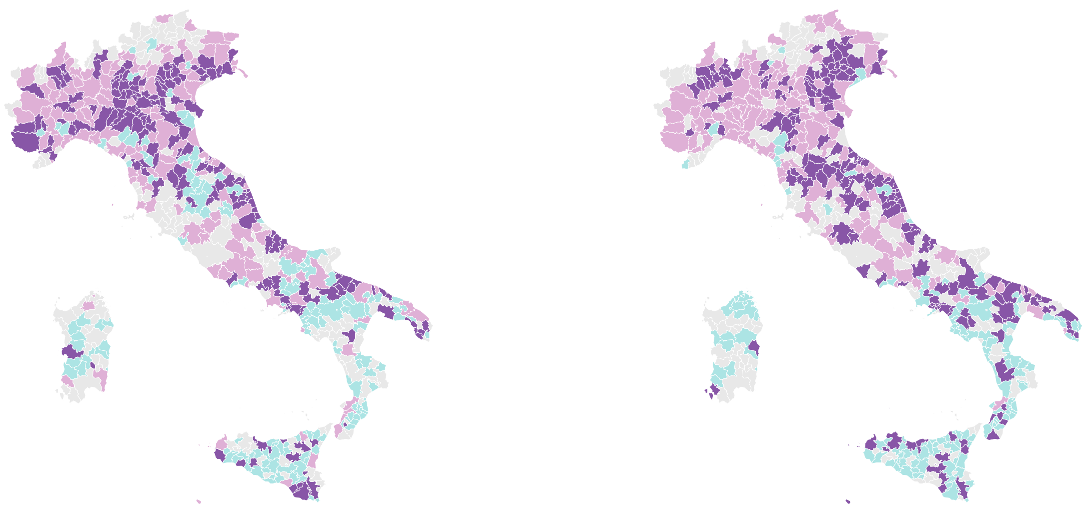
The result also qualifies a purely local interpretation of industrial districts. Dense within-LLM relationships remain economically meaningful, but most exposure reaches local firms through suppliers outside the district and often outside the surrounding region. Resilience consequently depends on both local diversity and the structure of extra-local sourcing. A place-based stress test that considers only firms physically located in the LLM would miss the majority of the network channel; conversely, a national stress test would not reveal which local cost bases ultimately inherit it.

Figure 3 classifies LLMs according to whether direct and indirect exposure are above or below the source-specific median. LLMs with both components above the median are especially frequent in the Center-North, consistent with internationally connected manufacturing systems. At the same time, several LLMs in the Center-South and the islands have low direct but high indirect exposure. They are not major importers themselves, but are connected to firms and places that transmit foreign-input dependence.

The two maps reveal a common spatial logic. Vulnerability is a feature both of direct-importing industrial cores and of local economies reached through domestic links. The pattern also clarifies the relationship between local clustering and national hierarchy. Same-LLM links matter for specialized production systems, but they account for a relatively small share of total indirect exposure. Distant suppliers connect those systems to larger hubs and to other specialized areas, so high indirect exposure can arise without a large local importer.

The association between direct and indirect exposure is positive but far from mechanical. For extra-EU imports excluding China, variation in total indirect exposure is especially closely associated with the non-neighboring component. For China, the same-LLM and non-neighboring components are more balanced. Spatially, clustering is statistically significant for both source groups, yet direct exposure in one LLM is essentially uncorrelated with indirect exposure in adjacent LLMs. Across sources, finally, China and other extra-EU exposure are positively related, but only 19.6% of the union of their top-quintile sets is shared. Thus, a common national production structure coexists with source-specific local vulnerability. Table B.4 reports the clustering and cross-source overlap statistics, while Table B.5 reports the component correlations; both are in Appendix B.3.

**Figure 3:** Direct and indirect import exposure by LLM



**a:** Extra-EU excluding China

**b:** China

Low direct–Low indirect
Low direct–High indirect
High direct–Low indirect
High direct–High indirect

*Notes*: The figure classifies Italian local labor markets according to their direct and indirect import exposure by source market. Panel (a) reports exposure to extra-EU imports excluding China; Panel (b) reports exposure to imports from China. Direct and indirect exposure are computed at the LLM level as firm-level cost-weighted averages, using firm total costs as weights, and are expressed as shares of total costs, as in Equations (5) and (7). For each source market, direct and indirect exposure are classified as high or low depending on whether the LLM value is above or below the corresponding median across LLMs. Hence, colours identify the relative position of each LLM within the source-market-specific distribution, rather than absolute exposure levels across source markets.

## 4.3 Exposure to input categories

We now turn from source markets to input categories. Throughout this subsection, exposure refers to imports from all extra-EU source markets, including China. Exposure differs substantially across product categories (top panel in Table B.6). Metals and mineral inputs generate the largest total exposure, at 2.7% of total costs, of which 0.9 points are direct and 1.8 indirect. Agrifood follows at 1.5%, chemicals at 1.2%, and machinery at 1.0%. Textiles, leather, and footwear also generate 1.0% of total exposure; computers and optical equipment and electrical equipment each account for 0.8%; motor vehicles account for 0.7%. Pharmaceuticals, rubber and plastics, wood and paper, energy products within the retained coverage, and other transport equipment are smaller in the national average but can still matter locally. Across most groups, total indirect exposure exceeds direct exposure and first-round links explain only part of the indirect component. In most categories, more than 90% of LLMs have indirect exposure above direct exposure, indicating that product-specific dependence is widely transmitted through domestic supply chains.

We separately identify exposure to AI-enabling and green products because they are central to digitalization and the green transition.[10] Their average total exposure is 0.9% and 1.0%, respectively (bottom panel in Table B.6).

These national values conceal distinct territorial patterns. Motor-vehicle exposure is visible in parts of Piedmont and selected central areas (left panel in Figure B.6); textiles in Veneto and along the central Adriatic; agrifood in several island LLMs; electronics in the North-West; metals and mineral products in the Lombardy–Po Valley area; and wood and paper in selected LLMs including Tuscany. Such patterns reflect local capabilities and specialization (Boschma, 2024). AI-enabling exposure is concentrated mainly in the Center-North, with pockets in Piedmont, Lombardy, Veneto, and central Italy, whereas green-product exposure is more diffuse and reaches areas outside the main northern industrial core (right panel in Figure B.6).

This product dimension changes the interpretation of aggregate dependence. Inputs with the largest national value need not generate the highest exposure in every place, because local incidence also depends on the importing firms and domestic paths associated with the product. Conversely, a product with a modest national share can be pivotal in a specialized LLM. Product-place combinations are therefore more informative for territorial resilience than either a national product ranking or a broad local sector share alone.

[10] AI-enabling products are defined as in World Trade Organization (2025). Products classified as green are from Conteduca et al. (2025).

## 4.4 Mechanisms of exposure: intermediaries and large importers

We next examine the role of specific groups of firms in shaping the level and spatial distribution of exposure to foreign input-cost shocks. The first exercise focuses on wholesalers and retailers, which may act as intermediaries between foreign suppliers and domestic producers and therefore amplify the indirect propagation of import shocks through the domestic production network. The second focuses on the largest importing firms, to assess the extent to which measured exposure is driven by a relatively small set of firms with highly concentrated foreign sourcing.

To quantify the contribution of these groups, we conduct two counterfactual accounting exercises. In each exercise, imports from the source market of interest are reassigned to a fictitious origin not subject to the shock, while firm size, total costs, and the domestic production network are held constant. We then recompute the complete exposure system. The difference relative to the baseline measures the share of exposure associated with the at-risk sourcing of the selected group of firms.

These exercises are not intended to describe the equilibrium effects of removing those firms from the economy. Rather, they provide a transparent accounting device for isolating their contribution to the propagation of foreign input-cost shocks.

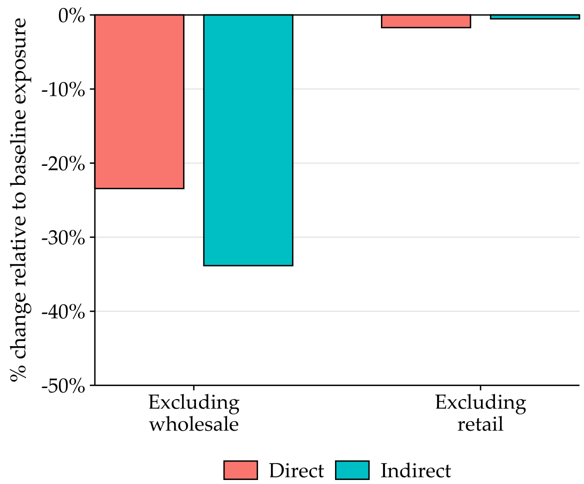
### 4.4.1 The role of wholesalers and retailers

Trading and distribution firms often connect domestic producers and buyers with foreign markets (Bernard et al., 2007; Bernard, Grazzi and Tomasi, 2015; Crozet, Lalanne and Poncet, 2013; Ganapati, 2025). Figure 4 reports the change in exposure when wholesale or retail imports are neutralized. The firms remain in the domestic network; only their imports from the at-risk source are reassigned.

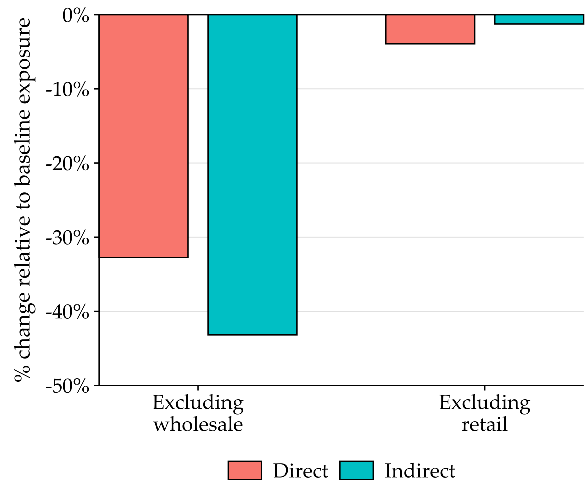
Wholesale trade is a major transmission channel, especially for China. For extra-EU imports excluding China, neutralizing wholesale imports reduces direct exposure by 23.4% and indirect exposure by 33.8%. For China, the reductions are 32.7% and 43.2%. The larger decline in the indirect component shows that wholesalers are not merely large direct importers: their foreign-input exposure is passed to many domestic customers through the production network. Retail trade plays a much smaller role. Neutralizing retail imports reduces direct exposure by 1.7% and indirect exposure by 0.5% for the comparison group; for China, the reductions are 3.9% and 1.2%. Exposure associated with the intermediary channel is therefore concentrated in wholesale rather than retail trade.

Intermediaries do not necessarily increase vulnerability. They may buffer disruptions if they maintain more diversified supply networks, inventories, or foreign alternatives

**Figure 4:** Drop in import exposure after neutralizing wholesale and retail imports




**a:** Extra-EU excluding China




**b:** China

*Notes*: The figure reports the percentage change in national import exposure relative to the baseline after neutralizing imports by wholesale and retail firms. Panel (a) refers to extra-EU imports excluding China; Panel (b) refers to imports from China. In the wholesale counterfactual, imports from the relevant source market by firms in ATECO 46 are reassigned to a fictitious origin not subject to the shock. In the retail counterfactual, the same reassignment is applied to firms in ATECO 47. Firms are not removed from the economy; only their direct imports from the source market are reassigned to the non-shocked origin. Bars report changes in direct and indirect cost exposure. Exposure measures are aggregated at the national level using firm total costs in 2022 as weights. Negative values indicate a reduction relative to baseline exposure.

than direct manufacturing importers (Perello, 2025). Their scale and customer reach can therefore make them both transmission nodes and potential shock absorbers. The counterfactual identifies the size of the exposure passing through wholesale imports; it does not establish whether wholesalers would amplify or mitigate realized output losses after substitution and inventory adjustment.

A caveat concerns firms that import and re-export. Equation (4) assigns every buyer the supplier's average unit-cost response, while some imported content handled by wholesalers or retailers may never enter domestic production. This can overstate transmission to domestic buyers, so the intermediary exercise should be read as an accounting attribution within the benchmark rather than as a realized pass-through estimate.

#### 4.4.2 The role of top importing firms

National exposure is highly granular, especially for extra-EU imports excluding China. Neutralizing the top 10 importers reduces total exposure from 8.2% to 7.1%; neutralizing the top 100 lowers it to 5.0%. Direct exposure falls from 2.9% to 1.8% and indirect exposure from 5.3% to 3.2%. The top 100 importers therefore account for roughly 40% of baseline total exposure and matter through both their own sourcing and their downstream links. This granularity echoes the role of large firms in shaping aggregate outcomes (Gabaix, 2011) and, in the trade context, the disproportionate contribution of a small number of large traders to aggregate fluctuations (Di Giovanni, Levchenko and Mejean, 2014).

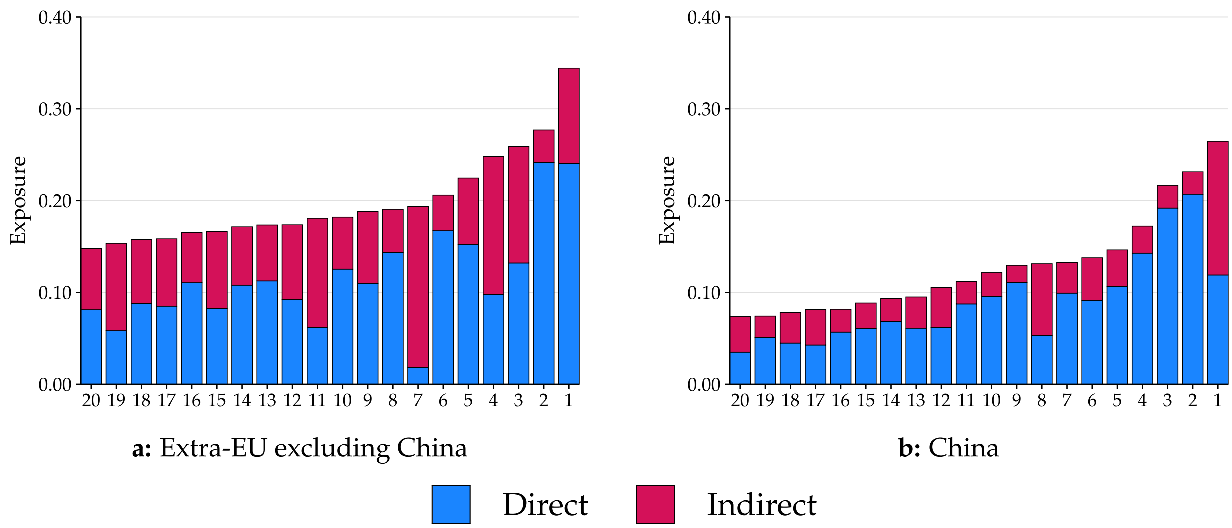
For China, neutralizing the top 10 importers reduces total exposure from 3.3% to 3.1%, while neutralizing the top 100 lowers it to 2.5%. Direct exposure falls from 1.3% to 1.0% and indirect exposure from 2.0% to 1.5%. Concentration is less pronounced than for the comparison group, particularly at the very top of the importer distribution. The contrast remains visible farther down the ranking: after neutralizing the top 500 importers, total exposure is 3.2% for other extra-EU origins and 1.8% for China; after the top 1,000, it is 2.3% and 1.3%.

In both source groups, however, indirect exposure remains sizable after the largest direct importers are neutralized. Domestic links continue to transmit dependence originating in a wider set of firms, so vulnerability is not reducible to the largest traders. The exercise also distinguishes size from network relevance. A firm can account for a large direct import value but transmit relatively little if it sells mainly to final demand or abroad; another firm can have a smaller import value but a larger domestic footprint because it supplies many buyers. The counterfactual captures both margins through the recomputed network solution. We report the complete sequence for both sources in Table B.7.

## 4.5 Highly exposed local labor markets

Because factors are imperfectly mobile across sectors and places, concentrated risks can imply large local effects even when the national average is moderate (Caliendo, Dvorkin and Parro, 2019). Figure 5 focuses on the twenty most exposed LLMs. Total exposure exceeds 30% of local costs for the most exposed LLM to extra-EU imports excluding China, while the upper tail for China is slightly lower but still substantial.

**Figure 5:** Decomposition of import exposure among the top-20 most exposed LLMs




*Notes*: The figure reports the decomposition of cost-side import exposure among the top-20 most exposed local labor markets. Panel (a) refers to extra-EU imports excluding China; Panel (b) refers to imports from China. In each panel, LLMs are ranked by total import exposure within the corresponding source market, with rank 1 denoting the most exposed LLM. Bars decompose total exposure into direct and indirect components. LLM-level exposure measures are firm-level cost-weighted averages, using total firm costs as weights, and are expressed as shares of total costs, as in Equation (5) and Equation (7).

The upper tail is not driven by direct imports alone. Direct exposure is the largest component in several highly ranked LLMs, but indirect exposure remains sizable throughout the distribution. In some LLMs, total exposure lies far above direct exposure, indicating that domestic suppliers account for a first-order share of local vulnerability. The most vulnerable places are therefore not simply those with the highest direct import shares; they also include LLMs connected to foreign-input exposure embodied elsewhere in the economy. This distinction is especially important for local policy because the relevant importer may be located outside the affected labor market.

Further decompositions show that no single mechanism explains all top LLMs: Figures B.7 to B.9 isolate, in turn, the wholesale contribution, the LLM-specific top importer, and the leading product class.[11] These figures, together with the national-versus-local product comparison in Table B.8, are collected in Appendix B.5. Wholesalers account for a visible share of exposure in several highly exposed places, but their role is strongly heterogeneous. In some LLMs they are important local entry points; in others, exposure is generated mainly by manufacturing and other non-trade firms. The contrast with their large national contribution shows that the nodes driving average transmission need not be the same as those driving local extremes.

The role of the leading firm is more systematic. The LLM-specific top importer accounts for a sizable share of total exposure in many top-ranked places for both source groups. Product concentration is also pronounced: a leading product class can explain much of local exposure, especially for China. Yet neither the top firm nor the top product generally explains the entire upper tail. Many LLMs retain substantial net-of-top-node exposure, reflecting other products and domestic links. Dominant firms and specialized product lines can therefore act as anchors of local systems—the "rivet effect" of Martin and Sunley (2015)—while the consequences extend beyond the directly exposed activity.

Finally, Table B.8 shows that the products associated with local tail risks overlap only partially with those that dominate national import values. For extra-EU imports excluding China, only two product classes appear in both top-ten lists; for China, three do so. Local exposure depends on where importing firms are located and how their sourcing is embedded in local and extra-local networks, not only on the national value of the product flow.

The right tail therefore combines three forms of concentration: direct dependence on a source market, firm concentration around a leading importer, and product concentration around a narrow input category. These dimensions need not coincide. A highly exposed LLM may host a large manufacturer importing a specific input, may inherit exposure through an external supplier, or may depend on a wholesale node serving several local activities. The firm-level data allow these cases to be distinguished rather than assigning the same sectoral exposure to all firms in the place.

# 5 Aggregation bias from sector–region input-output exposure measures

Empirical analyses of foreign-shock exposure often rely on input-output (IO) or multi-region input-output tables (Baldwin and Freeman, 2022; Imbs and Pauwels, 2024). These

[11] We define product classes at the four-digit Harmonized System (HS) level.

provide a tractable representation of linkages across sectors and places, but necessarily replace heterogeneous firms within a sector–region cell with a representative unit (Koopman, Wang and Wei, 2012; Kee and Tang, 2016; De Gortari, 2019; Bems and Kikkawa, 2021). As a result, firms that differ in foreign sourcing patterns, customer bases, and network position are assigned the same input structure and exposure profile.

Our objective is not to compare firm-level transaction data with conventional national or multi-regional IO systems. Differences between these approaches may also arise from distinct statistical conventions, including valuation methods, the treatment of trade and transport margins, the allocation of investment expenditures, and differences in source coverage. Instead, we isolate a narrower question: how much information is lost purely because firms and transactions are aggregated before exposure is computed.

To do so, we compare two measures built from exactly the same 2022 firm-to-firm level data. The firm-first approach solves exposure on the firm-level network and then aggregates the resulting measures. The aggregate-first approach collapses the same firms and links into sector–LLM cells and solves exposure on that aggregated network. It turns out that direct exposure is preserved by construction. However, a gap arises in the indirect component. Such aggregation bias reflects differences in indirect propagation generated by aggregation rather than differences in data, accounting conventions, source coverage, or years of observation. This formal result is reported in Appendix D.1.

**A minimal numerical example.** Consider a supplier cell $q$ with two equal-weight firms, $A_1$ and $A_2$, and a buyer cell $c$. Buyers in $c$ spend 40% of their costs on inputs from $q$, but all purchases in the firm network go to $A_1$. Suppose one supplier has direct exposure $d = 0.20$. The aggregate network observes only the cell average,

$$D_q = (0.20 + 0)/2 = 0.10,$$

and therefore assigns the buyer cell indirect exposure $M_c^{aggr} = 0.40 \times 0.10 = 0.04$.

If the exposed firm is the central supplier $A_1$, the firm network gives $M_c^F = 0.40 \times 0.20 = 0.08$, so the aggregate-first measure understates exposure by 4 percentage points. If instead the exposed firm is the peripheral $A_2$, actual buyers are connected to an unexposed supplier and $M_c^F = 0$, while the aggregate-first measure remains 0.04. It therefore overstates exposure by 4 points. The same sector–region table can thus generate over- or under-estimation depending solely on the within-cell allocation of exposure and supplier links.

A Monte Carlo simulation, reported in Appendices D.2 and D.3, generalizes this intuition. It holds fixed the economy, the firm network, the sector–region aggregation, firm size, and the amount of direct exposure assigned to each cell; only the identity and network centrality of the exposed firm vary. Figure D.1 shows that aggregate bias increases monotonically with exposed-firm supplier centrality and can change sign across otherwise identical economies. Table D.1 further shows that regional errors can substantially exceed national errors, implying that aggregation may generate sizable local distortions even when aggregate discrepancies appear modest.

The actual-data comparison yields the same qualitative message. Table D.2 reports the comparison for China, and Table D.3 extends it to the fifteen largest source markets. National firm-first and aggregate-first estimates are often relatively close, but the corresponding sector–LLM discrepancies span both signs. For China, aggregate-first indirect exposure equals 2.5% of total costs, compared with 2.0% in the firm network, while the distribution of cell-level differences ranges from $-0.5$ percentage points at the 10th percentile to 1.1 percentage points at the 90th percentile. The main implication is that firm-level data reveal where exposure is located within sectors and places, and whether exposed firms occupy central or peripheral positions in domestic production networks—-information that aggregate data cannot recover. As a result, aggregate data may imply very different indirect exposure patterns, especially for the least and most exposed regions.

# 6 Conclusions

This paper investigates how domestic production networks shape exposure to foreign input-cost shocks originating in extra-EU countries, highlighting heterogeneity across geography, sectors, firms, and products. Using firm-to-firm transaction data for Italy, we measure both direct exposure through imports and indirect import exposure transmitted through domestic suppliers. Throughout, the measures are ex-ante network indicators of where foreign cost shocks enter and propagate before adjustment.

Many local labor markets with limited direct imports become highly exposed once upstream domestic dependencies are taken into account, and a large share of this transmission occurs across distant parts of the country. Direct trade data therefore identify only the initial point of entry of a foreign shock, whereas production networks determine its ultimate incidence across firms and places.

Vulnerabilities are associated with particular firms, intermediaries, and product categories rather than being uniformly distributed across sectors or territories. Wholesale firms are key transmission channels, especially for imports from China, because their direct sourcing reaches many downstream domestic buyers, while a relatively small number of large importers accounts for a substantial share of national and local exposure. Nevertheless, indirect exposure remains sizable even after neutralizing the sourcing of the largest importers, showing that vulnerability is not confined to firms directly engaged in international trade. Among the most exposed LLMs, tail risks are often driven by a few firms and narrow product categories, but they are amplified through local and extra-local supplier networks.

Our findings suggest that policymakers should account for the geography of domestic production networks when evaluating risks from external shocks. The evidence supports three complementary diagnostics. Place-based stress tests should identify LLMs in which exposure is large relative to local costs and employment; product-based diagnostics should focus on inputs with large propagation footprints and limited substitutability; and network-based monitoring should examine wholesalers and importer-suppliers that transmit exposure to many downstream firms.

These findings are highly relevant to the current European debate on critical dependencies and trade relations with China. Trade-defense measures may reduce competitive pressure from Chinese producers, but they can also raise input costs for downstream firms and encourage the further weaponization of strategic dependencies. Accurately assessing how these costs propagate across local economies is therefore essential for informed policy design.

Enabling such assessments requires access to highly detailed firm-level data, such as those used in this work. It is therefore crucial to collect and make such microdata available for research purposes under appropriate confidentiality safeguards. Looking ahead, matching detailed firm-level data across countries will be essential to measure foreign upstream exposure that cannot be observed within domestic transaction data alone. In this context, we support the call by Pichler et al. (2023) for an alliance to map global supply networks, and leave this important challenge for future research.

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# A Data Appendix

We construct the analytical dataset by integrating the following sources:

- **FATTEL (Electronic Invoicing Data)**: Data are provided by SOGEI S.p.A. and they cover all the domestic B2B transactions and the B2C transactions that require the emission of an electronic invoice. The dataset contains the total taxable amount of invoices issued in each quarter, broken down by seller and buyer. For confidentiality, the transactions that involve sole proprietorships or consumers are aggregated. However, for sole proprietorships, we also have information on the sector (NACE 2-digit). Outliers are identified and flagged by the data provider.

- **Dogane (Customs Transactions)**: Includes export and import flows of physical goods, matched to firms via VAT numbers. The dataset excludes natural gas in gaseous form and electricity. Overall, these products account for 0.4% of Italian exports and 9.8% of imports as of 2022.

- **Cerved (Balance Sheet Data)**: Provides reclassified financial statements of Italian corporations; partnerships are excluded from the dataset.

- **Infocamere (Firm Registry)**: Supplies legal form, sector classification (NACE), firm age, and location. Used to fill missing identifiers and validate firm-level information.

- **INPS and Auxiliary Employment Data**: Reports for each firm the number of employees and their spatial distribution, detailed at the municipal level.

- **ISTAT (Local Labor Markets)**: Maps municipalities into local labor markets identified by the national institute of statistics.

**Data Processing Steps** Firm identifiers are harmonized across datasets, including corrections for sole proprietorships and VAT groups.[12] In the case of multiplant firms, characterized by a single VAT identifier and multiple plants, we impute transactions to each plant proportionally to the number of employees at the municipality level. Based on 2022 balance sheet data, Italian corporations belonging to VAT groups account for approximately 6% of total revenues. In our exercise, we consolidate all transactions at the group level for VAT groups.

[12] A VAT group is a fiscal arrangement that allows multiple entities — closely linked financially, economically, and organizationally — to be treated as a single taxable person for VAT purposes. This means that intra-group transactions are not subject to VAT, and the group submits a single VAT return.

We merge registry and financial data, then match transaction records (FATTEL, Dogane) to firms. Transactions are aggregated at the firm-pair level for the entire year 2022. For firms in VAT groups, transactions are consolidated at the group level. By combining these datasets, we compute total revenues and total costs for each enterprise. Total revenues are calculated as the sum of the total taxable amount of invoices issued by the firm and its exports. Total costs are calculated as the sum of the total taxable amount of invoices received by the enterprise, total imports, and labor costs.

A few caveats are in order. Revenues from the export of services are not accounted for due to the lack of granular data. For 2022, the export of services from Italy, excluding travel, financial, and insurance services, is around €70 billion, whereas for imports it is around €90 billion. Moreover, the data do not allow us to distinguish between revenues from ordinary business activities and those resulting from disinvestment. At the same time, total costs include also investments, which cannot be separated from expenditures on intermediate goods and services. Hence, the total costs may be inflated for firms undergoing an expansion of their investments. Finally, when the balance sheet is not available, labor costs are estimated based on the firm's sector of activity and number of employees.

To remove outliers from the data, we compare total revenues from our integrated dataset with the sum of turnover and disinvestment reported in the balance sheet. This helps to determine whether to retain or exclude flagged observations. VAT groups and enterprises with IAS financial statements are excluded from this comparison, as their turnover is calculated using different criteria. In cases where the financial statement is unavailable (including VAT groups and IAS financial statements), we apply the most frequently adopted decision: retaining the outliers.

**Correcting Costs** Due to the data limitations described above, our estimates of costs may be subject to downward bias. This bias could artificially amplify the direct and indirect exposure calculated in our exercise. To address this issue, we compare our estimates with financial statement data for firms with available balance sheets. We detect significant underestimation in several sectors, particularly in transportation and trade. In retail trade, transactions with consumers are generally not subject to electronic invoicing requirements. Similarly, air and maritime transport often operate internationally, with a substantial portion of sales excluded from our dataset. For these reasons, we correct our dataset by adding residual sales to an unknown counterpart whenever our turnover estimates for a specific firm fall below the official figures from the financial statement.

The underestimation of supply costs is less likely for trading sectors, thus we apply a similar adjustment only to the transportation sector, where deviations from balance sheet data are more pronounced, probably due to purchases of fuel and supplies abroad.

In some cases, especially for small firms in the retail trade sector, financial statements are not available. In such instances, we compare estimated costs with estimated turnover and adjust turnover whenever it is lower than the estimated costs.

# B Additional results and robustness

## B.1 Data and network descriptives

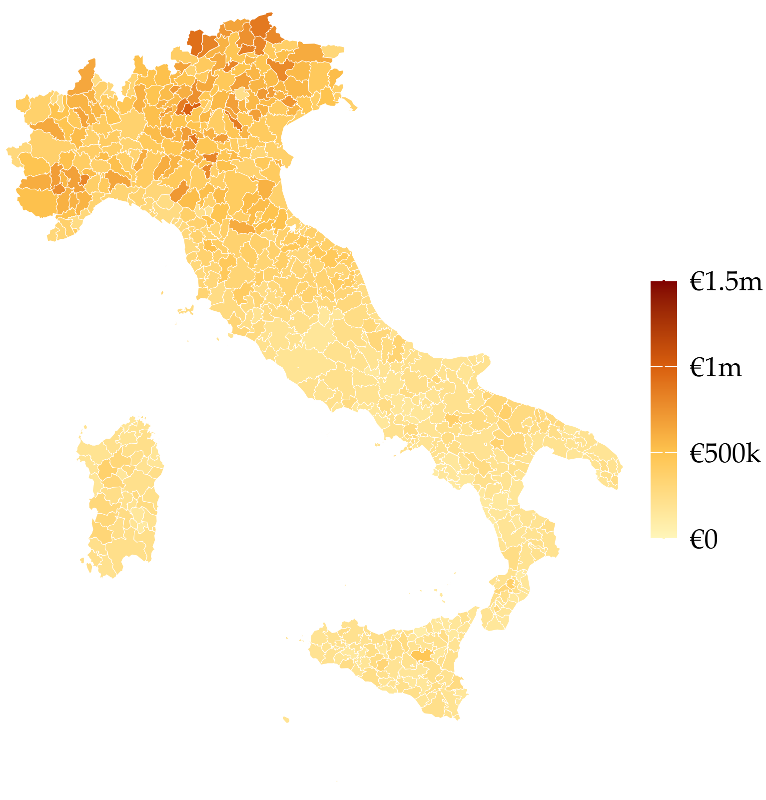
**Table B.1:** Main extra-EU source markets in the firm-to-firm network, 2022

| Rank | Source market | Import value (EUR bn) | Rank | Source market | Import value (EUR bn) |
|---|---|---|---|---|---|
| 1 | China | 46.3 | 14 | Thailand | 2.2 |
| 2 | United States | 12.7 | 15 | Tunisia | 2.1 |
| 3 | Türkiye | 8.4 | 16 | South Africa | 1.5 |
| 4 | Switzerland | 7.9 | 17 | Ukraine | 1.5 |
| 5 | India | 7.1 | 18 | Canada | 1.5 |
| 6 | United Kingdom | 5.3 | 19 | Egypt | 1.4 |
| 7 | Brazil | 5.2 | 20 | Malaysia | 1.3 |
| 8 | Republic of Korea | 4.5 | 21 | Albania | 1.3 |
| 9 | Japan | 4.2 | 22 | Morocco | 1.1 |
| 10 | Vietnam | 4.0 | 23 | Bangladesh | 1.1 |
| 11 | Russia | 3.4 | 24 | Argentina | 1.1 |
| 12 | Taiwan | 3.3 | 25 | Mexico | 1.1 |
| 13 | Indonesia | 2.6 | | | |

*Notes*: The table reports all extra-EU source markets with import values greater than or equal to EUR 1 billion in the final matched firm-to-firm production network in 2022. The ranking excludes imports of mineral fuels, mineral oils and products of their distillation, bituminous substances, and mineral waxes, corresponding to Chapter 27 of the Harmonized System. Countries are ranked by total import value.

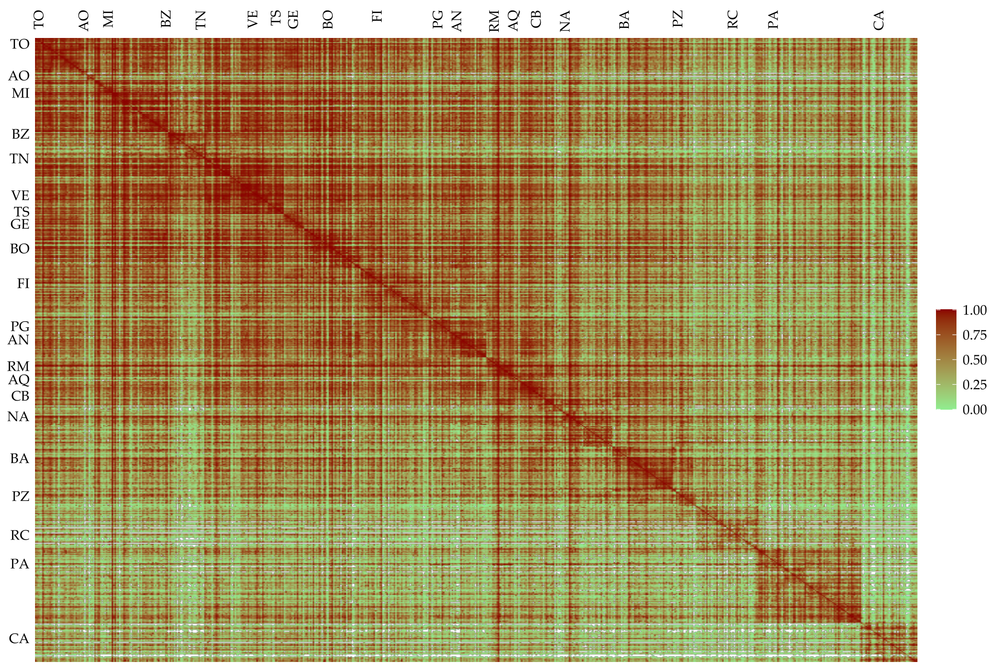
Table B.1 reports all extra-EU origins with at least EUR 1 billion of matched imports. China accounts for roughly one third of the value represented by these markets and is more than three times larger than the United States, the next-largest origin.

**Figure B.1:** Median firm costs across Local Labor Markets




*Notes*: The figure reports median firm costs across Italian local labor markets in 2022. Costs are measured on the buyer side and correspond to firm total costs allocated to LLMs. For firms operating in multiple LLMs, costs are allocated across LLMs using the distribution of employees. Values are expressed in millions of euros.

**Figure B.2:** Heatmap of transaction flows between LLMs




*Notes:* Heatmap of transaction flows between local labor markets in 2022. Rows correspond to origin LLMs, columns to destination LLMs. Labels indicate the capital cities of Italy's 19 regions and two autonomous provinces. Each square represents the percentile of the trade flow value between two LLMs within the nationwide distribution.

Figure B.1 shows the North–South gradient in median firm costs, with several localized exceptions in the South. Figure B.2 reports the percentile rank of transaction values between LLM pairs. Within-LLM and nearby links are visible, but major cities also operate as regional and national hubs, and the network connects many non-adjacent areas.

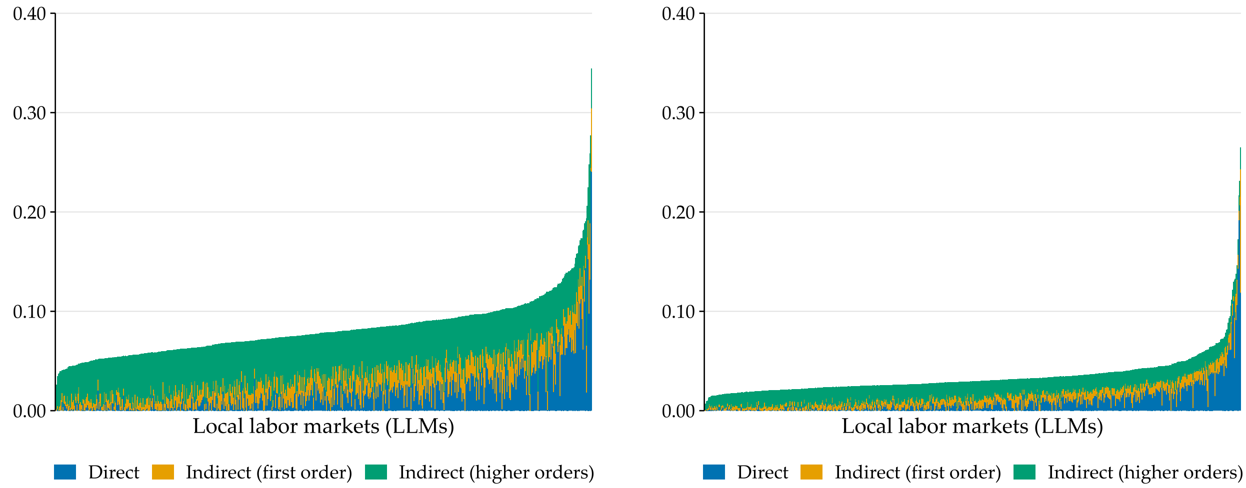
## B.2 Additional exposure diagnostics

Figure B.3 separates direct, first-round indirect, and higher-order indirect exposure for every LLM. Higher-order links are quantitatively important for both source groups and are particularly visible among LLMs with low direct exposure.

Figure B.4 reports the complete LLM distribution underlying the quintile averages in the main text. The non-neighboring component is the largest source of indirect exposure across most of the distribution.

High-exposure LLMs have a non-negligible employment footprint. The most exposed quintile accounts for 21.9% of national employment for China and 18.9% for extra-EU imports excluding China; the top twenty LLMs account for 1.7% and 2.2%, respectively (Table B.2).

**Figure B.3:** Import exposure across LLMs: direct and indirect components




**a:** Extra-EU excluding China    **b:** China

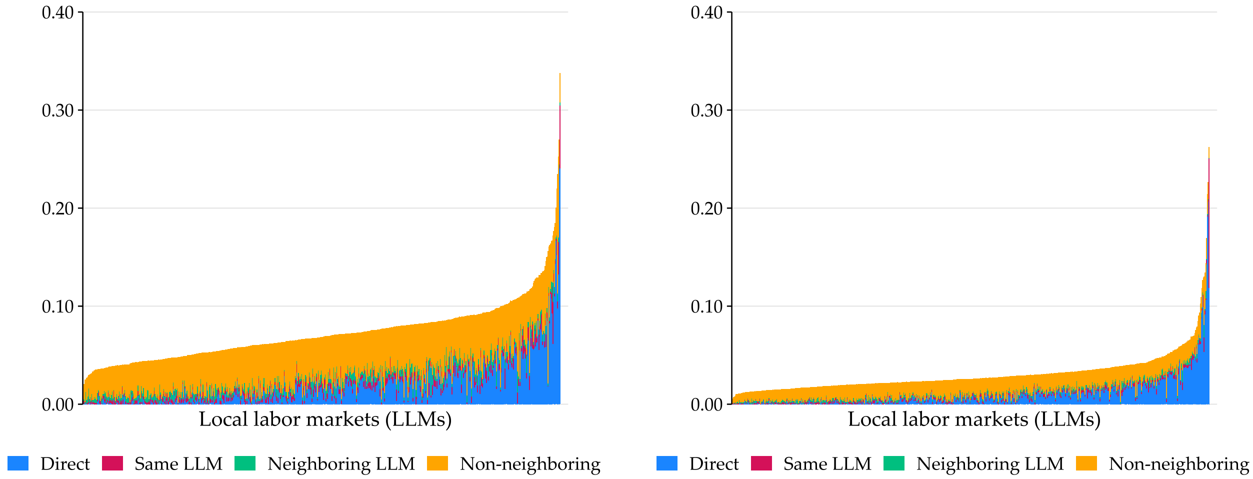
*Notes*: The figure reports the decomposition of cost-side import exposure across local labor markets. The left panel refers to extra-EU imports excluding China, while the right panel refers to imports from China. In each panel, LLMs are ordered by total import exposure within the corresponding source market. Direct exposure captures the share of total costs accounted for by direct imports from the source market. *Indirect (first order)* captures foreign-input exposure transmitted through first-round domestic firm-to-firm linkages. *Indirect (higher orders)* is computed as total indirect exposure minus first-order indirect exposure and captures exposure transmitted through higher-order domestic production-network linkages. LLM-level exposure measures are firm-level cost-weighted averages, using total firm costs as weights, and are expressed as shares of total costs, as in Equation (5).

**Table B.2:** Employment incidence of import exposure across local labor markets

| Source market | Top quintile employment share (%) | Top-20 LLMs employment share (%) | Employment share in LLMs with Indirect > Direct (%) | LLMs with Indirect > Direct (%) |
|---|---|---|---|---|
| Extra-EU imports | 17.5 | 1.2 | 95.9 | 93.9 |
| China | 21.9 | 1.7 | 91.5 | 89.8 |
| Extra-EU excluding China | 18.9 | 2.2 | 95.7 | 94.3 |

*Notes*: The table reports the employment incidence of import exposure across local labor markets. For each source market, LLMs are ranked by baseline total exposure, computed as the firm-level cost-weighted average within each LLM. The first column reports the share of national employment located in LLMs belonging to the most exposed quintile of the total exposure distribution. The second column reports the share of national employment located in the 20 LLMs with the highest total exposure. The third column reports the share of national employment located in LLMs where total indirect exposure exceeds direct exposure. The last column reports the corresponding unweighted share of LLMs. Employment is measured using the distribution of employees across LLMs in 2022.

**Figure B.4:** Import exposure decomposition by proximity of domestic production-network partners




**a:** Extra-EU excluding China **b:** China

*Notes*: The figure reports the decomposition of cost-side import exposure across local labor markets by the geographic proximity of domestic partner LLMs in the firm-to-firm production network. Panel (a) refers to extra-EU imports excluding China; Panel (b) refers to imports from China. Within each panel, LLMs are ordered by total import exposure. Direct exposure captures the share of total costs accounted for by direct imports from the source market. Same LLM, Neighboring LLM, and Non-neighboring LLM capture indirect exposure transmitted through domestic firm-to-firm linkages with partner firms located, respectively, in the same LLM, in geographically adjacent LLMs, and in non-adjacent LLMs. LLM-level exposure measures are firm-level cost-weighted averages using total firm costs as weights and are expressed as shares of total costs, as in Equation (5).

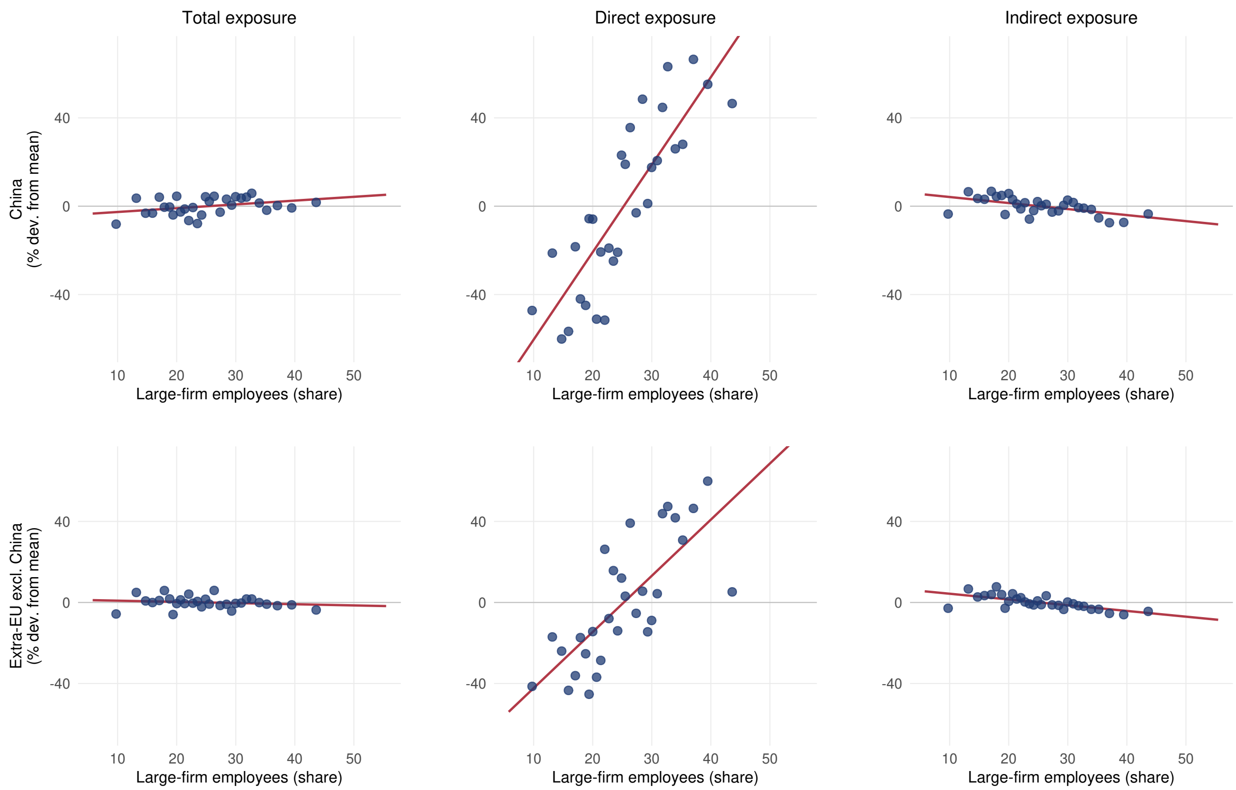
**Table B.3:** Robustness of LLM import exposure rankings to alternative weights

| Source market | Weighting scheme | Spearman rank corr. | Top-quintile overlap (%) | Top-quintile Jaccard (%) | Top-quintile emp. share (%) | Emp. share with Indirect > Direct (%) |
|---|---|---|---|---|---|---|
| China | Cost weights (baseline) | 1.000 | 100.0 | 100.0 | 21.9 | 91.5 |
| China | Labor-cost weights | 0.874 | 77.0 | 62.7 | 22.6 | 96.4 |
| China | Employment weights | 0.871 | 77.9 | 63.8 | 20.9 | 98.8 |
| Extra-EU excluding China | Cost weights (baseline) | 1.000 | 100.0 | 100.0 | 18.9 | 95.7 |
| Extra-EU excluding China | Labor-cost weights | 0.811 | 61.5 | 44.4 | 15.2 | 98.9 |
| Extra-EU excluding China | Employment weights | 0.783 | 60.7 | 43.5 | 13.5 | 99.5 |

*Notes*: The table compares LLM total exposure rankings across alternative weighting schemes. The baseline measure computes LLM exposure as the firm-level cost-weighted average within each LLM. The labor-cost and employment-weighted measures replace total-cost weights with, respectively, estimated labor costs and employment. Spearman rank correlations and top-quintile overlaps are computed relative to the baseline cost-weighted measure for the same source market. Top-quintile overlap is the share of baseline top-quintile LLMs that remain in the top quintile under the alternative weighting scheme. The Jaccard index is the size of the intersection divided by the size of the union of the two top-quintile sets. The employment-weighted measure changes the object of interest: it should be interpreted as exposure incidence for the worker-weighted firm distribution, rather than as an elasticity of the local cost base.

The baseline rankings are robust to alternative aggregation weights. Labor-cost- and employment-weighted exposure remains strongly correlated with the total-cost-weighted measure, although these alternatives change the object from the elasticity of the local cost base to exposure in a worker-weighted distribution (Table B.3).

**Figure B.5:** Exposure versus characteristics of LLMs




*Notes:* The figure shows total, direct, and indirect exposure against the employment share of large firms (i.e., those with more than 250 employees) across local labor markets, separately for imports from China and from extra-EU countries excluding China.

Figure B.5 relates exposure to the employment share of large firms (i.e., those with more than 250 employees). Direct exposure increases sharply with the large-firm share, consistent with fixed costs of global sourcing (Antras, Fort and Tintelnot, 2017); indirect exposure is comparatively flat because it reaches firms of all sizes through domestic supplier links.

**Table B.4:** Spatial clustering and cross-source similarity of import exposure

| | Extra-EU excluding China | China |
|---|---|---|
| *Panel A: Within-source spatial clustering* | | |
| Moran's $I$, direct exposure | 0.181*** | 0.167*** |
| Moran's $I$, indirect exposure | 0.191*** | 0.087*** |
| Moran's $I$, total exposure | 0.179*** | 0.132*** |
| Spatial-lag corr.: direct vs. neighboring indirect | 0.020 | 0.018 |
| *Panel B: Across-source similarity* | | |
| Spearman corr., direct exposure | 0.638*** | |
| Spearman corr., indirect exposure | 0.462*** | |
| Spearman corr., total exposure | 0.437*** | |
| Agreement rate, bivariate map classes | 0.510 | |
| Cohen's $\kappa$, bivariate map classes | 0.345 | |
| Jaccard overlap, high-direct/high-indirect class | 0.320 | |
| Jaccard overlap, top quintile of total exposure | 0.196 | |
| Spatial-lag corr.: Extra-EU total vs. neighboring China total | 0.165*** | |
| Spatial-lag corr.: China total vs. neighboring Extra-EU total | 0.175*** | |

*Notes*: The table reports spatial clustering and cross-source similarity statistics for import exposure across Italian local labor markets. Panel A reports within-source spatial autocorrelation. Moran's $I$ statistics are computed using row-standardized queen-contiguity weights. The spatial-lag correlation in Panel A correlates direct exposure in an LLM with the spatial lag of indirect exposure in neighboring LLMs; significance is assessed using the corresponding bivariate Moran permutation test. Panel B compares exposure to extra-EU imports excluding China with exposure to imports from China. Spearman correlations compare the cross-LLM ranking of source-specific exposure measures. Agreement and Cohen's $\kappa$ refer to the four bivariate direct-indirect map classes. Jaccard indices measure overlap in the high-direct/high-indirect class and in the top quintile of total exposure. Spatial-lag correlations in Panel B compare exposure to one source market in an LLM with exposure to the other source market in neighboring LLMs. All statistics are computed across 610 LLMs. Spatial permutation tests are based on 9,999 random permutations. Stars denote statistical significance from correlation tests or permutation tests: *** $p < 0.01$.

**Table B.5:** Correlation matrix for import exposure decomposition by source market

| | Direct | Total indirect | Same LLM | Neighboring LLM | Non-neighboring LLM |
|---|---|---|---|---|---|
| *Panel A: Extra-EU excluding China* | | | | | |
| Direct | 1.00 | | | | |
| Total indirect | 0.20 | 1.00 | | | |
| Same LLM | 0.41 | 0.41 | 1.00 | | |
| Neighboring LLM | 0.03 | 0.34 | 0.13 | 1.00 | |
| Non-neighboring LLM | 0.07 | 0.90 | 0.07 | 0.05 | 1.00 |
| *Panel B: China* | | | | | |
| Direct | 1.00 | | | | |
| Total indirect | 0.35 | 1.00 | | | |
| Same LLM | 0.28 | 0.72 | 1.00 | | |
| Neighboring LLM | 0.17 | 0.27 | 0.04 | 1.00 | |
| Non-neighboring LLM | 0.19 | 0.69 | 0.03 | 0.10 | 1.00 |

*Notes*: The table reports Pearson correlation matrices for cost-side import exposure across Italian local labor markets. Panel A reports correlations for exposure to extra-EU imports excluding China. Panel B reports correlations for exposure to imports from China. Each observation is an LLM. Direct exposure captures exposure due to direct imports from the source market. Total indirect exposure is the sum of the indirect components transmitted through domestic firm-to-firm linkages. Same LLM, Neighboring LLM, and Non-neighboring LLM identify whether the domestic partner firms transmitting indirect exposure are located, respectively, in the same LLM, in geographically adjacent LLMs, or in non-adjacent LLMs. Correlations are computed across LLM-level exposure measures.

## B.3 Spatial diagnostics

The diagnostics reinforce four main points. Exposure is spatially clustered for both source groups, but direct exposure in one LLM is essentially uncorrelated with indirect exposure in neighboring LLMs. China and other extra-EU exposure are positively related, yet the overlap is limited in the high-direct/high-indirect class and in the top quintile of total exposure. Within each source group, the non-neighboring component is especially important for variation in total indirect exposure.

## B.4 Product-category exposure

**Table B.6:** Average extra-EU import exposure by input category

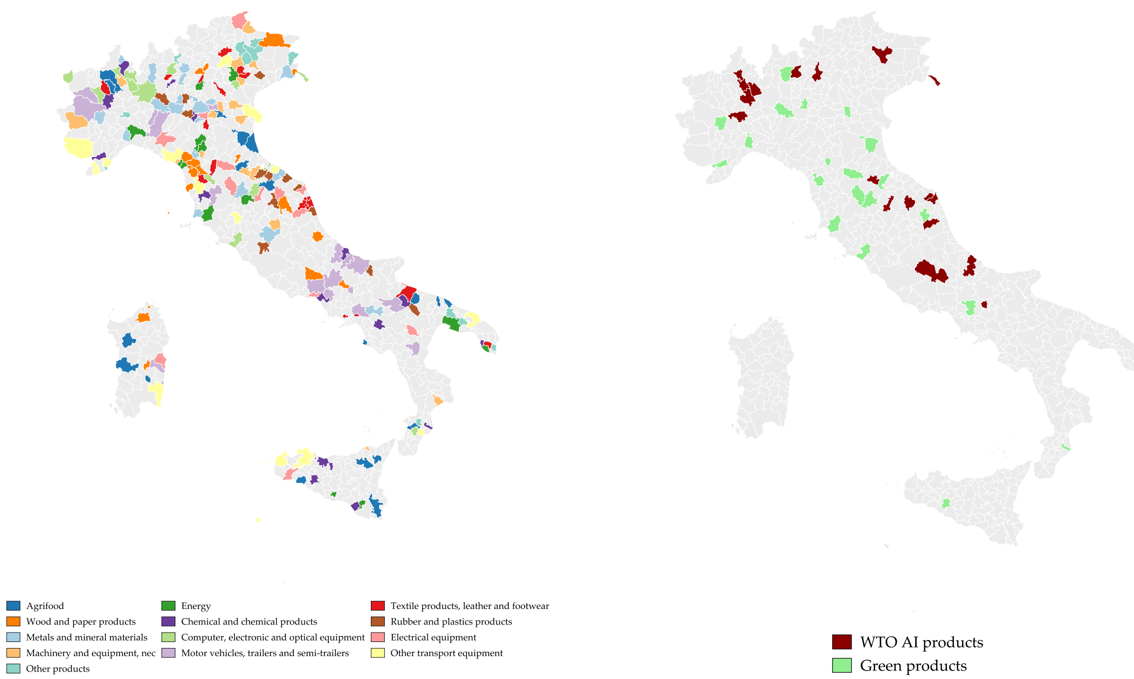
| | Exposure share (%) | | | | |
|---|---|---|---|---|---|
| Product category | Direct | First-round indirect | Total indirect | Total exposure | LLMs with Indirect > Direct (%) |
| Agrifood | 0.4 | 0.3 | 1.1 | 1.5 | 94.3 |
| Energy | 0.1 | 0.1 | 0.2 | 0.3 | 94.9 |
| Textile products, leather and footwear | 0.5 | 0.2 | 0.5 | 1.0 | 81.8 |
| Wood and paper products | 0.1 | 0.1 | 0.2 | 0.4 | 90.3 |
| Chemical and chemical products | 0.4 | 0.2 | 0.8 | 1.2 | 92.6 |
| Pharmaceuticals, medicinal chemical and botanical products | 0.1 | 0.0 | 0.1 | 0.2 | 93.0 |
| Rubber and plastic products | 0.1 | 0.1 | 0.2 | 0.3 | 92.5 |
| Metals and mineral products | 0.9 | 0.5 | 1.8 | 2.7 | 96.4 |
| Computer, electronic and optical equipment | 0.3 | 0.2 | 0.5 | 0.8 | 96.6 |
| Electrical equipment | 0.3 | 0.2 | 0.5 | 0.8 | 92.5 |
| Machinery and equipment, nec | 0.4 | 0.2 | 0.6 | 1.0 | 91.0 |
| Motor vehicles, trailers and semi-trailers | 0.2 | 0.2 | 0.5 | 0.7 | 95.4 |
| Other transport equipment | 0.1 | 0.0 | 0.1 | 0.2 | 89.5 |
| Other products | 0.2 | 0.1 | 0.2 | 0.4 | 85.1 |
| AI-enabling products | 0.3 | 0.2 | 0.5 | 0.9 | 94.8 |
| Green products | 0.3 | 0.2 | 0.6 | 1.0 | 93.3 |

*Notes*: The table reports cost-weighted average firm-level exposure to extra-EU imports by product category, expressed as percentage shares of total costs, as in Equation (5). Input categories are aggregated starting from OECD TiVA sectors. AI-enabling products are defined as in World Trade Organization (2025). Products classified as green are from Conteduca et al. (2025). Direct exposure captures direct imports from extra-EU source markets within the corresponding product category. First-round indirect exposure captures foreign-input exposure embodied in purchases from direct domestic suppliers. Total indirect exposure includes the first round and all higher-order rounds transmitted through the domestic firm-to-firm production network. Total exposure equals direct exposure plus total indirect exposure. The last column reports the share of local labor markets for which LLM-level total indirect exposure exceeds LLM-level direct exposure, expressed as a percentage of LLMs with valid exposure measures. LLM-level exposure is computed as the firm-level cost-weighted average within each LLM. Imports of mineral fuels and related products corresponding to Chapter 27 of the Harmonized System are assigned to a separate oil-and-gas origin and are not included in extra-EU product-category shocks.

Table B.6 reports direct, first-round indirect, total indirect, and total exposure for detailed input groups. Metals and mineral products have the largest total exposure, at 2.7%

of total costs, followed by agrifood and chemicals. AI-enabling and green products are not the largest categories in average import value, but they are strategically salient and generate total exposure of 0.9% and 1.0%, respectively. In most categories, indirect exposure exceeds direct exposure in more than 90% of LLMs.

**Figure B.6:** Top-exposed LLMs by extra-EU import input category




**a:** Aggregated TiVA Sectors

**b:** WTO AI and green products

*Notes*: The figure maps local labor markets that are among the top 20 most exposed to extra-EU imports in each product category. Input categories in the left panel are aggregated starting from OECD TiVA sectors. In the right panel, AI-enabling products are defined as in World Trade Organization (2025), whereas products classified as green are from Conteduca et al. (2025). For each category, LLMs are ranked by total import exposure, defined as direct exposure plus total indirect exposure. If an LLM belongs to the top-20 set of more than one category, it is assigned to the category for which its total exposure is largest. Grey areas denote LLMs that are not assigned to any selected top-20 category after this rule. Product categories are defined at the HS6 level. LLM-level exposure is computed as the firm-level cost-weighted average within each LLM, using firm total costs as weights, and is expressed as a share of total costs, as in Equation (5).

Figure B.6 maps the twenty most exposed LLMs for each product category. Motor-vehicle exposure is visible in parts of Piedmont and selected central areas; textiles in Veneto and the central Adriatic; agrifood in several island LLMs; electronics in the North-West; metals and mineral products in the Lombardy–Po Valley area; and wood and paper in selected LLMs including Tuscany. These patterns reflect local capabilities and specialization (Boschma, 2024). AI-enabling exposure is concentrated in the Center-North, with pockets in Piedmont, Lombardy, Veneto, and selected central LLMs. Green-product exposure is more dispersed and reaches areas outside the northern industrial core.

## B.5 Counterfactual and tail decompositions

**Table B.7:** Direct and indirect import exposures after neutralizing top importers

*Panel A: Extra-EU excluding China*

| Top-$k$ neutralized | Direct (%) | Indirect (%) | Total (%) |
|---|---|---|---|
| *Baseline* | 2.9 | 5.3 | 8.2 |
| 1 | 2.8 | 5.2 | 8.0 |
| 3 | 2.7 | 5.1 | 7.7 |
| 5 | 2.6 | 4.9 | 7.5 |
| 10 | 2.4 | 4.7 | 7.1 |
| 50 | 2.0 | 3.7 | 5.7 |
| 100 | 1.8 | 3.2 | 5.0 |
| 500 | 1.1 | 2.1 | 3.2 |
| 1000 | 0.8 | 1.5 | 2.3 |

*Panel B: China*

| Top-$k$ neutralized | Direct (%) | Indirect (%) | Total (%) |
|---|---|---|---|
| *Baseline* | 1.3 | 2.0 | 3.3 |
| 1 | 1.3 | 2.0 | 3.3 |
| 3 | 1.3 | 2.0 | 3.2 |
| 5 | 1.3 | 1.9 | 3.2 |
| 10 | 1.2 | 1.9 | 3.1 |
| 50 | 1.1 | 1.7 | 2.7 |
| 100 | 1.0 | 1.5 | 2.5 |
| 500 | 0.7 | 1.1 | 1.8 |
| 1000 | 0.5 | 0.8 | 1.3 |

*Notes*: The table reports national cost-side import exposure after neutralizing the top importers from each source market. Panel A refers to extra-EU imports excluding China; Panel B refers to imports from China. Top importers are ranked by the value of their direct imports from the corresponding source market. In each counterfactual, imports from the relevant source market by the top-$k$ importing firms are reassigned to a fictitious origin not subject to the shock. Firms are not removed from the domestic production network, and their total costs are preserved. Direct exposure captures direct imports from the source market. Indirect exposure captures foreign-input exposure transmitted through domestic firm-to-firm linkages. Total exposure equals direct plus indirect exposure. Exposure measures are national cost-weighted averages and are expressed as percentages of total costs. The baseline row reports exposure before neutralizing any top importer.

Table B.7 reports the full sequence obtained by neutralizing the top $k$ importers. Exposure to extra-EU origins excluding China is more concentrated among the largest importers than exposure to China. Even after the top 100 importers are neutralized, however, indirect exposure remains 3.2% and 1.5%, respectively.

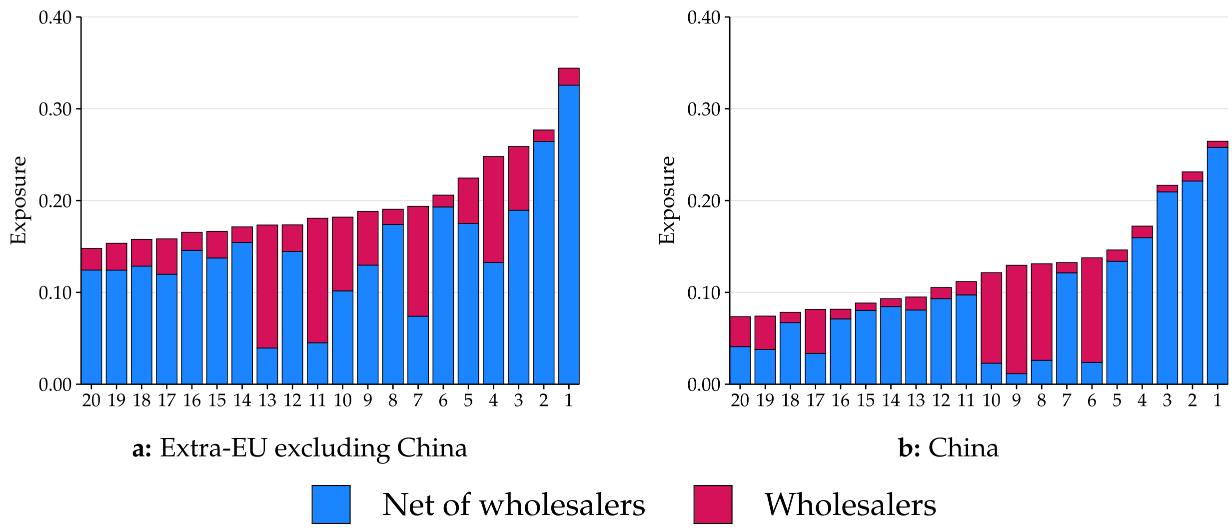
Wholesale intermediaries explain a large share of exposure in some top LLMs but little in others (Figure B.7). The upper tail is therefore not systematically a wholesale phenomenon.

Figure B.8 shows that the LLM-specific top importer accounts for a sizable share of total exposure in many highly exposed places, for both source groups. This confirms that firm-level granularity is a central feature of local tail risk.

A similar pattern appears at the product level. In Figure B.9, the leading HS4 category accounts for a large share of total exposure, especially for China, although many LLMs retain substantial exposure after that product is neutralized. Local vulnerability therefore combines product concentration with broader network transmission.

National import composition and local tail risks overlap only partially. Two HS4 products appear in both top-ten lists for extra-EU origins excluding China, and three do so for China (Table B.8). The products most relevant for place-based resilience are therefore not necessarily those with the largest national import values.

**Figure B.7:** Decomposition of total import exposure by wholesale contribution among the top-20 most exposed LLMs

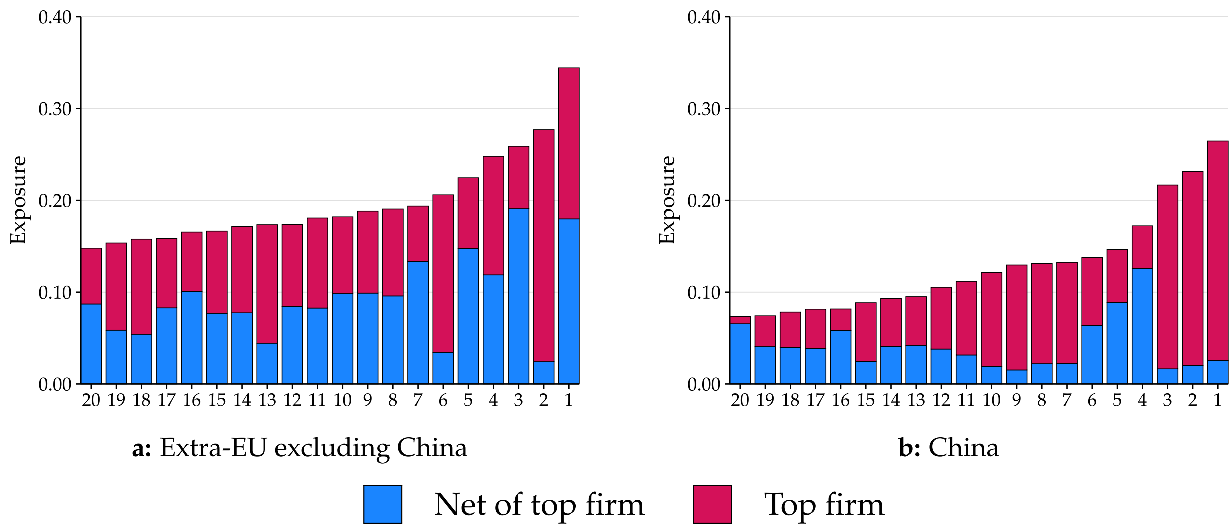



**a:** Extra-EU excluding China

**b:** China

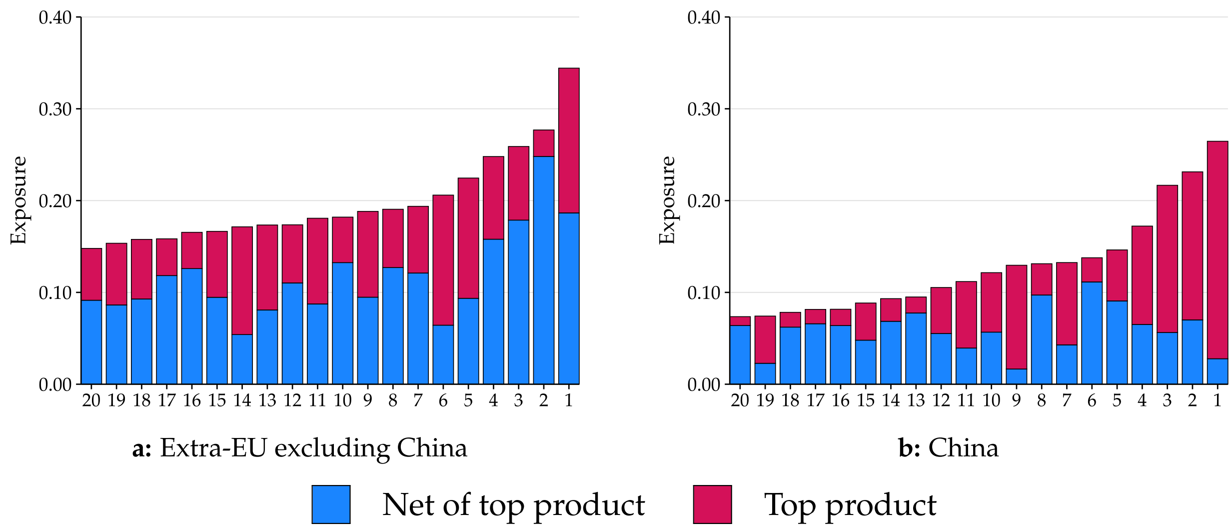
*Notes*: The figure reports the decomposition of total cost-side import exposure among the top-20 most exposed local labor markets. The left panel refers to extra-EU imports excluding China; the right panel refers to imports from China. In each panel, LLMs are ranked by baseline total import exposure within the corresponding source market, with rank 1 denoting the most exposed LLM. Bars decompose total exposure into the counterfactual exposure remaining after neutralizing imports by wholesale firms and the residual contribution attributed to wholesalers. The wholesale contribution is computed as the difference between baseline total exposure and total exposure in the counterfactual in which imports by ATECO 46 firms from the corresponding source market are reassigned to a fictitious origin not subject to the shock. Firms are not removed from the economy; only their imports from the relevant source market are neutralized. LLM-level exposure measures are firm-level cost-weighted averages using total firm costs as weights and are expressed as shares of total costs, as in Equation (5).

**Figure B.8:** Decomposition of total import exposure by top-firm contribution among the top-20 most exposed LLMs




*Notes*: The figure reports the decomposition of total cost-side import exposure among the top-20 most exposed local labor markets. The left panel refers to extra-EU imports excluding China; The right panel refers to imports from China. In each panel, LLMs are ranked by baseline total import exposure within the corresponding source market, with rank 1 denoting the most exposed LLM. Bars decompose total exposure into the counterfactual exposure remaining after neutralizing the top importer within each LLM and the residual contribution of that top importer. The top-firm contribution is computed as the difference between baseline total exposure and total exposure in the counterfactual in which the LLM-specific top importer from the corresponding source market is neutralized. Firms are not removed from the economy; only the imports of the LLM-specific top importer from the relevant source market are reassigned to a fictitious origin not subject to the shock. LLM-level exposure measures are firm-level cost-weighted averages using total firm costs as weights and are expressed as shares of total costs, as in Equation (5).

**Figure B.9:** Decomposition of total import exposure by top-product contribution among the top-20 most exposed LLMs




**a:** Extra-EU excluding China

**b:** China

*Notes*: The figure reports the decomposition of total cost-side import exposure among the top-20 most exposed local labor markets. The left panel refers to extra-EU imports excluding China; the right panel refers to imports from China. In each panel, LLMs are ranked by baseline total import exposure within the corresponding source market, with rank 1 denoting the most exposed LLM. Bars decompose total exposure into the counterfactual exposure remaining after neutralizing the top HS4 product within each LLM and the residual contribution of that product. The top-product contribution is computed as the difference between baseline total exposure and total exposure in the counterfactual in which imports of the LLM-specific top HS4 product from the corresponding source market are reassigned to a fictitious origin not subject to the shock. Firms are not removed from the economy; only imports of the relevant HS4 product from the corresponding source market are neutralized. LLM-level exposure measures are firm-level cost-weighted averages using total firm costs as weights and are expressed as shares of total costs, as in Equation (5).

**Table B.8:** Top-10 HS4 codes for import exposure at the national and LLM level

| Code | Product | Aggregate | Most exposed LLMs | Both |
|---|---|---|---|---|
| *Panel A: Extra-EU excluding China* | | | | |
| 0901 | Coffee, coffee husks and substitutes | X | | |
| 3004 | Medicaments in doses or retail packs | X | | |
| 4703 | Chemical wood pulp, soda or sulphate | X | | |
| 7110 | Platinum, unwrought, semi-manufactured or powder | X | | |
| 7208 | Hot-rolled flat products of iron/non-alloy steel | X | | |
| 7219 | Flat-rolled stainless steel, width 600 mm or more | X | | |
| 8517 | Telephones and data transmission apparatus | X | | |
| 8703 | Motor cars and vehicles for persons | X | | |
| 0713 | Dried leguminous vegetables, shelled | | X | |
| 1001 | Wheat and meslin | | X | |
| 1201 | Soya beans | | X | |
| 3102 | Nitrogenous mineral or chemical fertilisers | | X | |
| 3104 | Potassic mineral or chemical fertilisers | | X | |
| 7103 | Precious/semi-precious stones, except diamonds | | X | |
| 7206 | Iron/non-alloy steel in ingots or primary forms | | X | |
| 7602 | Aluminium waste and scrap | | X | |
| 7108 | Gold, unwrought, semi-manufactured or powder | | | X |
| 7207 | Semi-finished iron/non-alloy steel | | | X |
| *Panel B: China* | | | | |
| 2933 | Nitrogen heterocyclic compounds | X | | |
| 4202 | Trunks, cases, bags and similar containers | X | | |
| 7219 | Flat-rolled stainless steel, width 600 mm or more | X | | |
| 8501 | Electric motors and generators | X | | |
| 8517 | Telephones and data transmission apparatus | X | | |
| 8708 | Motor vehicle parts and accessories | X | | |
| 9405 | Luminaires, lighting fittings and illuminated signs | X | | |
| 1518 | Modified fats and oils; inedible mixtures | | X | |
| 5102 | Fine/coarse animal hair, not carded or combed | | X | |
| 8418 | Refrigerators, freezers and heat pumps | | X | |
| 8431 | Parts for lifting or earth-moving machinery | | X | |
| 8703 | Motor cars and vehicles for persons | | X | |
| 9003 | Spectacle/goggle frames and mountings | | X | |
| 9505 | Festive, carnival and entertainment articles | | X | |
| 8415 | Air conditioning machines | | | X |
| 8504 | Transformers, static converters and inductors | | | X |
| 8507 | Electric accumulators and separators | | | X |

*Notes*: The table compares the product composition of aggregate imports with the products driving exposure in the most exposed local labor markets. Product descriptions are shortened from the official HS 2022 heading titles. Panel A refers to extra-EU imports excluding China; Panel B refers to imports from China. Products are identified at the four-digit level of the Harmonized System. The *Aggregate* column reports products that appear among the ten HS4 codes with the largest matched import value in the final firm-to-firm network for the corresponding source market. The *Most exposed LLMs* column reports products obtained by ranking LLMs by total import exposure, selecting the HS4 product with the largest direct import value within each LLM, and retaining the first ten unique products along the exposure ranking. The *Both* column identifies products that appear in both lists. Chapter 27 products are excluded from the import-source construction and are not included in these product lists.

# C Methodological details

This appendix provides the derivation of the firm-level exposure measure, its higher-order network representation, and its aggregation and spatial decomposition at the LLM level.

## C.1 Firm-level cost exposure

Consider a firm $j$ that uses primary factors, foreign inputs, and domestic intermediate inputs from suppliers $i \in \mathcal{S}_j$. Let its unit cost function be

$$c_j = c_j\Big(W_j, P_F, \{p_i\}_{i\in\mathcal{S}_j}\Big)\,, \tag{C.1}$$

where $W_j$ is the price of primary factors, $P_F$ is the price index of inputs sourced from foreign market $F$, and $p_i$ is the price of supplier $i$'s variety. The unit cost function is assumed to be differentiable and homogeneous of degree one in input prices.

By Shephard's lemma,

$$d\log c_j = s_{vj} d\log W_j + s_{Fj} d\log P_F + \sum_{i\in\mathcal{S}_j} s_{ij} d\log p_i, \tag{C.2}$$

where $s_{vj}$, $s_{Fj}$, and $s_{ij}$ are the shares of total costs spent on primary factors, inputs from $F$, and inputs from domestic supplier $i$. The denominator includes labor, foreign inputs, and domestic intermediates. Because Equation (C.2) is an envelope condition, benchmark expenditure shares are sufficient statistics for the local first-order cost response even when firms can substitute across inputs.

Let $d\log P_F = d\log\tau$ and define exposure by

$$s^T_{Fj} = \frac{\partial \log c_j}{\partial \log \tau}. \tag{C.3}$$

Holding primary-factor prices fixed and assuming price taking or constant markups implies $d\log p_i = d\log c_i$. Dividing Equation (C.2) by $d\log\tau$ therefore gives

$$s^T_{Fj} = s_{Fj} + \sum_{i\in\mathcal{S}_j} s_{ij} s^T_{Fi}, \tag{C.4}$$

which is Equation (5) in the main text.

## C.2 Network representation and higher-order rounds

Let $\mathbf{s}_F^T$ and $\mathbf{s}_F$ collect total and direct exposure, and let $\mathbf{S}$ be the firm-to-firm cost-share matrix with element $S_{ji} = s_{ij}$. Then

$$\mathbf{s}_F^T = \mathbf{s}_F + \mathbf{S}\mathbf{s}_F^T. \tag{C.5}$$

If $\rho(\mathbf{S}) < 1$, the unique solution is

$$\mathbf{s}_F^T = (\mathbf{I} - \mathbf{S})^{-1}\mathbf{s}_F = \mathbf{s}_F + \mathbf{S}\mathbf{s}_F + \mathbf{S}^2\mathbf{s}_F + \cdots . \tag{C.6}$$

The first term is direct exposure, $\mathbf{S}\mathbf{s}_F$ is exposure through direct suppliers, and the remaining terms capture suppliers of suppliers and progressively more distant network layers. A firm can consequently be exposed even when it does not import from $F$ itself.

## C.3 Aggregation to local labor markets

Let $\mathcal{F}_\ell$ be the firms located in LLM $\ell$ and define their total cost base as

$$C_\ell = \sum_{j \in \mathcal{F}_\ell} C_j. \tag{C.7}$$

LLM exposure is the elasticity of this gross cost base:

$$S_{F\ell}^T = \frac{\partial \log C_\ell}{\partial \log \tau}. \tag{C.8}$$

For the ex-ante exercise, quantities are fixed, so $d \log C_j = d \log c_j$. Hence

$$d \log C_\ell = \sum_{j \in \mathcal{F}_\ell} \frac{C_j}{C_\ell} d \log C_j, \tag{C.9}$$

$$S_{F\ell}^T = \sum_{j \in \mathcal{F}_\ell} \omega_{j\ell}^C s_{Fj}^T, \qquad \omega_{j\ell}^C = \frac{C_j}{\sum_{h \in \mathcal{F}_\ell} C_h}. \tag{C.10}$$

This establishes the total-cost weights used in Equation (7). The empirical sequence is therefore to solve propagation on the firm network and only then aggregate the resulting firm exposures geographically.

## C.4 Spatial decomposition of LLM exposure

The LLM aggregate can be partitioned without changing its weighting. Direct and indirect exposure are

$$S_{F\ell}^{T}=\underbrace{\sum_{j\in\mathcal{F}_\ell}\omega_{j\ell}^{C}s_{Fj}}_{\text{direct}}+\underbrace{\sum_{j\in\mathcal{F}_\ell}\omega_{j\ell}^{C}\sum_{i\in\mathcal{S}_j}s_{ij}s_{Fi}^{T}}_{\text{indirect}}. \tag{C.11}$$

Let $\mathcal{N}_\ell$ be the LLMs contiguous to $\ell$ and $\mathcal{L}$ the set of all LLMs. The indirect component can be separated according to supplier location:

$$\begin{aligned} S_{F\ell}^{T}&=\sum_{j\in\mathcal{F}_\ell}\omega_{j\ell}^{C}s_{Fj}+\sum_{j\in\mathcal{F}_\ell}\omega_{j\ell}^{C}\sum_{i\in\mathcal{S}_j\cap\mathcal{F}_\ell}s_{ij}s_{Fi}^{T}\\ &\quad+\sum_{j\in\mathcal{F}_\ell}\omega_{j\ell}^{C}\sum_{k\in\mathcal{N}_\ell}\sum_{i\in\mathcal{S}_j\cap\mathcal{F}_k}s_{ij}s_{Fi}^{T}\\ &\quad+\sum_{j\in\mathcal{F}_\ell}\omega_{j\ell}^{C}\sum_{k\in\mathcal{L}\setminus(\{\ell\}\cup\mathcal{N}_\ell)}\sum_{i\in\mathcal{S}_j\cap\mathcal{F}_k}s_{ij}s_{Fi}^{T}. \end{aligned} \tag{C.12}$$

The terms correspond to direct exposure and indirect exposure from suppliers in the same, neighboring, and non-neighboring LLMs. Because each uses the same total-cost weights, the decomposition preserves the exposure object and only identifies its geographic transmission channel.

## C.5 Interpretation and adjustment margins

The derivation requires differentiability and a benchmark mapping from supplier unit costs to prices; constant returns are a convenient way to write unit costs but are not essential to the first-order result. Elasticities of substitution affect costs beyond the local first-order approximation (Hulten, 1978; Baqaee and Farhi, 2019). For a finite input-price increase expressed in price levels, concavity implies that the cost of retaining the benchmark input bundle is an upper bound on minimized cost, so substitution weakens the fixed-bundle response. The elasticity in Equation (C.3), however, is a local log derivative and is not a universal upper bound for every finite log-price shock.

The measure does not incorporate supplier switching, markup adjustment, entry and exit, demand changes, or general-equilibrium responses of factor prices and quantities (Baqaee and Farhi, 2019; Carvalho and Tahbaz-Salehi, 2019). These margins are important for realized outcomes; the purpose of the indicator is instead to locate the initial cost sensitivity embodied in the observed production network.

# D Details on the aggregation-bias exercise

This appendix compares two exposure measures constructed from the same firm-level transactions: a firm-level benchmark that solves propagation before aggregation and a sector–region approximation that aggregates transactions first and solves propagation afterward.

## D.1 Formal aggregation result

Let $\mathbf{d}$ and $\mathbf{m}$ denote firm-level direct and total exposure shares, so that

$$\mathbf{m} = \mathbf{d} + \mathbf{S}\mathbf{m}, \qquad \mathbf{m} = (\mathbf{I} - \mathbf{S})^{-1}\mathbf{d}, \tag{D.1}$$

where $\mathbf{S}$ is the firm-to-firm cost-share matrix. Let $\mathbf{G}$ be a group-membership matrix whose rows are disjoint sector–region cells and whose columns are firms. If $\mathbf{c}$ is the vector of firm costs and $\widetilde{\mathbf{c}} = \mathbf{G}\mathbf{c}$, define the within-cell cost-weighting matrix

$$\mathbf{P} = \operatorname{diag}(\widetilde{\mathbf{c}})^{-1}\mathbf{G}\operatorname{diag}(\mathbf{c}). \tag{D.2}$$

Thus $\mathbf{P}\mathbf{d}$ and $\mathbf{P}\mathbf{m}$ are the cost-weighted cell averages of direct and total firm exposure.

Aggregating the same transactions gives the cell-level cost-share matrix

$$\widetilde{\mathbf{S}} = \mathbf{P}\mathbf{S}\mathbf{G}', \tag{D.3}$$

and the aggregate-first exposure vector

$$\widetilde{\mathbf{m}} = (\mathbf{I} - \widetilde{\mathbf{S}})^{-1}\mathbf{P}\mathbf{d}. \tag{D.4}$$

Define the bias as firm-first exposure minus aggregate-first exposure:

$$\mathbf{b} = \mathbf{P}\mathbf{m} - \widetilde{\mathbf{m}} = \sum_{k=1}^{\infty}\left(\mathbf{P}\mathbf{S}^k - \widetilde{\mathbf{S}}^k\mathbf{P}\right)\mathbf{d}. \tag{D.5}$$

The $k = 0$ direct term cancels, so aggregation affects only indirect propagation and the bias can have either sign.

**Proposition 1** *Aggregation is exact for every direct-exposure vector* $\mathbf{d}$ *if and only if*

$$\widetilde{\mathbf{S}}\mathbf{P} = \mathbf{P}\mathbf{S}. \tag{D.6}$$

**Proof 1** *If Equation (D.6) holds, induction gives* $\widetilde{\mathbf{S}}^k\mathbf{P} = \mathbf{P}\mathbf{S}^k$ *for every k, and each term in Equation (D.5) is zero. Conversely, exact aggregation for every* $\mathbf{d}$ *implies* $\mathbf{P}(\mathbf{I}-\mathbf{S})^{-1} = (\mathbf{I}-\widetilde{\mathbf{S}})^{-1}\mathbf{P}$*. Multiplying by the two inverse operators gives* $(\mathbf{I}-\widetilde{\mathbf{S}})\mathbf{P} = \mathbf{P}(\mathbf{I}-\mathbf{S})$*, which is equivalent to Equation (D.6).*

The condition requires aggregation to commute with network propagation. It is restrictive when firms grouped in the same cell differ in direct exposure and in the buyers they serve. For a given $\mathbf{d}$, the first-round bias vanishes whenever $\widetilde{\mathbf{S}}\mathbf{P}\mathbf{d} = \mathbf{P}\mathbf{S}\mathbf{d}$; higher-order equality requires the analogous condition at subsequent rounds.

The simulation exercises below can be linked to the formal result through a simple spectral approximation. Retaining only the first-round term of Equation (D.5) gives

$$\mathbf{b} \approx \left(\mathbf{P}\mathbf{S} - \widetilde{\mathbf{S}}\mathbf{P}\right)\mathbf{d}. \tag{D.7}$$

Suppose further that the firm network is approximated by its dominant spectral component,

$$\mathbf{S} \approx \lambda_1 \mathbf{v}\mathbf{u}', \tag{D.8}$$

where $\lambda_1$ is the leading eigenvalue and $\mathbf{v}$ and $\mathbf{u}$ are the corresponding right and left eigenvectors. Then the magnitude and sign of the bias depend on the projection of direct exposure onto the dominant network component, $\mathbf{u}'\mathbf{d}$. Exposure concentrated on firms with high eigenvector centrality generates larger positive propagation terms than implied by aggregation, whereas exposure concentrated on peripheral firms generates weaker propagation. Aggregate-first measures therefore tend to understate indirect exposure when exposed firms are central suppliers and overstate it when exposure falls on peripheral suppliers. This mechanism motivates the simulation design below, which varies the identity and centrality of exposed firms while holding fixed the underlying economy, network, and aggregate exposure.

## D.2 Simulation design

The simulation isolates exposed-firm centrality. It uses one fixed economy, one fixed firm-to-firm network, one fixed sector–region aggregation, and one fixed set of exposed cells. Across Monte Carlo scenarios, only the identity of the exposed firm within each exposed cell changes.

The economy has $N = 1{,}000$ firms, $R = 10$ regions, and $S = 10$ sectors, yielding 100 sector–region cells with 10 equal-cost firms each. Every buyer draws $K = 5$ suppliers without replacement. Supplier attractiveness is

$$\eta_i = \exp(\varepsilon_i), \qquad \varepsilon_i \sim \mathcal{N}(0,1). \tag{D.9}$$

To generate geographically clustered links, supplier $i$ receives sampling weight

$$\widetilde{\eta}_{ij} = \eta_i \left[1 + (h-1)\mathbf{1}\{r(i) = r(j)\}\right], \qquad h = 8. \tag{D.10}$$

Selected suppliers each receive cost share $\alpha/K$, with $\alpha = 0.65$, so every row of the firm cost-share matrix $\mathbf{S}$ sums to $\alpha < 1$.

Let $a_{ji}$ denote purchases by buyer $j$ from supplier $i$. The supplier eigenvector centrality corresponds to the share of aggregate domestic purchases accounted for by firm $i$:

$$z_i = \frac{\sum_{j=1}^{N} a_{ji}}{\sum_{i=1}^{N}\sum_{j=1}^{N} a_{ji}} \tag{D.11}$$

i.e. $z_i$ solves the equation

$$\sum_j s_{ij} z_j = \lambda_{max} z_i$$

where $\lambda$ is the largest eigenvalue of the matrix $S$. Using the notation of Appendix D.1, the corresponding sector–region aggregate cost-share matrix is

$$\widetilde{\mathbf{S}} = \mathbf{PSG}', \tag{D.12}$$

where $\mathbf{G}$ is the firm-to-cell membership matrix and $\mathbf{P}$ is the within-cell cost-weighting matrix defined in Equation (D.2).

Fifty cells are selected once and held fixed as exposed cells. In each scenario, one of the ten firms in every exposed cell is drawn uniformly and assigned direct exposure $d_i = 0.30$, while all remaining firms receive zero exposure. Because firms have equal costs, each exposed cell always contributes the same aggregate direct exposure when exposures are averaged within cells.

If $\mathbf{d}_q$ denotes the firm-level direct-exposure vector in scenario $q$, the corresponding aggregate exposure vector is

$$\mathbf{Pd}_q. \tag{D.13}$$

The identity and centrality of exposed firms therefore vary across scenarios, while aggregate direct exposure remains constant.

For scenario $q$, firm-first and aggregate-first exposure are

$$\mathbf{m}_q = (\mathbf{I} - \mathbf{S})^{-1}\mathbf{d}_q, \qquad \widetilde{\mathbf{m}}_q = (\mathbf{I} - \widetilde{\mathbf{S}})^{-1}\mathbf{P}\mathbf{d}_q. \tag{D.14}$$

The national indirect bias is

$$B_q = 100\left(E_q^{F,ind} - E_q^{AGG,ind}\right), \tag{D.15}$$

with regional and cell-level biases defined analogously.

Scenarios are ranked by the mean centrality of their 50 exposed firms,

$$\bar{z}_q = \frac{1}{50}\sum_{i:d_{iq}>0} z_i, \tag{D.16}$$

and divided into equal-count deciles.

## D.3 Simulation results

Figure D.1 plots national indirect bias against mean exposed-firm centrality. The relationship is strongly positive: exposure assigned to relatively peripheral suppliers produces negative bias, while exposure assigned to central suppliers produces positive bias.

Table D.1 summarizes scenarios by centrality decile. IO indirect exposure is constant, while firm-level indirect exposure rises from 0.0196 in the lowest decile to 0.0344 in the highest. In the lowest decile, national bias is $-0.695$ percentage points and the most negative regional bias averages $-1.103$ points. In the highest decile, national bias is 0.781 points and the largest positive regional bias reaches 1.503 points. National averages can therefore conceal larger local measurement errors.

## D.4 Comparison using actual transactions

The actual-data exercise first solves exposure on the firm network and then compares it with exposure obtained after collapsing the same transactions to sector–LLM cells. Direct exposure is identical by construction.

The theoretical bias in Equation (D.5) is defined as firm-first minus aggregate-first exposure. For ease of interpretation, Tables D.2 and D.3 report the opposite difference, aggregate-first minus firm-first, so that positive values indicate that aggregation generates the larger exposure estimate.

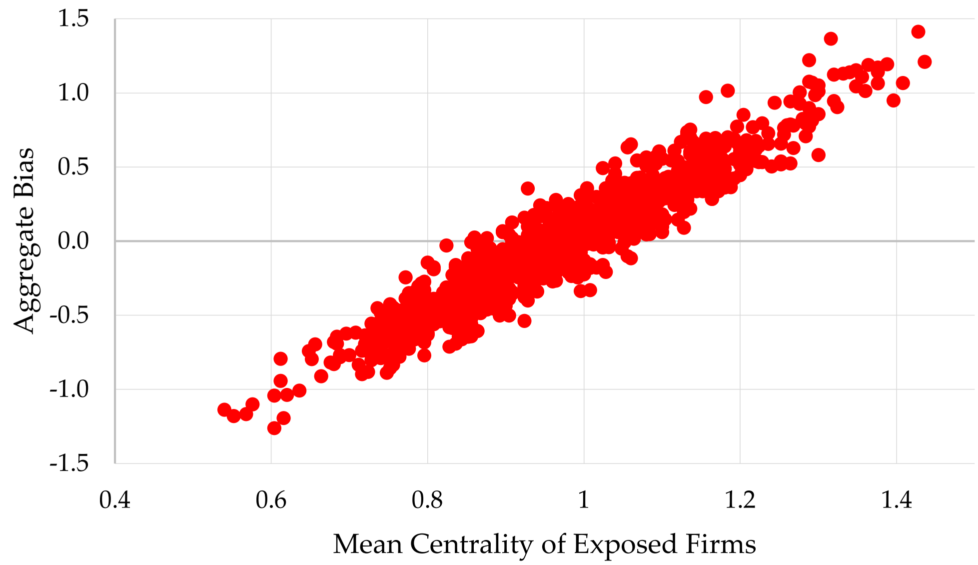



**Figure D.1:** Aggregation bias and exposed-firm centrality

*Notes*: Each point is one Monte Carlo scenario. The horizontal axis is the mean supplier centrality of directly exposed firms. The vertical axis is nationwide indirect aggregation bias, defined as firm-level indirect exposure minus sector–region IO indirect exposure, in percentage points. Positive values indicate that the IO representation understates indirect exposure; negative values indicate overstatement.

**Table D.1:** Indirect exposure and regional bias tails by exposed-firm centrality decile

| Centrality decile | $N$ | Firm indirect exposure | IO indirect exposure | National bias p.p. | Max positive regional bias p.p. | Min negative regional bias p.p. |
|---|---|---|---|---|---|---|
| D1 (lowest) | 100 | 0.0196 | 0.0266 | -0.695 | 0.023 | -1.103 |
| D2 | 100 | 0.0221 | 0.0266 | -0.443 | 0.103 | -0.886 |
| D3 | 100 | 0.0230 | 0.0266 | -0.359 | 0.180 | -0.832 |
| D4 | 100 | 0.0244 | 0.0266 | -0.219 | 0.309 | -0.677 |
| D5 | 100 | 0.0253 | 0.0266 | -0.122 | 0.420 | -0.587 |
| D6 | 100 | 0.0264 | 0.0266 | -0.015 | 0.540 | -0.510 |
| D7 | 100 | 0.0274 | 0.0266 | 0.086 | 0.688 | -0.415 |
| D8 | 100 | 0.0292 | 0.0266 | 0.264 | 0.889 | -0.240 |
| D9 | 100 | 0.0309 | 0.0266 | 0.435 | 1.057 | -0.149 |
| D10 (highest) | 100 | 0.0344 | 0.0266 | 0.781 | 1.503 | -0.047 |

*Notes*: The table sorts randomized exposed-firm assignments by realized mean supplier centrality and reports averages within equal-count deciles. Firm and IO columns report nationwide indirect exposure on the firm network and sector–region IO representation.

Table D.2 reports the decomposition for China, while Table D.3 extends the comparison to the fifteen largest source markets.

**Table D.2:** Aggregation bias in import exposure measures: China

| Exposure measure | Micro | Aggregate | Difference, aggregate - micro (p.p.) |
|---|---|---|---|
| Direct | 1.3 | 1.3 | 0.0 |
| First-round indirect | 0.7 | 0.8 | 0.1 |
| Total indirect | 2.0 | 2.5 | 0.5 |
| Total exposure | 3.3 | 3.8 | 0.5 |

*Notes*: The table compares exposure to imports from China computed using two aggregation orders. The micro approach computes exposure on the firm-level production network and then aggregates using firm total costs as weights. The aggregate approach first collapses the production network to sector–LLM cells and then computes exposure on the aggregated network. Exposure measures are expressed as percentage shares of total costs. *Difference, aggregate - macro* (p.p.) reports the percentage point difference between the aggregate and micro measures.

**Table D.3:** Aggregation bias by source market

| | | Direct | | Indirect | | Total | | Gap across sector–LLM cells | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Rank | Source market | Micro | Macro | Micro | Macro | Micro | Macro | P10 | P25 | P50 | P75 | P90 |
| 1 | Germany | 2.1 | 2.1 | 4.4 | 4.4 | 6.5 | 6.5 | -1.1 | -0.2 | 0.1 | 0.5 | 1.0 |
| 2 | China | 1.3 | 1.3 | 2.0 | 2.5 | 3.3 | 3.8 | -0.5 | 0.0 | 0.3 | 0.7 | 1.1 |
| 3 | France | 0.9 | 0.9 | 1.9 | 1.8 | 2.9 | 2.8 | -0.5 | -0.1 | 0.1 | 0.3 | 0.5 |
| 4 | Netherlands | 0.8 | 0.8 | 1.8 | 1.7 | 2.6 | 2.5 | -0.6 | -0.1 | 0.0 | 0.2 | 0.4 |
| 5 | Spain | 0.7 | 0.7 | 1.5 | 1.5 | 2.2 | 2.2 | -0.3 | -0.0 | 0.1 | 0.2 | 0.4 |
| 6 | Belgium | 0.5 | 0.5 | 0.9 | 0.9 | 1.3 | 1.3 | -0.3 | -0.0 | 0.1 | 0.1 | 0.3 |
| 7 | United States | 0.4 | 0.4 | 0.5 | 0.6 | 0.8 | 0.9 | -0.0 | 0.0 | 0.1 | 0.2 | 0.3 |
| 8 | Poland | 0.3 | 0.3 | 0.6 | 0.6 | 0.9 | 0.9 | -0.1 | -0.0 | 0.0 | 0.1 | 0.2 |
| 9 | Austria | 0.3 | 0.3 | 0.6 | 0.6 | 0.9 | 0.9 | -0.2 | -0.0 | 0.0 | 0.1 | 0.2 |
| 10 | Türkiye | 0.2 | 0.2 | 0.5 | 0.5 | 0.8 | 0.7 | -0.2 | -0.1 | 0.0 | 0.1 | 0.1 |
| 11 | Switzerland | 0.2 | 0.2 | 0.2 | 0.3 | 0.5 | 0.6 | 0.0 | 0.1 | 0.1 | 0.2 | 0.2 |
| 12 | Romania | 0.2 | 0.2 | 0.4 | 0.4 | 0.6 | 0.6 | -0.1 | -0.0 | -0.0 | 0.0 | 0.1 |
| 13 | Czechia | 0.2 | 0.2 | 0.5 | 0.5 | 0.7 | 0.7 | -0.1 | -0.0 | 0.0 | 0.1 | 0.1 |
| 14 | India | 0.2 | 0.2 | 0.3 | 0.4 | 0.5 | 0.6 | -0.1 | 0.0 | 0.0 | 0.1 | 0.2 |
| 15 | Hungary | 0.2 | 0.2 | 0.4 | 0.4 | 0.6 | 0.6 | -0.1 | 0.0 | 0.0 | 0.1 | 0.2 |

*Notes*: The table compares import exposure computed using the micro and aggregate-first approaches for the top-15 source markets. Source markets are ranked by import value in the final matched firm-to-firm network and include both intra-EU and extra-EU origins. The micro approach computes exposure on the firm-level production network and then aggregates using firm total costs as weights. The macro approach first collapses the production network to sector–LLM cells and then computes exposure on the aggregated network. Direct, indirect and total exposure are national cost-weighted averages and are expressed as percentage shares of total costs. The last five columns report the distribution across sector–LLM cells of the indirect-exposure gap, defined as macro indirect exposure minus micro indirect exposure, expressed in percentage points. Positive values indicate that the aggregate-first approach generates a larger indirect exposure than the micro approach in the corresponding sector–LLM cell.

Table D.3 shows that national micro and aggregate-first estimates are often similar, but this correspondence masks heterogeneity across sector–LLM cells. China is a clear example: aggregate-first indirect exposure is 2.5%, compared with 2.0% in the firm network, while the cell-level macro-minus-micro gap ranges from $-0.5$ percentage points at the 10th percentile to 1.1 at the 90th. Aggregation therefore overstates exposure in some cells and understates it in others. Agreement at the national level does not imply an accurate spatial allocation of exposure.

# E Reconciliation with aggregate import content

Let $x_{ij}$ denote the value of sales from firm $i$ to domestic firm $j$, so that $s_{ij} = x_{ij}/C_j$ as in Section 3.1, and let $f_i$ denote firm $i$'s sales to final demand (households, government, investment, and exports). Firm $i$'s total sales are

$$y_i = f_i + \sum_j x_{ij} = f_i + \sum_j s_{ij}\, C_j. \tag{E.1}$$

Recall that the $ji$-th element of the cost-share matrix $\mathbf{S}$ is $s_{ij}$; hence $\sum_j s_{ij}C_j$ is the $i$-th element of $\mathbf{S}'\mathbf{C}$, and Equation (E.1) reads, in matrix form,

$$\mathbf{y} = \mathbf{f} + \mathbf{S}'\mathbf{C}. \tag{E.2}$$

Assume that firm revenues are exhausted by input payments, so that $y_i = C_i$ for every firm; equivalently, any residual profit is treated as the payment to a fixed primary factor and included in the cost base, as in the Domar-weight convention of Hulten (1978). Substituting $\mathbf{y} = \mathbf{C}$ into Equation (E.2) and solving,

$$(\mathbf{I} - \mathbf{S}')\,\mathbf{C} = \mathbf{f} \qquad \Longrightarrow \qquad \mathbf{C}' = \mathbf{f}'\,(\mathbf{I} - \mathbf{S})^{-1}. \tag{E.3}$$

Now weight firm-level total exposures by final demand. Using $\mathbf{s}_F^T = (\mathbf{I} - \mathbf{S})^{-1}\mathbf{s}_F$ and then Equation (E.3),

$$\sum_j \frac{f_j}{F}\, s_{Fj}^T \;=\; \frac{1}{F}\,\mathbf{f}'(\mathbf{I} - \mathbf{S})^{-1}\mathbf{s}_F \;=\; \frac{1}{F}\,\mathbf{C}'\,\mathbf{s}_F \;=\; \frac{1}{F}\sum_j C_j\, s_{Fj} \;=\; \frac{M_F}{F}, \tag{E.4}$$

where $F = \sum_j f_j$ and $M_F = \sum_j M_{Fj}$ are aggregate final expenditure and aggregate imports from market $F$, and the last step uses $s_{Fj} = M_{Fj}/C_j$.

Under the accounting convention above, final-demand-weighted total exposure therefore equals the aggregate import content of final expenditure exactly: propagation through the domestic network reallocates exposure across firms, but the Leontief inverse applied to the direct-share vector is fully absorbed by the Leontief structure of the cost base itself, so that no amplification survives at the aggregate level. By contrast, weighting the same firm-level exposures by total costs yields $\mathbf{C}'\mathbf{s}_F^T/(\mathbf{C}'\boldsymbol{\iota}) > M_F/(\mathbf{C}'\boldsymbol{\iota})$ whenever the network transmits any exposure, because the gross cost bases of vertically linked firms each record the cost increase generated by the same imported input.

With a constant markup $\mu > 1$, so that $\mathbf{y} = \mu\mathbf{C}$, Equation (E.2) gives $\mathbf{f}' = \mu\mathbf{C}' -$

$\mathbf{C}'\mathbf{S}$ and hence $\mathbf{f}'\mathbf{s}_F^T = \mathbf{C}'\mathbf{s}_F + (\mu - 1)\,\mathbf{C}'\mathbf{s}_F^T$: final-demand-weighted exposure exceeds the import content by the exposure accruing to profits, which also absorb the shock.