Critical Networks and Structural Power: An Application of the Economic Security Index to the US–China–EU Conflict

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Abstract

The growing geopolitical fragmentation has transformed the landscape of international trade, exposing previously underestimated economic vulnerabilities. This paper proposes a new economic security indicator that overcomes the limitations of traditional approaches by systematically capturing indirect trade dependencies transmitted through intermediary countries. By integrating Input-Output matrices, network theory, and shock propagation algorithms, our indicator quantifies both direct and indirect dependencies, revealing hidden vulnerabilities in global supply chains. The empirical application of the indicator to European trade data demonstrates that traditional analyses significantly underestimate the EU's exposure to external disruptions in strategic sectors. These findings have important implications for European strategic autonomy policies, suggesting that effective diversification must consider the entire structure of the global trade network, rather than just direct bilateral relations.

Keywords: Economic security, Trade dependencies, Network theory, Strategic autonomy, Global value chains
JEL Codes: F14, F15, F52, C67, D85

1. Introduction

In a context of growing geoeconomic fragmentation, systemic tensions between major powers, and frequent disruptions in global supply chains, the assessment of national economic security requires more refined analytical tools. Existing literature has predominantly focused on aggregated metrics of bilateral trade or direct dependency, without capturing the structural interdependencies that emerge through global production networks and indirect trade.

This paper addresses this gap by developing an Economic Security Index (ESI), designed to measure a country's exposure to exogenous disruptions by integrating both direct and indirect dependencies, and considering the structural relevance of critical intermediaries.

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For the purposes of this research, we define economic security as "a nation's capacity to maintain the integrity of its essential economic functions and critical supply chains in the face of exogenous disruptions, whether these arise from natural disasters, technological failures, or deliberate actions by other actors."

This definition distinguishes economic security from related concepts:

First, unlike economic sovereignty, which often implies autarky or minimal dependence on foreign inputs, economic security acknowledges the reality and benefits of interdependence while focusing on managing critical vulnerabilities.

Second, While resilience refers to the ability to recover from disruptions, economic security encompasses both preventing critical disruptions and maintaining functionality during them.

Third, in contrast to economic competitiveness, which focuses on relative advantage in global markets, economic security centers on the stability and reliability of economic functions essential to national welfare, regardless of comparative advantage.

Four, unlike traditional conceptions of national security, which primarily address military threats, economic security acknowledges that existential threats can emerge from supply disruptions, technological dependence, or economic coercion.

Our Economic Security Index operationalizes this definition by measuring both direct and indirect vulnerabilities across industries, with particular attention to sectors where disruptions would have cascading effects throughout the economy. The index is designed to identify not just obvious dependencies in direct bilateral trade, but also hidden vulnerabilities that emerge from a country's position within complex global supply networks.

We start with the matrix representation of international trade, where a matrix $\mathbf{X}$ captures trade flows between countries, with each element x_{ij} representing the imports that country j receives from country i. Based on this, we develop a methodology that goes beyond the simple quantification of bilateral flows, also incorporating dependencies generated through intermediary countries. This approach is particularly relevant in a world where global value chains have created intricate networks of trade interdependence.

Identifying and measuring these indirect dependencies is not just an academic exercise. In a context where supply chain disruptions can have cascading effects, understanding the full range of trade dependencies becomes crucial for the formulation of trade policies and risk management. A country may have a seemingly low dependence on another if only direct exchanges are considered, but it could be significantly exposed through third-party countries acting as intermediaries.

To address this complexity, we propose a methodological framework that combines a normalized measure of direct dependency with an adapted algorithm that captures indirect dependencies. This algorithm, based on graph theory principles, incorporates relevance thresholds and convergence criteria, allowing for efficient calculation even in large-scale trade networks. The resulting methodology provides a comprehensive measure of dependency that reflects both the direct and indirect channels through which one country may depend on another.

The main contribution of this paper is fourfold. First, methodologically, we propose an original approach based on graph theory and path analysis in economic networks, incorporating computational acceleration for the efficient calculation of indirect dependencies. This methodology allows for the characterization of structural and "hidden" vulnerability of each country in terms of critical supply routes. Second, empirically, we apply the index to an extensive set of global trade data (ITP, 2019), generating a systematic mapping of trade dependencies by industry, with a particular focus on strategic sectors, while identifying key intermediaries and critical bilateral relationships. Third, normatively and policy-wise, we offer concrete implications for European strategic autonomy, identifying areas where supplier diversification or regional cooperation can mitigate structural risks. Our index can serve as a tool to guide industrial policies, trade agreements, or strategic reserves.

In the following sections, we formally develop this methodological framework. We begin by providing a precise definition of what we mean by trade dependency, followed by a detailed description of the construction of direct and indirect dependency measures. Finally, we illustrate the application of this methodology through an example that allows us to visualize how indirect dependencies can significantly alter our understanding of a country's trade vulnerabilities.

2. Theoretical Foundations of the Economic Security Index

This paper anchors its approach to measuring economic security in three complementary theoretical frameworks: complex interdependence theory, structural power in international political economy, and weaponized interdependence.

Complex Interdependence and Network Vulnerability

Building on Keohane and Nye (1977) foundational work on complex interdependence, we conceptualize economic security not merely as the absence of bilateral dependencies, but as a property emerging from a country's position within multiple, overlapping networks of exchange. As Farrell and Newman (2019) note, "interdependence has created complex networks with particular topographies," where certain nodes become critical junctures for global flows.

Our Economic Security Index operationalizes this network-based understanding by explicitly modeling how disruptions propagate through multiple paths within the global trade system. Unlike traditional dependency measures focused on dyadic relationships, our approach captures what Oatley et al. (2013) call the "emergent properties" of the international economic system—properties that cannot be reduced to the sum of bilateral relations.

Structural Power in International Political Economy

The second theoretical pillar supporting our index is Strange's 1988 concept of structural power, understood as "the power to shape and determine the structures of the global political economy [...] within which other states, their political institutions, their economic enterprises [...] have to operate." In Strange's framework, structural power operates through control over security, production, finance, and knowledge.

Our index specifically operationalizes structural power in the production domain by quantifying how control over critical nodes in supply chains confers influence that extends far beyond direct bilateral relationships. By identifying indirect dependencies and critical intermediaries, we make visible what Strange described as the "indirect, unobservable exercise of power" in global economic relations.

Weaponized Interdependence

Finally, our work engages with Farrell and Newman's 2019 theory of "weaponized interdependence," which posits that "states with political authority over the nodes in the international networked structures through which money, information, and goods travel are uniquely positioned to impose costs on others." This theory distinguishes between "panopticon effects" (the ability to monitor flows) and "chokepoint effects" (the ability to restrict flows).

Our Economic Security Index specifically measures vulnerability to chokepoint effects by identifying both direct dependencies and indirect chokepoints. The "critical intermediaries" analysis we develop reveals potential chokepoints in global supply chains where economic leverage can be exercised—precisely the "weaponization" mechanism that Farrell and Newman describe.

By integrating these three theoretical frameworks, our index moves beyond traditional conceptions of trade dependency to provide a more nuanced understanding of economic security in an era of complex, networked interdependence.

2.1. Economic Security in the Context of Systemic Crises

Recent systemic crises have dramatically revealed the vulnerability of global supply chains, elevating economic security to a global strategic priority. The COVID-19 pandemic served as a profound shock that exposed critical weaknesses in international supply chains, demonstrating how disruptions in production and distribution of essential goods—from personal protective equipment to semiconductors—can lead to critical shortages with cascading effects across multiple economic sectors Swiss Re Institute (2025). During this period, many nations discovered the limitations of their understanding of indirect dependencies, as traditional statistical methods failed to adequately capture the complexity of modern supply chains.

The Russian invasion of Ukraine further amplified these concerns, particularly exposing acute vulnerabilities in European energy and food sectors. Europe's dependence on Russia for essential energy supplies demonstrated how such reliance can be exploited as a tool of geopolitical pressure, accelerating the search for alternative sources and prompting a re-evaluation of economic security policies. Additionally, the use of trade barriers as diplomatic instruments has highlighted the susceptibility of trade relations to non-economic considerations Boston Consulting Group (2024).

These developments have fundamentally altered our understanding of economic security. No longer can it be conceived merely as the absence of direct trade dependencies; rather, it must be understood as a multidimensional property emerging from a country's position within complex networks of exchange Strange (1988). This network-based conceptualization of economic security aligns with what Farrell and Newman Farrell and Newman (2019) identify as "weaponized interdependence"—the capacity of states with authority over key nodes in international networked structures to leverage that position for strategic advantage.

2.2. Modeling Propagation of Economic Shocks

The translation of these theoretical concepts into our methodological approach is accomplished through three key innovations. First, our incorporation of network theory allows us to operationalize what Kahler (2009) calls "networked politics"—the way power operates through position within complex global networks rather than through purely dyadic relationships. Second, our path-based calculation of indirect dependencies quantifies what Hirschman (1945) identified as the asymmetric vulnerability that creates potential for influence in interdependent relationships.

A key advancement in our approach is the explicit modeling of shock propagation mechanisms through trade networks. Recent research has shown that "local idiosyncratic shocks can propagate through the global economy and generate considerable global fluctuations" Frontiers in Sustainable Food Systems (2025) due to the interconnected nature of production networks. Our algorithm systematically traces these potential propagation paths, incorporating both the magnitude of trade flows and the structural position of each country within the network.

This approach enables the identification of what the literature refers to as "chokepoints"—critical nodes in supply chains where disruptions can have disproportionate effects Association for Supply Chain Management (2025). By quantifying both direct and indirect dependencies, our Economic Security Index (ESI) offers a more comprehensive assessment of vulnerability that captures the "hidden" risks embedded in complex supply networks, providing policymakers with crucial information for designing effective diversification strategies Herman (2017).

3. Motivation

Economic security has emerged as a global strategic priority in a context marked by successive systemic crises that have revealed critical vulnerabilities in international supply chains. Recent years have shown how excessive dependence on specific suppliers can undermine not only economic stability but also national security in a broader sense.

The COVID-19 pandemic represented the first systemic shock that clearly exposed these fragilities. Disruptions in the production and distribution of essential products—from personal protective equipment to semiconductors—demonstrated that the geographic concentration of production capacities can lead to critical shortages with cascading effects across multiple economic sectors. During this period, many countries discovered they lacked accurate knowledge of their indirect dependencies, as traditional statistics did not adequately capture the complexity of modern supply chains.

The Russian invasion of Ukraine further intensified these concerns, revealing particularly acute vulnerabilities in the European energy and food sectors. Europe's energy dependence on Russia demonstrated how essential supplies can become tools of geopolitical pressure, accelerating the search for alternatives and the redesign of economic security policies. Recently, trade barriers have been used as diplomatic tools, exemplified by the tariffs imposed by the Trump administration on countries like Canada and Mexico, highlighting the vulnerabilities of trade relations to non-economic considerations.

On April 2, 2025, the Trump administration escalated its trade war by announcing new tariffs on a broad range of imports, including goods from the European Union, China, and several other global powers. These "reciprocal tariffs" include a minimum 10% tariff on all imports to the United States, with specific tariffs as high as 34% on Chinese goods and 20% on European products. This decision is a direct continuation of the administration's protectionist stance, amplifying concerns over the fragility of global supply chains and the growing geopolitical fragmentation of trade. These measures underscore how national security concerns are increasingly interwoven with trade policy, reshaping the global economic order and fueling uncertainty in international markets.

Simultaneously, the growing rivalry between the United States and China is driving a profound reshaping of global value chains. The imposition of technological restrictions, selective tariffs, and investment controls is generating "selective deglobalization," fragmenting international trade into distinct spheres of influence. This new geoeconomic reality is gradually transforming a relatively integrated global trading system into a more regionalized framework, where national security considerations increasingly influence trade decisions.

In this context, the very concept of national security has expanded to incorporate economic dimensions that were once peripheral. Access to critical raw materials, emerging technologies, and digital infrastructures has become central to strategic planning. Entities such as the European Union have developed "open strategic autonomy" strategies to balance the benefits of open trade with the need to secure access to essential resources and capabilities in adverse scenarios.

This evolving landscape demands analytical tools that allow policymakers to more accurately identify and manage trade vulnerabilities. Traditional approaches, focused primarily on direct bilateral relationships, prove inadequate to capture the complexity of contemporary value chains, where dependencies are transmitted through multiple intermediaries and trade routes.

The need for indicators that systematically capture both direct and indirect dependencies is particularly urgent in a world where "connector countries" are emerging, serving as intermediaries between geopolitically distant blocs. Without adequate tools to identify these transmission channels for vulnerabilities, commercial diversification strategies may prove ineffective, creating a false sense of security while critical dependencies persist through indirect routes.

This paper addresses this gap by developing a comprehensive indicator that combines matrix analysis, network theory, and propagation algorithms to identify and quantify hidden trade vulnerabilities. This innovative methodological approach allows for the assessment of the resilience of trade systems in the face of potential disruptions, informing effective diversification strategies and analyzing alternative scenarios for trade reorganization in a context of increasing geopolitical fragmentation.

4. Literature Review

The study of trade dependence has evolved significantly over the past decades, driven by the growing complexity of global value chains and the increasing recognition that economic interdependence creates both opportunities and vulnerabilities. What began as simple bilateral trade concentration measures has progressively developed into sophisticated analytical frameworks that attempt to capture the multifaceted nature of economic dependencies in an interconnected world.

4.1. Evolution of Trade Dependency Measurement

The measurement of trade dependence has been a central concern in international economics since the mid-20th century, but the analytical approaches have undergone substantial transformation in response to changes in the structure of global trade. Early approaches focused primarily on bilateral relationships and import concentration, reflecting a period when trade flows were predominantly characterized by final goods exchange between countries. As global production fragmented across borders and value chains became increasingly complex, the inadequacy of these traditional measures became apparent, motivating the development of more sophisticated methodologies.

The integration of global value chains (GVCs) has fundamentally altered the nature of trade dependencies. Countries no longer simply trade final goods; instead, they exchange intermediate inputs that traverse multiple borders before reaching final consumers. This transformation implies that a country's vulnerability to external shocks cannot be adequately assessed by examining only its direct trading partners. A disruption in a seemingly distant economy can cascade through intermediary countries, affecting production processes and supply chains in unexpected ways. The COVID-19 pandemic and recent geopolitical tensions have starkly illustrated these hidden vulnerabilities, demonstrating that supply chain resilience depends not only on first-order relationships but also on the robustness of entire networks of interdependencies (Baldwin and Freeman, 2020; Stoll and Thethi, 2022).

This evolution in the nature of global trade has been accompanied by parallel developments in analytical methodologies. The emergence of detailed international input-output databases, advances in network theory, and increasing computational capacity have enabled researchers to develop more nuanced approaches to measuring dependencies. Contemporary methods now integrate elements from multiple disciplines—including graph theory, structural economics, and complexity science—to provide a more comprehensive understanding of how economic vulnerabilities emerge and propagate through international trade systems (Cerina et al., 2015; Acemoglu et al., 2012).

The current geopolitical context has further elevated the importance of accurately measuring trade dependencies. The concept of "economic security" has expanded beyond traditional concerns about strategic raw materials to encompass dependencies in critical technologies, essential inputs, and key intermediaries in global supply chains (Farrell and Newman, 2019; European Commission, 2021). Policymakers increasingly recognize that trade diversification strategies must account not only for direct supplier concentration but also for indirect dependencies that may create vulnerabilities through less obvious channels. This recognition has created urgent demand for analytical tools capable of identifying these hidden dependencies and quantifying their potential impact on economic resilience (Arriola et al., 2024; Fernández-Villaverde et al., 2024).

4.2. Methodological Approaches to Measuring Dependencies

The literature on trade dependencies has developed along several methodological trajectories, each offering distinct perspectives on how to conceptualize and quantify economic vulnerabilities. These approaches range from simple concentration measures to sophisticated network models and dynamic propagation frameworks. Understanding the strengths and limitations of each methodology is essential for situating our contribution within the broader research landscape.

4.2.1. Concentration Indices and Bilateral Measures

One of the most widely used methods for measuring trade dependence has been the application of concentration indices to bilateral trade flows. The Herfindahl-Hirschman Index (HHI), originally developed to measure market concentration, has been extensively adapted to assess the geographic concentration of a country's imports or exports (Michaely, 1962; Balassa, 1965). For a given product or sector, the HHI is calculated as:

$$HHI = \sum_{i=1}^{N} s_i^2 \tag{1}$$

where s_i represents the share of country i in the total imports (or exports) of the analyzed country. Higher values indicate greater concentration and, by extension, potentially higher vulnerability to supply disruptions from dominant trading partners.

Institutions such as the European Commission have employed this index to identify strategic dependencies, establishing specific thresholds (HHI > 0.4) to flag highly concentrated imports that may pose economic security risks (European Commission, 2021; Arjona et al., 2023). Similarly, various national governments and international organizations have developed monitoring frameworks based on import concentration metrics to track dependencies in critical sectors (Bonneau and Nakaa, 2020; Jean, 2023).

Despite their widespread use and intuitive appeal, concentration indices present several fundamental limitations. First, they provide only a static snapshot of trade relationships without capturing the dynamic processes through which dependencies evolve or through which shocks propagate (Cadot et al., 2014). Second, and most critically, they fail to account for indirect dependencies that emerge through third-party countries. A country may appear to have diversified suppliers when examined bilaterally, yet remain vulnerable if those suppliers themselves depend on a common source for critical inputs. Third, these measures exhibit high temporal instability, with significant year-to-year turnover in the products identified as concentrated, raising questions about their reliability as a basis for long-term policy interventions (Vicard and Wibaux, 2023).

Furthermore, concentration indices typically focus exclusively on the import side, neglecting the symmetric vulnerabilities that arise from export concentration. A country highly dependent on a single export market faces distinct but equally important risks, particularly in scenarios of geopolitical fragmentation or demand shocks in destination markets (Balteanu et al., 2025). As Vicard and Wibaux (2023) demonstrate, this purely bilateral perspective may significantly underestimate a country's exposure to systematic trade vulnerabilities, making concentration indices problematic as the sole basis for economic security policy.

4.2.2. Input-Output Analysis and Inter-sectoral Linkages

Input-output (I-O) analysis, pioneered by Leontief (1951), has provided a powerful framework for understanding the complex web of inter-sectoral dependencies within and across economies. The fundamental insight of I-O analysis is that economic activity in one sector generates demand for inputs from other sectors, creating indirect effects that propagate through the production structure. The Leontief inverse matrix, defined as:

$$(I - A)^{-1} \tag{2}$$

where I represents the identity matrix and A the matrix of technical coefficients, captures both the direct and indirect requirements of each sector for the output of all other sectors. Each element a_{ij} of the technical coefficient matrix indicates the amount of input from sector i required to produce one unit of output in sector j.

This methodology has been extensively applied to analyze the fragmentation of global value chains and their implications for trade patterns and economic vulnerability. Antrás et al. (2012) introduced the concept of "upstreamness" to measure the distance of production stages from final demand, providing insights into how countries position themselves within global supply chains.

Johnson and Noguera (2012) and Koopman et al. (2014) developed accounting frameworks to trace value-added through international production networks, enabling more accurate assessments of trade dependencies than gross trade flows alone.

An important extension of traditional I-O analysis for vulnerability assessment is the concept of "average propagation lengths" (APL) developed by Dietzenbacher et al. (2005). The APL measures the economic distance between sectors, allowing researchers to identify production chains and assess the potential transmission of economic shocks. Sectors with low APL to many other sectors occupy strategic positions in the production network and may serve as critical transmission channels for disruptions.

The international extension of I-O analysis through multi-regional input-output (MRIO) tables has enabled researchers to trace dependencies across borders. Miller and Blair (2009) provide comprehensive treatments of these methodologies, which allow for the quantification of both direct and indirect trade dependencies. These tables capture not only the bilateral trade in final goods but also the complex flows of intermediate inputs that characterize modern global value chains.

However, traditional I-O models face two key limitations when applied to dependency analysis. First, they typically assume fixed technical coefficients, implying that production recipes cannot be adjusted in response to supply disruptions. This assumption may be reasonable in the short run but becomes increasingly problematic when analyzing longer-term resilience, where factor substitution and supply chain reorganization become feasible (Arriola et al., 2024). Second, while I-O analysis captures inter-sectoral linkages, it does not naturally incorporate the network structure of trade relationships that would allow for the identification of alternative supply routes and critical intermediaries. The matrix representation provides information about aggregate dependencies but not about the specific pathways through which shocks propagate or the existence of bottleneck countries in supply chains.

4.2.3. Network Analysis and Centrality Measures

Network analysis has emerged as a complementary approach that explicitly models trade as a complex system of interconnected nodes and links. In this framework, countries (or sectors) are represented as nodes, and trade flows as directed, weighted edges connecting them. This representation enables the application of graph-theoretic concepts to identify structural properties that traditional methods cannot capture.

Pioneering work by Fagiolo et al. (2010) applied weighted network analysis to characterize the evolution of the World Trade Network (WTN), documenting that it exhibits "small-world" properties—high clustering combined with short path lengths—and a scale-free degree distribution, where a few highly connected hubs coexist with many peripheral nodes. These topological properties have important implications for vulnerability: the presence of hubs means that disruptions to a few central countries can have disproportionate systemic effects, while the small-world property implies that shocks can propagate rapidly through the network.

De Benedictis et al. (2014) extended this approach using highly disaggregated product-level data, revealing substantial heterogeneity in network structure across different types of goods. Their analysis demonstrates that network properties vary systematically with product characteristics, with more technologically sophisticated goods traded through denser, more centralized networks.

This heterogeneity suggests that vulnerability assessments must account for sectoral specificities rather than relying on aggregate network measures.

Central to network analysis is the concept of centrality, which quantifies the structural importance of nodes within the network. Different centrality measures capture distinct dimensions of importance. Degree centrality counts the number of trading partners, measuring the extent of a country's integration into global trade. Closeness centrality assesses how directly a country can reach all others, with shorter average path lengths indicating greater centrality. Betweenness centrality identifies nodes that lie on many shortest paths between other nodes, revealing which countries serve as critical intermediaries or bottlenecks in trade networks. Eigenvector centrality extends the notion of importance by considering not just the number of connections but also the centrality of one's trading partners—a country trading with other central countries achieves higher eigenvector centrality.

Korniyenko et al. (2017) developed a product-level vulnerability index based on network centrality measures, specifically using the standard deviation of weighted out-degree centrality to identify products with concentrated export bases. Their methodology quantifies product fragility in global supply chains by considering three components: export concentration, clustering tendencies, and international substitutability. The weighted out-degree centrality for each country i exporting product k is calculated as:

$$C_i^{out} = \sum_{j=1}^{n-1} \frac{w_{ij}}{\langle w_j \rangle} \tag{3}$$

where w_{ij} represents the value of exports from country i to country j and $\langle w_j \rangle$ is the average value of imports for country j. The product-level vulnerability measure is then:

$$C_k = \sqrt{\frac{\sum_{i=1}^{n} (C_{ik}^{out} - \bar{C}_k^{out})^2}{n-1}} \tag{4}$$

where C_k captures the dispersion of export centrality across supplying countries, with higher values indicating greater concentration risk.

More recently, Costa et al. (2022) applied social network analysis to domestic and international input-output tables, proposing a novel taxonomy of sectors based on their capacity to transmit economic shocks. Their classification distinguishes between: (i) *widespread transmission sectors*, which propagate shocks extensively and rapidly through large, dense ego-networks; (ii) *hierarchical transmission sectors*, characterized by extensive but slow transmission due to large but sparse networks; (iii) *selective transmission sectors*, with fast but limited propagation through small, dense networks; and (iv) *weak transmission sectors*, exhibiting both limited extent and slow speed of shock propagation. This taxonomy is based on two key ego-network properties: size (the number of sectors within two steps in the network) and density (the proportion of active relationships among potential connections).

A critical insight from Costa et al. (2022) is the identification of a mismatch between sectors that are central in international trade networks and those that play central roles in domestic shock propagation. This finding underscores the importance of analyzing both the international and domestic dimensions of trade networks when assessing vulnerability. A sector may be highly integrated internationally but peripheral domestically, limiting its ability to transmit foreign shocks into the domestic economy. Conversely, a domestically central sector with limited international exposure may be a critical propagation channel for domestic shocks but insulated from foreign disruptions.

Caputo (2024) extends the network analysis of trade by examining how network structure shapes multilateral resistance terms—the trade barriers that countries face when trading with all partners. Her analysis demonstrates strong correlations between network centrality measures and trade costs: countries with higher betweenness centrality—those serving as critical intermediaries—face distinct patterns of trade resistance compared to peripheral countries. This work establishes an important link between network position and the economic costs of trade, suggesting that centrality measures capture not just topological properties but also economically meaningful characteristics of trade relationships.

Despite these advances, network analysis approaches face two key challenges when applied to measuring trade dependencies. First, while they excel at identifying structural importance and connectivity patterns, standard network measures do not naturally translate into quantitative assessments of economic dependency intensity. Betweenness centrality, for instance, identifies critical intermediaries but does not measure the degree to which one country's production depends on imports channeled through that intermediary. Second, most network analyses focus on the structure of existing trade relationships rather than on potential alternative pathways that might be activated in response to disruptions. As Cerina et al. (2015) note, the ability to switch suppliers or reroute trade flows—substitutability—is crucial for resilience but not captured by static network topology alone.

4.2.4. Shock Propagation Models

Beyond static measures of dependency and network structure, recent research has focused on understanding the *dynamic* mechanisms through which economic shocks propagate through production networks. This literature recognizes that the ultimate impact of a disruption depends not only on the initial exposure but also on how the shock cascades through interconnected supply chains.

Acemoglu et al. (2012) and Carvalho and Gabaix (2013) provided seminal theoretical contributions demonstrating that micro-level shocks to individual firms or sectors can have aggregate effects when production networks exhibit certain structural properties. Contrary to the traditional diversification argument—that idiosyncratic shocks average out in large economies—these authors show that network structure can amplify rather than dampen micro-level volatility. When the economy's input-output network is characterized by a few highly influential suppliers (high out-degree centrality in the supply network), shocks to these central suppliers propagate widely, generating substantial aggregate fluctuations.

The "granular hypothesis" of Gabaix (2011) complements this network-based explanation by demonstrating that firm size distributions following power laws—as they empirically do—imply that the largest firms are "too big to be negligible." Shocks to these granular firms affect aggregate outcomes precisely because their size violates the conditions required for the law of large numbers to apply. di Giovanni and Levchenko (2012) provide empirical evidence for this mechanism in the context of international trade, showing that firm-level export shocks generate measurable aggregate fluctuations in countries where export concentration is high.

Huneeus (2018) makes a critical contribution by developing a dynamic general equilibrium model with endogenous production networks where firm-to-firm links have adjustment frictions. Using detailed Chilean firm-level transaction data, he documents that supplier relationships are costly to form and adjust: links react sluggishly to firm-specific trade shocks and are unresponsive to small shocks but strongly responsive to large ones. These adjustment frictions have profound implications for shock propagation. In Huneeus's counterfactual analysis of international trade shocks during the Great Recession, he finds that without link adjustment frictions—with a completely flexible network that could costlessly reorganize—output losses would have been 30% lower. This result emphasizes that the *dynamics* of network reconfiguration, not merely the static network structure, critically determine aggregate vulnerability. Slow adjustment of supply relationships implies that economies cannot quickly reroute around disruptions, amplifying the impact of shocks.

Borsos (2021) advances this literature by demonstrating the critical importance of firm-level heterogeneity for shock propagation analysis. He shows that even within narrowly-defined industries (4-digit NACE classifications), firms exhibit extreme heterogeneity in their input structures. For example, 69.1% of firm pairs in the same detailed industry sector share zero suppliers in common. This heterogeneity implies that sector-level shock analyses can produce highly inaccurate results, as the impact of a shock depends critically on which specific firms within a sector are affected. Using Hungarian production network data, Borsos develops a framework that combines Leontief production functions (for crucial, non-substitutable inputs) with linear components (for substitutable inputs) to trace shock propagation accounting for this firm-level heterogeneity. His simulations demonstrate that allocating a sector-level shock of identical magnitude across different firms within that sector generates vastly different aggregate outcomes—up to an order of magnitude difference in total losses—depending on which firms are hit.

Burkholz and Schweitzer (2019) examine shock propagation specifically in international crop trade networks, analyzing how production failures in agricultural sectors cascade through global supply chains. Their work introduces cascade analysis to agricultural trade, demonstrating that network structure determines not only first-order trade disruptions but also higher-order effects as countries substitute disrupted imports with alternative sources, potentially creating secondary shortages. They find that the most vulnerable products are not necessarily those with the highest direct import concentration, but rather those embedded in network structures where cascade effects amplify initial shocks.

This shock propagation literature collectively establishes several key insights. First, network structure matters for aggregate outcomes—economies with sparse, decentralized production networks are more resilient than those dependent on a few central suppliers. Second, adjustment dynamics are crucial—the speed at which supply chains can reorganize determines the severity and duration of disruption impacts. Third, firm-level heterogeneity cannot be ignored—sectoral aggregation masks critical dependencies and leads to substantial mismeasurement of vulnerability. These findings imply that effective vulnerability assessment requires not just identifying dependencies but also understanding the mechanisms and speed of shock propagation through the specific network structure of an economy.

4.3. Scale of Analysis: From Sectoral to Firm-Level

A fundamental methodological debate in the literature on economic dependencies concerns the appropriate level of aggregation for analysis. Traditional approaches have operated primarily at the country-sector level, leveraging readily available international trade statistics and input-output tables. However, recent theoretical and empirical work has increasingly challenged the adequacy of this aggregation level, arguing that firm-level analysis is essential for accurately assessing vulnerability and shock propagation.

The theoretical case for disaggregation was established by Gabaix (2011) and Acemoglu et al. (2012), who demonstrated that firm-level idiosyncratic shocks do not necessarily average out in the aggregate. The classical intuition—rooted in the law of large numbers—holds that if an economy consists of many independent production units, shocks to individual units should cancel out, leaving aggregate outcomes determined solely by systematic factors. However, this reasoning breaks down when firm size distributions follow power laws, as they empirically do in most economies. In such distributions, the largest firms are so disproportionately large that shocks affecting them violate the conditions required for diversification to eliminate idiosyncratic volatility. This "granular hypothesis" implies that microeconomic shocks can have first-order macroeconomic effects, providing theoretical justification for firm-level analysis.

Empirical evidence strongly supports the relevance of firm-level heterogeneity for understanding trade dependencies and shock propagation. di Giovanni and Levchenko (2012) demonstrate that in countries with concentrated export structures, shocks to the largest exporting firms generate measurable aggregate fluctuations. Their analysis of cross-country data reveals that countries with higher export concentration—measured by the share of exports accounted for by the largest firms—exhibit greater aggregate volatility, consistent with the granular hypothesis operating through the trade channel.

Borsos (2021) provides perhaps the most compelling evidence for the necessity of firm-level analysis in the context of production networks and vulnerability assessment. His examination of Hungarian firm-level transaction data reveals that even within narrowly-defined industries (4-digit NACE classifications), firms exhibit extreme heterogeneity in their input structures. To illustrate this point concretely, Borsos analyzes the sector "Manufacture of fabricated metal products except machinery and equipment" (NACE C25), which contains 178 firms, yielding 15,753 possible pairwise comparisons. Calculating Jaccard similarity coefficients for each pair based on the 4-digit industry classification of their suppliers, he finds that 69.1% of all firm pairs share *zero* suppliers in common. This striking result implies that if we compare two arbitrary firms from the same detailed industry classification, they most likely have completely different supplier networks.

This within-industry heterogeneity has profound implications for shock propagation analysis. When a crisis scenario affects a sector, the aggregate impact depends critically on the distribution of the shock across firms within that sector—information that is lost in sectoral aggregation. Borsos demonstrates this through simulation exercises where a 20% shock to a single sector is allocated differently across firms within that sector in 1,000 distinct scenarios. The distribution of downstream and upstream losses across industries varies by an order of magnitude depending on which specific firms within the initially shocked sector are affected. For example, if the shock primarily hits animal production firms within the agriculture sector, the veterinary services sector experiences substantial downstream effects. However, if the shock concentrates on crop production firms, the impact on veterinary services is negligible, while other sectors face greater losses. Sectoral-level analysis, by averaging across these firm-specific patterns, fundamentally mischaracterizes the economy's vulnerability structure.

Huneeus (2018) reinforces these conclusions from a different angle, emphasizing the role of firm-specific relationships and adjustment frictions. His analysis of Chilean production networks demonstrates that the links between specific firms are not generic—they embody relationship-specific capital, search costs, and contractual arrangements that make them costly to form and adjust. When shocks hit particular firms, their specific network of relationships determines how the shock propagates, and the costs of forming new relationships limit the speed of adjustment. This micro-level structure and dynamics cannot be captured by sectoral input-output coefficients, which represent only aggregate, average relationships.

Despite the compelling evidence for firm-level analysis, significant practical and conceptual challenges limit its widespread application, particularly for international comparisons and policy analysis. First, comprehensive firm-to-firm transaction data remains available only for a handful of countries—primarily Chile, Hungary, Belgium, and a few others—and typically covers only domestic transactions. Cross-border firm-to-firm linkages, which are crucial for assessing international dependencies, are almost never observed. This data scarcity severely constrains the scope of firm-level vulnerability assessments.

Second, even when firm-level data are available, computational challenges become substantial. The number of potential firm-to-firm links grows quadratically with the number of firms, and realistic shock propagation simulations require solving large-scale dynamic optimization problems. Borsos (2021) addresses this challenge by exploiting the empirical sparsity of firm-to-firm networks—most potential links are never active—but computational demands remain orders of magnitude higher than for sectoral analysis.

Third, firm-level analysis introduces confidentiality concerns that complicate data access and result dissemination. Detailed firm-to-firm transaction data is highly sensitive from both commercial and privacy perspectives, typically requiring restricted access protocols and preventing the publication of firm-specific results. Aggregation is often necessary for research output, potentially negating some benefits of the disaggregated analysis.

Given these constraints, much contemporary research adopts a pragmatic approach, working at the country-sector level while acknowledging that this aggregation may mask important within-sector heterogeneity. Costa et al. (2022) exemplify this approach, conducting sectoral-level network analysis while explicitly recognizing that their taxonomy of shock transmission capacity represents sector-level averages that may not apply uniformly to all firms within those sectors. Their sectoral focus enables international comparisons and leverages widely available input-output data, but the interpretation of results must account for the potential heterogeneity within sectors.

Our methodology follows this pragmatic tradition, operating primarily at the country-sector level to enable comprehensive international analysis using available trade and input-output data. However, we explicitly design our framework to be scale-flexible—the mathematical structure of our dependency measures and propagation algorithms applies equally to firm-level networks when such data are available. This flexibility ensures that as firm-level international transaction data become more accessible, our methodology can be straightforwardly adapted to incorporate the finer granularity that research increasingly shows to be important.

The debate over aggregation level highlights a fundamental tension in vulnerability research:

the trade-off between empirical accuracy—which favors disaggregation—and practical implementability—which favors working with available data at coarser scales. Advances in data collection and computational methods are gradually relaxing this constraint, but for the foreseeable future, most policy-relevant vulnerability assessments will need to operate at the sector level while remaining cognizant of the limitations this aggregation imposes.

4.4. Integration Approaches and Research Gaps

The preceding review reveals that the literature on trade dependencies has evolved along multiple methodological trajectories—concentration indices, input-output analysis, network theory, and shock propagation models—each offering valuable but partial insights into the nature of economic vulnerabilities. Recent research has increasingly recognized that a comprehensive understanding of trade dependencies requires integrating elements from these distinct approaches rather than relying on any single framework.

Cerina et al. (2015) represent an early effort at methodological integration, constructing the World Input-Output Network (WION) that combines input-output accounting with network analysis. Their framework represents the global economy as a weighted, directed network where nodes are country-sectors and links capture inter-sectoral trade flows valued at their input-output coefficients. This representation enables the application of network centrality measures while preserving the economic content of input-output relationships. However, as the authors acknowledge, their approach does not incorporate dynamic propagation mechanisms or explicitly model the intensity of bilateral dependencies accounting for all possible transmission paths.

Korniyenko et al. (2017) integrate network analysis with product-specific vulnerability assessment, developing composite indicators that combine export concentration (measured through network centrality dispersion), clustering tendencies (the degree to which a product's exporters trade with similar partners), and international substitutability (the availability of alternative suppliers). Their methodology represents an important step toward multidimensional vulnerability metrics but remains focused on product-level fragility rather than comprehensive country-level dependency assessment. Moreover, their framework does not trace indirect dependencies through multiple intermediary layers—a critical limitation given the complex, multi-hop nature of modern supply chains.

More recently, Pourshahabi et al. (2024) developed the Potential Indirect Vulnerability Index (PIVI), which explicitly attempts to capture indirect vulnerabilities arising from the interdependence between trade networks and foreign direct investment (FDI) flows. Their model considers three components: a target country (the importer of goods), an investing country (the exporter of FDI), and intermediary countries that export commodities to the target and receive FDI from the investing country, serving as conduits for indirect vulnerabilities. The PIVI quantifies indirect vulnerabilities based on two fractions: the dependency of the target country on commodities from each intermediary, and the dependency of each intermediary on FDI from the investing country. Applied to US-China interdependence, Pourshahabi et al. identify Vietnam as a critical transmission channel—a country through which China's influence on the US economy operates indirectly despite efforts at bilateral decoupling.

While PIVI represents an important advance in recognizing indirect transmission channels, it focuses specifically on the FDI-trade nexus and limits analysis to two-step indirect paths (target →

intermediary → investor). Real-world dependencies often involve longer chains with multiple intermediary layers, and vulnerabilities can propagate through purely trade-based channels without requiring FDI linkages. Furthermore, the framework does not incorporate the input-output structure of production that determines how disruptions to imported inputs cascade through domestic sectors.

Fernández-Villaverde et al. (2024) contribute a different type of integration, developing a dynamic factor model with time-varying parameters to measure geopolitical fragmentation. Their index synthesizes information from multiple dimensions—trade flows, financial linkages, policy restrictions, geopolitical risks, and political alignment—into a single metric capturing the evolving degree of global economic fragmentation. This approach recognizes that dependencies are multifaceted and that single indicators (such as trade concentration alone) provide incomplete pictures. However, their focus is on measuring fragmentation at the global or regional level rather than quantifying specific bilateral dependencies or identifying critical transmission channels through which vulnerabilities propagate.

These integration efforts, while advancing the field, leave several critical gaps that our methodology addresses. First, *no existing framework simultaneously captures direct and indirect dependencies through multiple intermediaries, the intensity of trade relationships based on input-output linkages, network structural properties that identify critical bottlenecks, and propagation dynamics that trace how shocks cascade through the system.* Concentration indices identify first-order exposures but miss indirect channels entirely. Input-output models capture inter-sectoral linkages but typically lack explicit network representations of alternative supply routes. Network centrality measures identify structural importance but do not quantify the economic magnitude of dependencies. Shock propagation models trace dynamics but often require granular firm-level data unavailable for international analysis.

Second, existing approaches struggle to operationalize the concept of *hidden vulnerabilities*—dependencies that appear minor or nonexistent in standard bilateral analysis but become critical when indirect transmission channels are considered. A country may have successfully diversified away from direct imports of a strategic input, yet remain vulnerable if its alternative suppliers themselves depend heavily on the original source. Identifying these hidden dependencies requires tracing potential disruption paths through multiple layers of the trade network, accounting for both the probability and intensity of transmission at each step. Current methodologies either do not attempt this multi-hop analysis or do so in limited ways that do not fully capture the economic magnitude of indirect exposures.

Third, the literature lacks a unified metric that policymakers can readily interpret and apply across different sectors and countries. Concentration indices provide simple numerical thresholds but miss crucial dependencies. Network measures like betweenness centrality are informative but lack direct economic interpretation—a high betweenness score identifies an important intermediary but does not quantify how much of a country's production depends on flows through that intermediary. Input-output multipliers quantify sectoral interdependencies domestically but do not naturally extend to assessing international dependencies accounting for network structure. Researchers and policymakers seeking to assess economic security consequently face a fragmented landscape of indicators, each capturing different dimensions of vulnerability, with no clear framework for integrating them into actionable assessments.

Fourth, existing methodologies provide limited guidance for evaluating *counterfactual scenar-*

ios—the "what if" questions that are central to policy analysis. What would be the impact on Country A's production if Country B experienced a supply shock? How would a disruption in a specific intermediary country propagate through the global network to affect ultimate importers? Which alternative supply routes could be activated, and at what cost, if primary channels were disrupted? Answering these questions requires not just measuring existing dependencies but simulating disruption scenarios through dynamic propagation models that account for network structure, input-output relationships, and substitution possibilities. Most available frameworks lack this simulation capability or implement it in ways requiring data (such as firm-level production functions) that are impractical for broad international comparisons.

Our proposed indicator addresses these gaps by developing an integrated framework that combines normalized dependency measures with network-based propagation algorithms tracing indirect dependencies through multiple intermediary layers. Specifically, our contribution is fourfold:

First, we synthesize input-output accounting with network analysis in a way that preserves both the economic content of trade relationships (the magnitude of value flows and their importance for domestic production) and the structural properties of the trade network (the topology of connections and the identification of critical intermediaries). This synthesis enables us to measure not just whether Country A depends on Country B, but also how much of A's production relies on inputs from B, considering both direct trade and indirect flows through third parties.

Second, we develop a path-enumeration propagation algorithm that systematically quantifies indirect dependencies by exhaustively identifying all simple paths (without node repetition) connecting any pair of trading partners through intermediary countries. For computational efficiency, we implement a hybrid approach: paths of length 2 are computed via vectorized matrix operations (equivalent to $\sum_k T_{jk} \cdot T_{ki}$ where T is the transition matrix of trade shares), while longer paths (length 3 to maximun possible length) are enumerated explicitly using combinatorial methods. The algorithm incorporates two key efficiency mechanisms: (i) a path strength threshold that filters out economically negligible transmission channels (paths with cumulative probability below `path_strength_threshold`), and (ii) a convergence criterion that terminates enumeration when marginal contributions from longer paths fall below a specified tolerance. This design balances comprehensive coverage of significant indirect dependencies against computational tractability, enabling application to large-scale international trade networks.

Unlike the Leontief inverse approach, which aggregates all paths implicitly through matrix algebra and cannot distinguish between alternative routes, our path-explicit methodology enables the identification of specific critical intermediaries and the evaluation of alternative supply routes—information essential for policy analysis of supply chain resilience. Moreover, unlike Pourshahabi et al. (2024) who limit analysis to two-step paths, our framework captures multi-hop dependencies that may span several intermediary layers, revealing hidden vulnerabilities in deeply interconnected supply chains.

Third, we provide a composite dependency metric that integrates direct and indirect exposures into a single, policy-relevant indicator. This metric is normalized to facilitate cross-country and cross-sector comparisons, enabling policymakers to rank dependencies by severity and prioritize mitigation efforts. The metric's construction is transparent and interpretable—high values indicate that a substantial share of domestic production relies on imports from the partner country, either directly or through critical intermediaries that could not be easily bypassed in the event of disruption.

Fourth, our framework is designed for scenario analysis and counterfactual evaluation. By parameterizing the propagation algorithm—adjusting the maximum path length considered, the relevance thresholds for including intermediaries, and the substitutability assumptions for inputs—analysts can simulate different disruption scenarios and assess the robustness of supply chains under varying conditions. This flexibility makes the framework applicable to diverse policy questions, from evaluating the strategic importance of specific trade relationships to designing diversification strategies that account for indirect exposures.

The methodology's practical applicability is enhanced by its reliance on publicly available data—international trade statistics and multi-regional input-output tables—rather than requiring firm-level transaction data accessible only for a few countries. This ensures that our approach can be implemented for comprehensive international assessments covering the full set of countries and sectors relevant for economic security analysis. At the same time, the framework's mathematical structure is scale-flexible, meaning it can be adapted to incorporate firm-level granularity when such data become available, without requiring fundamental methodological changes.

In the context of growing geoeconomic fragmentation, where economic security considerations increasingly shape trade policy, our integrated approach offers a timely contribution. As Farrell and Newman (2019) demonstrate, economic networks can be weaponized—dominant positions in critical supply chains can be leveraged for coercive purposes. Identifying these positions requires moving beyond simple trade volume metrics to understand the structural dependencies embedded in production networks. Our methodology provides policymakers with the analytical tools to map these dependencies comprehensively, assess their strategic implications, and design mitigation strategies that address not just visible exposures but also the hidden vulnerabilities that emerge from the complex, multi-layered structure of contemporary global trade.

To ensure computational efficiency while maintaining accuracy, we implement an adaptive convergence criterion: the algorithm terminates path enumeration when the marginal contribution of longer paths falls below a specified threshold (convergence threshold). This approach recognizes that in most trade networks, dependencies transmitted through very long paths (> 5 steps) contribute negligibly to total exposure, consistent with the empirical finding by Costa et al. (2022) that shock transmission weakens substantially with network distance.

5. Development of the Proposed Indicator

The translation of these theoretical concepts into our methodological approach is accomplished through three key innovations. First, our incorporation of network theory allows us to operationalize what Kahler (2009) calls "networked politics"—the way power operates through position within complex global networks rather than through purely dyadic relationships. Second, our path-based calculation of indirect dependencies quantifies what Hirschman (1945) identified as the asymmetric vulnerability that creates potential for influence in interdependent relationships. Finally, our focus on critical intermediaries empirically identifies what scholars of global production networks (Gereffi et al., 2005) call "strategic coupling"—the way certain nodes become crucial junctures linking otherwise disconnected segments of the global economy.

5.1. Advantages of the Proposed Indicator

The trade dependence indicator we propose offers substantial advantages over traditional metrics, particularly in the current context of the geopolitical reconfiguration of international trade. These advantages stem from both its robust theoretical foundation and its design aimed at capturing the complexity of contemporary trade interdependencies.

Table 1 compares the main approaches used to measure trade dependence, highlighting how our indicator integrates and expands upon the strengths of existing methodologies. Beyond this technical comparison, our approach stands out for three key advantages that make it particularly valuable for economic security analysis: (1) the identification of hidden systemic vulnerabilities that remain invisible in conventional analyses, (2) the quantitative assessment of supply chain resilience to disruptions, and (3) the prospective analysis of geoeconomic fragmentation scenarios. Below, we elaborate on each of these distinctive advantages in detail.

5.1.1. Identification of Hidden Systemic Vulnerabilities

The systematic capture of indirect effects is perhaps the most significant contribution of our approach. Conventional indicators, by limiting themselves to direct bilateral flows, offer a partial and potentially misleading view of real trade vulnerabilities. In contrast, our model incorporates all relevant indirect trade routes, revealing dependencies that would remain hidden in simple bilateral analyses. This feature is especially valuable in the current landscape of highly fragmented global value chains, where countries rarely depend solely on direct trading partners.

The ability to identify and quantify these hidden dependencies allows for a much more accurate assessment of the risks associated with disruptions in specific countries. As noted by Koopman et al. (2014), "traditional trade statistics are becoming increasingly unreliable as an indicator of the value added by any particular country" because "intermediate inputs cross multiple borders." These authors reveal that "a significant portion of China's trade surplus with the United States in terms of gross trade actually reflects indirect value-added exports that China makes on behalf of Japan, Korea, and Taiwan" (p.461), illustrating dependencies that remain hidden in traditional trade statistics.

Our indicator addresses this deficiency by explicitly modeling how potential disruptions propagate through the entire trade network, reaching even distant partners through intermediaries. The "concealment ratio" (DT/DD) that we incorporate allows for the precise quantification of the magnitude of these invisible vulnerabilities. In our preliminary empirical analyses, we have identified cases where this ratio far exceeds 2, indicating that the actual exposure of a country is at least double what direct bilateral data suggest. Particularly in sectors such as rare earths, semiconductors, and advanced electronic components, these hidden dependencies can represent critical vulnerabilities for economic security.

Case studies conducted by Simchi-Levi et al. (2015) provide empirical evidence of this phenomenon in industrial supply chains. Analyzing the supplier network of Ford Motor Company, they discovered that "some of the greatest exposures reside in unexpected locations, such as non-strategic suppliers or parts in which the company spends relatively little money to acquire" (p.379-380). Similarly, they identified "supplier sites that have a material impact if interrupted, but were not recognized as high-exposure sites" (p.384). These observations confirm the importance of our approach, which systematizes the identification of hidden vulnerabilities by providing a rigorous methodology for evaluating a country's full exposure to disruptions in international supply.

As noted by various empirical studies, including those by Vicard and Wibaux (2023), assessments based solely on bilateral trade can significantly underestimate real exposure to supply risks. Bonneau and Nakaa (2020) explicitly recognize this methodological limitation by admitting the "impossibility of isolating re-export flows in these data, and therefore detecting indirect vulnerabilities through Tier 2 or higher suppliers" (p.3). Our indicator directly addresses this gap, systematically revealing dependencies that would remain invisible using conventional approaches.

5.1.2. Quantitative Assessment of Supply Chain Resilience

The dynamic assessment of economic resilience represents another fundamental advantage of the proposed indicator. By explicitly modeling shock propagation mechanisms within the global trade network, our approach allows for the analysis of dynamic scenarios where disruptions are sequentially transmitted between countries. This enables the study of how an adverse event in a specific node of the trade network can trigger cascading effects that affect economies seemingly disconnected from the source of the shock.

This analytical capacity is crucial in an environment where, as documented by Baldwin and Freeman (2020), trade disruptions frequently generate "contagion waves" that propagate across multiple countries and sectors. The "dilution" factor incorporated in our path strength calculation mathematically captures how impacts are attenuated or amplified as they are transmitted through the global trade network. Our indicator provides tools to anticipate these propagation patterns, identify potential vulnerability points, and assess the effectiveness of different strategies to enhance the resilience of the trade system.

As Cerina et al. (2015) emphasize, "the fact that industries are both highly connected and asymmetrically connected means that local idiosyncratic shocks can propagate through the global economy and generate considerable global fluctuations" (p.9). Our indicator allows for:

1. **Quantifying systemic resilience:** By evaluating all possible shock transmission routes, we can quantitatively determine how robust an economy is to disruptions in different nodes of the trade network.

2. **Identifying "critical nodes":** The indicator reveals countries or sectors whose disruption would have disproportionately wide effects due to their strategic position as intermediaries in multiple value chains.

3. **Evaluating mitigation strategies:** It allows the simulation of the impact of various diversification policies, domestic capacity building, or alternative trade agreements on the resilience of the system.

The application of this approach to recent crises, such as supply disruptions during the COVID-19 pandemic, has confirmed its ability to identify transmission channels that conventional analyses failed to anticipate. Our methodology allows not only to map existing vulnerabilities but also to proactively assess the resilience of different trade network configurations to potential shocks.

The coherent integration of Input-Output models and network theory is a distinctive methodological aspect that underpins this analytical capability. While traditional Input-Output matrix-based analyses focus on quantifiable economic flows but often ignore the topological structure of the trade network, network studies capture structural properties but typically lack direct linkage to economic magnitudes. Our indicator overcomes this dichotomy by combining both perspectives within a unified framework.

This integration enables a multidimensional analysis that simultaneously considers the topological structure of the trade network, the magnitude of economic flows, and the mechanisms of disruption propagation. As Cerina et al. (2015) argue, this type of hybrid approach is particularly well-suited for characterizing complex systems such as contemporary international trade, where a country's structural position within the network can be as important as the volume of its bilateral exchanges.

5.1.3. Prospective Analysis of Fragmentation Scenarios

The third distinctive advantage of our indicator is its ability to assess alternative scenarios for trade reorganization in a context of growing geopolitical fragmentation. As noted by Campos et al. (2023), the increasing divergence between geopolitical blocs is creating pressures for a partial reorganization of international trade along lines of political affinity rather than economic complementarity. Our methodology allows for the modeling of alternative fragmentation scenarios, evaluating how different patterns of trade reorganization would affect the vulnerabilities of specific countries.

The proposed indicator is particularly valuable for evaluating different diversification strategies. Following the distinction introduced by Aiyar and Ohnsorge (2024) between "vertical" and "horizontal" connectors, our approach can differentiate between "superficial" diversification (redistribution of direct imports among suppliers sharing the same indirect vulnerabilities) and "deep" diversification (which effectively reduces dependence on common sources throughout the supply chain). This distinction is crucial for the design of effective policies, especially in a context where, as noted by Alfaro and Chor (2023), there is a significant relocation of production chains driven by geopolitical considerations.

The practical applicability of the indicator extends to various institutional contexts. For governments and supranational institutions, such as the European Union in its pursuit of "open strategic autonomy" (ECB, 2023), it provides an analytical tool to identify critical dependencies and assess diversification strategies. As the European Central Bank (2023) notes, the goal is not economic autarky but a smart management of interdependencies that minimizes critical vulnerabilities without unnecessarily sacrificing the benefits of open trade. Our indicator provides precise analytical tools for this balance, enabling the identification of priority intervention areas and evaluating the potential effectiveness of different strategies.

For multinational corporations, it offers a framework to analyze risks in increasingly complex global supply chains, complementing existing approaches such as those proposed by Stoll and Thethi (2022). For international organizations monitoring the fragmentation of global trade, such as the IMF (Gopinath et al., 2024), it provides accurate quantitative metrics to assess the evolution of trade interdependencies in a context of increasing geopolitical polarization.

A particularly valuable aspect is the indicator's ability to identify what Gopinath et al. (2024) call "connector countries," economies that act as bridges between geopolitically distant trade blocs. Our approach allows for the evaluation of how a hypothetical worsening of tensions between the United States and China would affect intermediary economies like Mexico, Vietnam, or Singapore, which currently function as "bridge countries" between increasingly distant trade blocs. This type of scenario analysis provides crucial information for managing geopolitical risks, both for governments and for multinational companies with global supply chains.

The ability to systematically update dependency matrices as new trade data becomes available allows for the evaluation of whether implemented policies are effectively reducing critical vulnerabilities or if, conversely, new problematic dependency patterns are emerging. This dynamic evaluation capacity facilitates the continuous adaptation of strategies in response to an increasingly volatile and uncertain trade environment.

Together, these three advantages make the proposed indicator particularly suitable for the analysis of economic security in the current environment, characterized by growing geopolitical tensions, the reorganization of global value chains, and the reevaluation of strategic dependencies. Its ability to identify hidden vulnerabilities, quantify systemic risks, and evaluate mitigation strategies makes it a valuable tool for informing policies aimed at balancing the benefits of trade integration with the imperatives of national economic security. At a time when, as noted by Gopinath et al. (2024), international trade is undergoing significant structural transformations driven by considerations beyond purely economic logic, our indicator not only identifies existing vulnerabilities but also provides a framework to anticipate future reconfigurations and develop adaptation strategies in an increasingly complex and geopolitically fragmented trade environment.

6. Development of the Proposed Indicator

6.1. Advantages of the Proposed Indicator

The trade dependence indicator we propose presents substantial advantages over traditional metrics, particularly in the current context of the geopolitical reconfiguration of international trade. These advantages stem from both its robust theoretical foundation and its design aimed at capturing the complexity of contemporary trade interdependencies.

Figure 1 illustrates the fundamental differences between traditional approaches to measuring trade dependence and the proposed indicator in this paper. While conventional methods are limited to evaluating direct bilateral relationships, our approach captures the complex network of interdependencies that characterizes contemporary global trade, revealing vulnerabilities that remain hidden in traditional analyses.

6.2. Glossary of Key Terms

To facilitate understanding, we define the core concepts exactly as implemented in the current code (country–country matrix X, column–sum denominators, and path enumeration).

Trade dependence. A country's exposure to supply disruption originating in another country, measured as the share of the importer's supply attributable to that partner through *direct* and/or *indirect* channels.

Direct dependence (DD). The share of importer j's supply accounted for by *direct* imports from exporter i: $\mathrm{DD}_{ij} = x_{ij}/S_j$, where $S_j = \sum_k x_{kj}$ is the column–sum supply denominator used in the code.

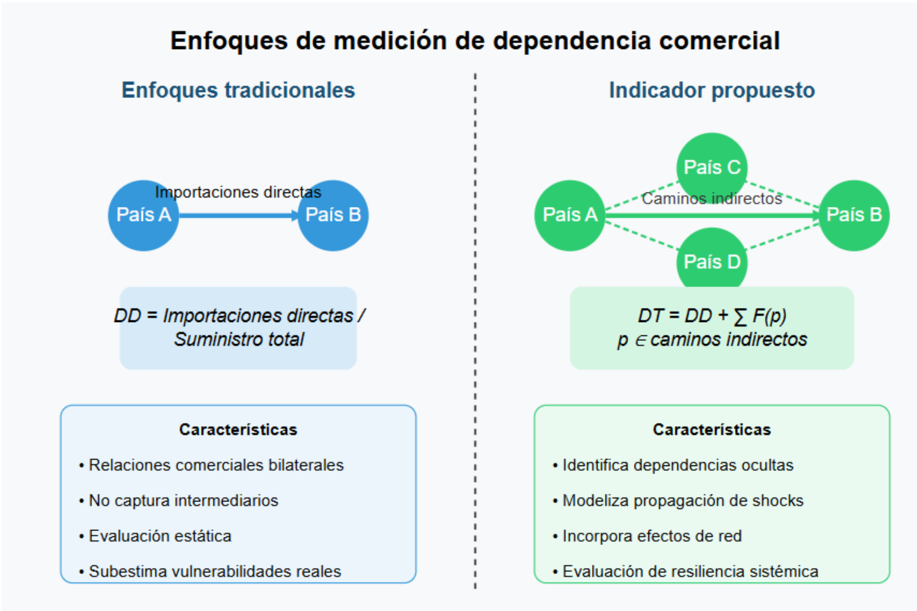

Figure 1: Comparison between traditional trade dependence measurement approaches (left) and the proposed indicator (right). While conventional methods focus on evaluating direct bilateral relationships, our approach captures the complex network of interdependencies that characterize contemporary global trade.

Indirect dependence (DI). The share of j's supply attributable to i through multi–step trade routes that traverse one or more intermediaries. Computed as the sum of strengths over all economically relevant paths from i to j.

Total dependence (DT). Overall exposure of j to i, defined as $\mathrm{DT}_{ij} = \mathrm{DD}_{ij} + \mathrm{DI}_{ij}$ (bounded in $[0, 1]$).

Hidden dependence. Situations where indirect channels dominate bilateral exposure, revealed by a large *concealment ratio* $\mathrm{DT}_{ij}/\mathrm{DD}_{ij} \gg 1$.

Trade path. An ordered sequence of countries connecting exporter j to importer i, $p = (j, k_1, k_2, \ldots, k_{\ell-1}, i)$, with $\ell \geq 2$ (the code enumerates paths in this exporter→importer order).

Path strength $F(p)$. The multiplicative transmission intensity along p, obtained by multiplying edge shares of the form x_{uv}/S_v at each hop. It captures how a disruption at the origin would attenuate/amplify en route to the importer.

Shock propagation. The transmission of a disruption through the directed, weighted trade network via all admissible paths, potentially affecting countries without a large direct bilateral link.

Concealment ratio. The diagnostic $\mathrm{DT}_{ij}/\mathrm{DD}_{ij}$ that quantifies how much bilateral indicators underestimate true exposure. Values > 2 suggest material hidden vulnerability.

Maximum path length ($L_{\max}$). Operational cap on route depth (default $L_{\max} = 3$) used to bound the search space of indirect routes.

Recorded–path threshold ($\theta_{\mathbf{path}}$). Significance cutoff for storing a route in the logs (`critical_paths`); only paths with $F(p) > \theta_{\text{path}}$ (default 10^{-3}) are retained.

Convergence threshold (ε). Early–stopping rule for each pair (i, j): the iteration over path length halts when the increase in DT_{ij} between consecutive depths falls below ε (default 0.01).

Intermediary weighting ($w = 1/r$). Positional weight applied to an intermediary at position r along a recorded path; emphasizes nodes closer to the final importer in the composite intermediary score.

Critical relationship (few–alternatives rule). A pair $(j \rightarrow i)$ flagged as critical when $\text{DT}_{ij} \geq \tau$ and the count of alternative routes is below m_{min} (defaults $\tau = 0.7$, $m_{\text{min}} = 3$).

Economic resilience. The system's capacity to withstand, adapt to, and recover from shocks. In this framework, resilience is assessed by routed exposures (DT), availability of alternatives, and the role of critical intermediaries.

Key Concepts of the Proposed Indicator

Total dependence (DT) Full exposure of a country to another, considering both direct and indirect channels.

Hidden dependence The difference between total and direct dependence, revealing invisible vulnerabilities in bilateral analyses.

Concealment ratio The ratio DT/DD that measures how much traditional analyses underestimate real dependence.

Path strength A measure quantifying the intensity with which a disruption is transmitted through a specific trade path.

Critical nodes Countries whose disruption would have amplified effects due to their position as intermediaries in multiple value chains.

6.3. Conceptualization

Traditional trade dependence analysis has typically focused on measuring direct trade flows between countries. However, in a world where global value chains (GVCs) have fragmented production across multiple economies, a country's trade dependence is not limited to its direct bilateral relationships; it is also transmitted through intermediaries. This structure creates economic interdependencies that conventional approaches fail to capture comprehensively.

6.3.1. Definition of Direct and Indirect Trade Dependence

The proposed indicator is based on a rigorous conceptualization of trade dependence as a country's exposure to supply disruptions from another, considering all possible channels (both direct and indirect). This approach overcomes the limitations of previous methods by integrating two fundamental dimensions:

1. **Direct dependence:** Captured by the proportion of direct imports in a country's total supply, including domestic production. This measure is consistent with previous indicators such as the ECB's CD2, but it only represents the first level of dependence.

2. **Indirect dependence:** Modeled by analyzing all possible trade paths that, starting from the exporting country, reach the importing country through intermediaries. This dimension is key for identifying vulnerabilities that remain hidden in conventional bilateral analyses.

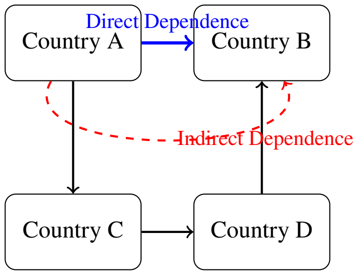

Figure 2: Schematic representation of direct and indirect dependencies in a simple trade network. Indirect dependencies (dashed red line) capture Country B's exposure to Country A via intermediaries (Countries C and D).

The direct dependence (DD_{ij}) of country j on country i is formally defined as:

$$\mathrm{DD}_{ij} = \frac{x_{ij}}{S_j} \tag{5}$$

where:

- x_{ij} represents the value of trade flows from exporter i (row) to importer j (column)
- $S_j = \sum_k x_{kj}$ is the total supply of imports to country j (column sum)

Matrix Convention: Throughout this paper, we adopt the convention that matrix $\mathbf{X}$ has exporters as rows and importers as columns. Thus, x_{ij} denotes exports from country i to country j. For computational efficiency, domestic production (x_{jj}, the diagonal elements) is excluded from our analysis, as we focus on international trade dependencies.

Indirect dependence (DI_{ij}) captures how country j may depend on another country i through third countries acting as intermediaries. Conceptually, this reflects situations where, for example, country j imports components from country k, which in turn depends on inputs from country i. This second-order dependence and subsequent levels are not captured by traditional indicators, but can represent significant vulnerabilities.

For a trade path $p = (i, k_1, k_2, \ldots, k_{\ell-1}, j)$ that starts in exporter i, passes through intermediaries $k_1, k_2, \ldots, k_{\ell-1}$, and ends in importer j, we define the **path strength** $F(p)$ as the measure of how a disruption in country i is transmitted to j through this specific route. This transmission considers how the impact propagates and potentially attenuates as it passes through each intermediary.

Normalized Transition Matrix: To facilitate the calculation of path strengths, we first define the normalized transition matrix $\mathbf{T}$, where each element represents the proportion of country j

To address the complexity of these interdependencies, the proposed indicator integrates three complementary methodological frameworks:

- **Input-Output Matrices:** Provide the fundamental structure to represent trade flows between countries and sectors. Following Miller and Blair (2009), we use a matrix representation where each element x_{ij} represents the value of imports from country i to country j. This approach explicitly links trade flows with the production structure of each economy, capturing how dependencies arise from specific input needs.

- **Network Theory:** Conceptualizes international trade as a directed and weighted network where the nodes are countries, and the links represent trade flows. As noted by Fagiolo et al. (2010), this approach allows for the analysis of structural properties such as centrality, connectivity, and community formation, revealing patterns of interdependence that are not evident in simple bilateral analyses. We apply concepts from graph theory to identify and quantify all possible paths through which a country may depend on another.
- **Shock Propagation Models:** Capture how a disruption in a node of the trade network propagates to others through multiple channels. Inspired by Bierkandt et al. (2014) and Cerina et al. (2015), we develop an adaptive algorithm that models the transmission of vulnerabilities, considering dilution factors at each intermediate node. This approach reflects the fact that the impact of a disruption tends to attenuate as it moves through the network, but can also be amplified when it converges at critical nodes.

The integration of these three frameworks allows us to overcome key limitations identified in previous literature:

1. **Systematic capture of indirect effects:** Unlike indicators focused solely on bilateral relationships, our approach explicitly models how dependencies are transmitted through intermediaries.
2. **Consideration of the complete trade network structure:** Instead of analyzing isolated pairs of countries, we assess the position of each economy within the global trade system, identifying systemic vulnerabilities.
3. **Precise quantification of dependency intensity:** The indicator not only identifies the existence of indirect dependencies but also quantifies their relative magnitude, allowing for the prioritization of policy intervention areas.

This integrated approach is particularly relevant in the current context of geoeconomic fragmentation, where, as noted by Gopinath et al. (2024), "connector countries" are emerging as bridges between geopolitically distant trade blocs. Our indicator explicitly identifies these critical nodes and evaluates their role in transmitting vulnerabilities across the global trade system.

The precise mathematical formulation that implements this conceptualization is developed in the next section, where we detail the specific algorithms used to calculate total dependence, integrating both direct and indirect components.

6.4. Mathematical Formulation

The calculation of the indicator is based on a matrix representation of international trade, where a matrix $X \in \mathbb{R}^{n \times n}$ describes the trade flows between n countries. Each element x_{ij} of the matrix represents the value of imports that country j receives from country i.

6.4.1. *Calculation of Direct Dependence*

Direct dependence (DD_{ij}) of country j on country i is defined as the proportion of direct imports in the total supply:

$$\mathrm{DD}_{ij} = \frac{\text{Imports from } i \text{ to } j}{\text{Total supply of } j} = \frac{x_{ij}}{S_j} \tag{6}$$

where:

- x_{ij} represents the value of imports that country j receives directly from i
- S_j is the total supply of country j, which includes both its domestic production (x_{jj}) and all imports: $S_j = x_{jj} + \sum_{k \neq j} x_{kj}$

This formulation ensures that direct dependence is normalized between 0 and 1, facilitating comparisons between countries.

6.4.2. *Calculation of Indirect Dependence*

Indirect dependence (DI_{ij}) captures how country j depends on country i through intermediaries. It is calculated by summing the path strengths of all indirect trade routes (paths with length $\ell \geq 2$):

$$\mathrm{DI}_{ij} = \sum_{p \in P_{ij}^{\ell \geq 2}} F(p) \tag{7}$$

where:

- $P_{ij}^{\ell \geq 2}$ is the set of all **simple paths** (without repeated nodes) from exporter i to importer j with path length at least 2
- $F(p)$ is the path strength defined in equation (5), measuring the transmission intensity of disruptions through that specific route

Computational Implementation: For efficiency, our algorithm treats paths of different lengths separately:

- **Length 2 (vectorized):** For paths with a single intermediary k, we compute:

  $$\mathrm{DI}_{ij}^{(\ell=2)} = \sum_{k \neq i,j} T_{i,k} \cdot T_{k,j} = \sum_{k \neq i,j} \frac{x_{i,k}}{S_k} \cdot \frac{x_{k,j}}{S_j} \tag{8}$$

  This can be computed efficiently using matrix operations.

- **Length $\ell \geq 3$ (enumeration):** For longer paths, we use explicit enumeration over combinations of intermediaries, computing $F(p)$ for each valid path and summing contributions.

For a trade path $p = (i, k_1, k_2, ..., k_n, j)$ that starts in country i, passes through intermediaries $k_1, k_2, ..., k_n$, and ends in country j, we calculate its strength by considering how dependence "dilutes" as it passes through each intermediary:

The path strength is computed as the product of transition probabilities along each edge of the path:

$$F(p) = \prod_{(a,b)\in \text{edges}(p)} T_{ab} \tag{9}$$

For the complete path $p = (i, k_1, k_2, \dots, k_{\ell-1}, j)$, this expands to:

$$F(p) = T_{i,k_1} \cdot T_{k_1,k_2} \cdots T_{k_{\ell-1},j} = \frac{x_{i,k_1}}{S_{k_1}} \cdot \frac{x_{k_1,k_2}}{S_{k_2}} \cdots \frac{x_{k_{\ell-1},j}}{S_j} \tag{10}$$

where ℓ is the path length (number of edges). This formulation captures how a supply disruption originating in country i would propagate through the chain to ultimately affect country j, with the impact potentially attenuating at each intermediary depending on their supplier diversification (reflected in the denominator S_k).

6.4.3. Convergence and Relevance Criteria

In theory, the number of possible trade paths between two countries can be infinite in a network with cycles. Additionally, the practical value of considering extremely long paths or those with marginal contributions is limited. Therefore, to ensure computational tractability and the economic relevance of the indicator, we incorporate three important methodological criteria.

The first is a trade relevance threshold (θ), which establishes that only trade flows representing at least θ% of total global trade are considered. This threshold, typically set between 0.05% and 0.1%, helps filter marginal trade relationships that could introduce noise into the analysis without adding substantial information. Applying this threshold transforms the dense matrix of global trade into a more sparse but meaningful representation, focusing on economically relevant flows.

The second criterion is a convergence threshold (ε), which determines when to stop the calculation of indirect dependencies. The iterative process is halted when the inclusion of additional paths does not significantly alter the total dependency value beyond this threshold (typically 0.01). This criterion reflects the empirical observation that extremely long or complex paths have a diminishing marginal contribution to total dependence. In practice, this means that, for most country pairs, only a limited number of paths need to be considered to obtain an accurate estimate of dependence.

The third criterion introduces a maximum path length ($L_{\max}$), which, for computational efficiency, limits the search for trade paths to a maximum number of intermediaries (typically between 3 and 5). Numerous empirical studies on global value chains suggest that this limit is sufficient to capture the main indirect dependencies in most trade networks, without significantly compromising the accuracy of the indicator.

These criteria are implemented in an adaptive algorithm that calculates indirect dependence iteratively. Formally, we define:

$$\mathrm{DI}_{ij}^{(l)} = \sum_{p \in P_{ij}^{(l)}} F(p) \tag{11}$$

where $P_{ij}^{(l)}$ is the set of paths of length exactly l between countries i and j. The algorithm proceeds iteratively, calculating $\mathrm{DI}_{ij}^{(1)}$, $\mathrm{DI}_{ij}^{(2)}$, and so on. It stops when $|\mathrm{DI}_{ij}^{(l)} - \mathrm{DI}_{ij}^{(l-1)}| < \varepsilon$ or when $l = L_{\max}$. This approach ensures that the calculation is computationally efficient while capturing the most significant indirect dependencies.

6.4.4. Total Dependence

Total dependence (DT_{ij}) of country j on country i is defined as the sum of both direct and indirect components:

$$\mathrm{DT}_{ij} = \mathrm{DD}_{ij} + \mathrm{DI}_{ij} \tag{12}$$

This formulation offers several desirable properties for a trade vulnerability indicator. First, DT_{ij} is bounded in the interval $[0, 1]$, facilitating the interpretation and comparability of results. Second, the difference $\mathrm{DT}_{ij} - \mathrm{DD}_{ij}$ provides a direct measure of the "hidden" vulnerability that would not be captured by conventional bilateral analyses. Third, when no significant indirect paths exist between i and j, we have $\mathrm{DT}_{ij} \approx \mathrm{DD}_{ij}$, meaning the indicator naturally reduces to the bilateral case when indirect dependencies are negligible.

The interpretation of the indicator is straightforward and intuitive: DT_{ij} represents the proportion of country j's total supply that depends, directly or indirectly, on country i. A high value indicates significant vulnerability to disruptions in country i, while values close to DD_{ij} suggest that indirect dependencies are marginal. This interpretation facilitates the communication of results to policymakers and its application in economic security analysis contexts.

It is important to note that, unlike other indicators, DT_{ij} is not simply a measure of trade exposure, but a specific quantification of vulnerability to supply disruptions. Its design explicitly incorporates the structure of the global trade network and shock propagation mechanisms, providing a more comprehensive and nuanced view of the economic interdependencies that characterize contemporary international trade.

6.5. Computational Implementation and Practical Considerations

The practical application of the indicator to real trade data requires addressing a number of significant computational challenges. The complexity of global trade networks, which can involve hundreds of countries and thousands of sectors, demands efficient implementation strategies that allow for the calculation of direct and indirect dependencies in reasonable time frames. In this section, we detail the key technical aspects of our implementation.

Enumerating paths in trade networks is perhaps the most important challenge. For realistically sized networks, the number of potential paths between pairs of countries grows exponentially with the maximum allowed path length. A brute-force approach that attempts to enumerate all possible paths would be computationally unfeasible even for moderate-sized networks. To overcome this limitation, we have developed an adaptive algorithm that explores the path space efficiently.

Our approach begins by identifying the shortest and most commercially significant paths, which typically represent the most significant indirect dependencies. We use a modified breadth-first search variant that prioritizes links with higher economic relevance. This strategy enables the quick identification of the paths that contribute most to indirect dependence. Subsequently, the relevance threshold is applied to eliminate paths whose contribution would be marginal, significantly reducing the search space.

To further optimize the process, we employ memoization techniques that store intermediate results of subpaths that have already been calculated. This avoids redundant computations in networks where multiple paths share common segments, a feature common in trade networks where certain countries act as regional hubs. As we explore longer paths, the algorithm iteratively refines the dependence estimate, stopping when convergence is reached according to the established criteria.

Efficient handling of sparse matrices is another key aspect of our implementation. International trade matrices naturally exhibit a high degree of sparsity: most countries trade significantly only with a relatively small subset of partners. This feature is accentuated when trade relevance thresholds are applied. Exploiting this sparsity is crucial for computational efficiency.

Our implementation uses specialized data structures for sparse matrices, explicitly representing only the non-zero elements of the trade matrix. This dramatically reduces memory requirements, enabling the analysis of detailed trade networks even with limited computational resources. Additionally, we implement optimized algorithms for sparse matrix algebra, particularly for key operations such as matrix-vector multiplication used in the recursive calculation of indirect dependencies.

For extensive historical data sets, we apply selective data compression techniques that preserve accuracy in the most relevant trade flows while reducing detail in marginal connections. This approach enables longitudinal analyses spanning decades of trade data without sacrificing computational efficiency.

The nature of the dependency calculation problem lends itself naturally to parallelization, offering significant opportunities to reduce processing times. We observe that the dependency between a specific pair of countries (i, j) can be calculated independently of other pairs, allowing for efficient distribution of work across multiple processors or cores.

Our parallelized implementation decomposes the global dependency matrix into submatrices that are computed concurrently. A central coordinator distributes these tasks across the available processors, implementing dynamic load balancing strategies that assign more resources to more complex calculations (typically those involving countries with many trade links). The partial results are then combined to construct the complete dependency matrix.

In distributed computing environments, we minimize communication between processes, transmitting only the essential information for each calculation. This strategy significantly reduces the overhead associated with coordinating parallel processes. The scalability of our implementation has been empirically validated: the computation time scales nearly linearly with the number of available processors up to approximately 64 cores, allowing detailed global network analyses in minutes rather than days.

The robustness of the indicator against variations in the calculation parameters and input data quality is a legitimate concern for any quantitative methodology. To address this, we have implemented extensive validation procedures that verify the stability and reliability of our results.

Sensitivity analysis with respect to key parameters (θ, ε, and $L_{\max}$) confirms that, for reasonable ranges of values, the main conclusions derived from the indicator remain stable. Moderate variations in these parameters may affect specific numerical values, but rarely alter the relative ordering of dependencies or the identification of critical vulnerabilities. This robustness reinforces the practical usefulness of the indicator in informing economic policy decisions.

To validate the algorithm's performance, we have conducted tests with synthetic networks of known structure, where theoretical dependencies can be calculated analytically. These experiments confirm that our implementation correctly recovers the expected dependencies, even in cases involving complex connectivity patterns. Additionally, for specific data subsets where alternative dependency measures exist, we have verified that our indicator produces results consistent with these external references.

Perhaps the most convincing validation comes from historical case studies. We have analyzed documented episodes of trade disruptions, such as the 2011 Japan earthquake and tsunami or certain phases of the U.S.-China trade war, retrospectively evaluating the predictive capacity of the indicator. These analyses confirm that countries with high total dependence values (especially those with significant indirect components) indeed experienced greater economic impacts during these disruptive episodes.

6.6. Advantages of the Proposed Indicator

The trade dependence indicator we propose offers substantial advantages over traditional metrics, particularly in the current context of the geopolitical reconfiguration of international trade. These advantages stem from both its robust theoretical foundation and its design aimed at capturing the complexity of contemporary trade interdependencies.

The systematic capture of indirect effects is perhaps the most significant contribution of our approach. Conventional indicators, by focusing solely on direct bilateral flows, provide a partial and potentially misleading view of actual trade vulnerabilities. Our model, in contrast, incorporates all relevant indirect trade paths, revealing dependencies that would remain hidden in simple bilateral analyses. This feature is especially valuable in the current landscape of highly fragmented global value chains, where countries rarely depend solely on direct trading partners.

The ability to identify and quantify these hidden dependencies allows for a much more precise assessment of the risks associated with disruptions in specific countries. As noted by several empirical studies, including those by Vicard and Wibaux (2023), evaluations based solely on bilateral trade can significantly underestimate actual exposure to supply risks. Our indicator corrects this deficiency by explicitly modeling how potential disruptions propagate across the entire trade network, even reaching distant partners via intermediaries.

The dynamic assessment of economic resilience represents another key advantage of the proposed indicator. By explicitly modeling shock propagation mechanisms in the global trade network, our approach enables the analysis of dynamic scenarios where disruptions are sequentially transmitted between countries. This allows for the study of how an adverse event in a specific node of the trade network can trigger cascading effects that affect economies seemingly disconnected from the shock's origin.

This analytical capacity is crucial in an environment where, as documented by Baldwin and Freeman (2020), trade disruptions frequently generate "contagion waves" that spread across multiple countries and sectors. Our indicator provides tools to anticipate these propagation patterns, identify potential vulnerability points, and assess the effectiveness of different strategies to enhance the resilience of the trade system. The application of this approach to recent crises, such as supply disruptions during the COVID-19 pandemic, has confirmed its ability to identify transmission channels that conventional analyses failed to anticipate.

The coherent integration of Input-Output models and network theory is a distinctive methodological aspect of our approach. While traditional Input-Output matrix-based analyses focus on quantifiable economic flows but often ignore the topological structure of the trade network, network studies capture structural properties but usually lack direct linkage to economic magnitudes. Our indicator overcomes this dichotomy by combining both perspectives into a unified framework.

This integration enables multidimensional analysis that simultaneously considers the topological structure of the trade network, the magnitude of economic flows, and the mechanisms of disruption propagation. As Cerina et al. (2015) argue, this type of hybrid approach is particularly well-suited for characterizing complex systems like contemporary international trade, where a country's structural position within the network can be as important as the volume of its bilateral exchanges.

The formal properties of the indicator facilitate its interpretation and practical application. Normalization in the interval [0, 1] allows for direct comparisons between different countries, sectors, and time periods. This is especially useful for policymakers and analysts who need to identify and prioritize critical vulnerabilities in a context of limited resources. The explicit separation between direct and indirect components of dependence provides additional information about the nature of vulnerabilities, allowing for more precise and effective policy responses.

Unlike complex indicators with abstract interpretations, our indicator maintains a direct connection to the underlying economic reality: it represents the proportion of a country's total supply that depends, directly or indirectly, on another country. This intuitive interpretation facilitates the communication of results to non-specialized audiences and their incorporation into decision-making processes.

Despite the underlying conceptual complexity, the indicator has been designed to ensure computational efficiency. Optimized algorithms allow for its calculation on detailed global trade networks using moderate computational resources, facilitating its regular update as new data becomes available. This computational efficiency is crucial for continuous vulnerability monitoring and near-real-time scenario analysis.

The practical applicability of the indicator extends to various institutional contexts. For governments and supranational institutions, such as the European Union in its pursuit of "open strategic autonomy" (ECB, 2023), it provides an analytical tool to identify critical dependencies and assess diversification strategies. For multinational corporations, it offers a framework for analyzing risks in increasingly complex global supply chains, complementing existing approaches such as those proposed by Stoll and Thethi (2022). For international organizations monitoring the fragmentation of global trade, such as the IMF (Gopinath et al., 2024), it provides accurate quantitative metrics for assessing the evolution of trade interdependencies in a context of growing geopolitical polarization.

Together, these advantages make the proposed indicator particularly suitable for the analysis of

Table 1: Comparison of Methods for Measuring Trade Dependence

Characteristic	**HHI**	**Conc. Imp.**	**TiVA**	**I-O Trad.**	**Net-works**	**Proposed Ind.**
Captures direct dep.	✓	✓	✓	✓	✓	✓
Captures indirect dep.	×	×	Partial	Direct only	✓	**Complete**
Normalization (0-1)	✓	✓	×	×	×	✓
Based on Input-Output	×	×	✓	✓	×	✓
Network theory	×	×	×	×	✓	✓
Models shock propagation	×	×	×	Limited	Partial	✓
Detects hidden vuln.	×	×	Partial	×	Partial	✓
Resilience analysis	×	×	Limited	Limited	Partial	✓

Notes: HHI: Herfindahl-Hirschman Index; Conc. Imp.: Import Concentration Index; TiVA: Trade in Value Added; I-O Trad.: Traditional Input-Output Models; Networks: Network Analysis; Proposed Ind.: This paper's indicator.

economic security in the current environment, characterized by growing geopolitical tensions, reorganization of global value chains, and reevaluation of strategic dependencies. Its ability to identify hidden vulnerabilities, quantify systemic risks, and evaluate mitigation strategies makes it a valuable tool for informing policies that seek to balance the benefits of trade integration with the imperatives of national economic security.

Table 1 compares the main approaches used to measure trade dependence, evaluating their capabilities across fourteen key dimensions: inclusion of indirect dependence, normalization, reliance on Input-Output models, use of network theory, and applicability in economic security analysis, among others.

Trade in Value Added (TiVA) offers a partial improvement by tracking the contribution of each country within global production, but it does not explicitly model how shocks propagate through the trade network. As noted by Koopman et al. (2014) (p.459-460), "traditional trade statistics are increasingly unreliable as indicators of the value added by any particular country" because "intermediate inputs cross borders multiple times."

On the other hand, traditional Input-Output models allow for the evaluation of sectoral interdependencies but do not incorporate a global trade network structure that represents the propagation of indirect dependencies. Cerina et al. (2015) (p.9) emphasize that "the fact that industries are both highly connected and asymmetrically connected means that local idiosyncratic shocks can propagate throughout the global economy," an aspect that these models fail to capture adequately.

Network analysis, such as the approach by Korniyenko et al. (2017), provides a structural visualization of international trade, detecting commercial hubs and centrality patterns. However, because it is not based on Input-Output matrices, it does not accurately quantify the flow of productive inputs nor provide a direct economic interpretation of trade dependence.

The proposed index overcomes these limitations by integrating the most relevant elements of Input-Output models and network analysis into a single methodological framework, also incorporating shock propagation algorithms. This combination allows for the identification of hidden dependencies that traditional approaches fail to detect, as evidenced by Simchi-Levi et al. (2015), who discovered that "some of the greatest exposures reside in unexpected places, such as non-strategic suppliers" (p.379-380).

Table **??** compares the main approaches used to measure trade dependence, evaluating their capabilities across four key dimensions: inclusion of indirect dependence, reliance on Input-Output models, use of network theory, and applicability in economic security analysis.

The Herfindahl-Hirschman Index (HHI) and Import Concentration Index are widely used to measure supplier concentration, but they present a critical limitation: their inability to capture trade dependencies transmitted through third countries. This can lead to an underestimation of risks when interdependencies are not evident in bilateral analyses.

Trade in Value Added (TiVA) offers a partial improvement by tracking each country's contribution to global production, but it does not explicitly model how shocks propagate through the trade network. On the other hand, traditional Input-Output models allow for the evaluation of sectoral interdependencies but fail to incorporate a global trade network structure that represents the propagation of indirect dependencies.

Network analysis, such as the approach by Korniyenko et al. (2017), provides a structural visualization of international trade, detecting commercial hubs and centrality patterns. However, because it is not based on Input-Output matrices, it does not accurately quantify the flow of productive inputs nor provide a direct economic interpretation of trade dependence.

The proposed index overcomes these limitations by integrating the most relevant elements of Input-Output models and network analysis into a single methodological framework, also incorporating shock propagation algorithms. This combination allows for:

- Identifying *hidden dependencies* that traditional approaches do not detect.
- Capturing both the intensity and structure of trade interdependencies.
- Quantitatively assessing how trade shocks can propagate across multiple levels of intermediaries.

Thanks to these improvements, the proposed indicator stands as a more suitable tool for assessing trade vulnerability in a context of growing geoeconomic fragmentation. Its application in policy design will enable governments and international organizations to develop more effective strategies to mitigate trade risks, strengthen supply chain resilience, and ensure economic security in an uncertain global environment.

6.7. Applications and Current Relevance

In the current geopolitical context, characterized by growing trade tensions and a reconfiguration of global value chains, the proposed indicator offers highly valuable applications for various institutional actors. Its ability to capture indirect dependencies is particularly relevant at a time when economic security considerations have risen on the international political agenda.

The identification of strategic vulnerabilities is perhaps the most immediate application of the indicator. National governments and supranational organizations can use this methodology to detect critical dependencies that could compromise their economic security in the face of disruptions in international trade. Unlike traditional analyses, our approach reveals not only the obvious vulnerabilities derived from direct trade relations but also those "hidden" vulnerabilities that manifest through intermediaries.

This aspect is especially relevant for economies like the European Union, where recent analyses by the European Commission (2021) have highlighted the need to develop more sophisticated tools to identify strategic dependencies. The indicator we propose complements these efforts by providing a more comprehensive and nuanced view of European trade vulnerabilities, particularly in critical sectors such as semiconductors, essential raw materials, or pharmaceuticals.

The assessment of diversification policies represents another highly valuable application. Policymakers frequently face the complex task of designing strategies to reduce trade vulnerabilities without sacrificing the benefits of specialization and international trade. Our indicator provides an analytical framework for simulating and evaluating the impact of different supplier diversification strategies, allowing for the identification of those that offer the greatest reductions in vulnerability with the lowest economic costs.

For example, the indicator allows for distinguishing between "superficial" diversification (redistributing direct imports among suppliers that share the same indirect vulnerabilities) and "deep" diversification (which effectively reduces dependence on common sources across the entire supply chain). This distinction is crucial for designing effective policies, especially in a context where, as pointed out by Alfaro and Chor (2023), there is a significant relocation of production chains driven by geopolitical considerations.

Sectoral resilience analysis is a third relevant application of our methodology. The indicator allows for a comparative assessment of different industrial sectors' vulnerability to trade disruptions, identifying those sectors that are most exposed to supply risks. This information is valuable for prioritizing industrial policy interventions and developing strategic productive capacities in particularly vulnerable areas.

Our preliminary empirical analyses, applying the indicator to detailed sectoral data, reveal heterogeneous patterns of vulnerability across sectors. Industries such as advanced electronics, certain pharmaceuticals, and emerging green technologies tend to show particularly high indirect dependencies, often concentrated in a small number of original suppliers. These findings align with the observations by Arriola et al. (2024) on the existence of "critical vulnerabilities" in specific value chains, but our approach provides a more precise quantification and better identification of indirect transmission channels.

Monitoring the temporal evolution of dependencies represents another valuable application of the proposed indicator. By systematically calculating dependency matrices for different periods, it is possible to identify worrying trends before they become critical vulnerabilities. This "early warning" approach allows for more effective and less costly preventive interventions than reactive responses to already materialized crises.

In this regard, our indicator contributes to what Ioannou and Pérez (2021) and **?** term "structural surveillance" in the economic field: the proactive identification of potential sources of instability before they generate significant disruptions. This capability is particularly valuable in a context of growing geopolitical fragmentation, where the reconfiguration of trade alliances can quickly alter established dependency patterns.

The evaluation of the potential impact of geopolitical conflicts on third countries constitutes an additional application that is especially relevant in the current context. The indicator allows for modeling how tensions or conflicts between certain actors could indirectly affect seemingly uninvolved countries through complex trade channels. This analytical capability is valuable for formulating mitigation strategies and contingency plans in the face of commercial fragmentation scenarios.

For example, our approach can assess how a hypothetical escalation of tensions between the United States and China would affect intermediary economies such as Mexico, Vietnam, or Singapore, which currently act as "bridge countries" between increasingly distant trade blocs. This type of scenario analysis provides crucial information for managing geopolitical risks, both for governments and multinational companies with global supply chains.

Together, these applications address urgent needs for sophisticated analytical tools at a time when, as Gopinath et al. (2024) point out, international trade is experiencing significant structural transformations driven by considerations that go beyond purely economic logic. The indicator we propose not only identifies existing vulnerabilities but also provides a framework for anticipating future reconfigurations and developing adaptation strategies in an increasingly complex and geopolitically fragmented trade environment.

6.8. Implications for Economic Security

The theoretical and methodological framework we have developed has profound implications for the conceptualization, measurement, and management of economic security in the current context. These implications extend beyond the purely technical aspect of measuring trade dependencies, reaching strategic considerations about the vulnerability of economies to exogenous disruptions and the design of policies to strengthen resilience.

The identification of hidden vulnerabilities is perhaps the most direct and significant implication of our approach. By systematically capturing the indirect dependencies transmitted through trade intermediaries, the proposed indicator reveals vulnerabilities that would remain invisible in analyses focused solely on bilateral relations. This more comprehensive "mapping" of the terrain of economic interdependencies allows for a more realistic assessment of the risks associated with the current configuration of international trade.

Case studies we have conducted applying our methodology to strategic sectors illustrate the magnitude of these hidden vulnerabilities. For example, in the field of rare earths, critical components for green technologies and defense applications, we discovered that the effective dependence of many European countries on China is substantially higher than suggested by direct trade statistics. This is because important processing intermediaries in Asia and North America also depend on Chinese raw materials, creating an indirect vulnerability that conventional indices such as the HHI fail to capture.

These findings align with the observations of Campbell et al. (2024) on how disruptions in specific nodes of supply chains can propagate globally, affecting economies that seem diversified in terms of direct suppliers. Our indicator provides a precise quantitative measure of this exposure, enabling systematic comparisons across countries, sectors, and time periods.

The assessment of contagion risks represents another fundamental implication of our methodology. The explicit modeling of trade paths allows us to analyze how disruptions in one node of the network can propagate through multiple channels, creating systemic effects that exceed the sum of bilateral relations. This "systemic risk" perspective in international trade complements similar approaches developed in the financial sector after the global crisis of 2008.

Our methodology allows for the identification of "critical nodes" in the global trade network: countries or sectors whose disruption would have disproportionately large effects due to their strategic position as intermediaries in multiple value chains. These nodes do not always coincide with the largest economies or the largest exporters; instead, they often include specialized countries that occupy critical niches in particular production chains.

For example, preliminary analyses applying our indicator to recent trade data suggest that economies such as Singapore, South Korea, Taiwan, and increasingly Vietnam play particularly important roles as transmitters of dependencies in advanced technological sectors. Identifying these critical nodes provides valuable information for managing systemic risks in global trade, allowing for the anticipation of propagation patterns in the face of localized disruptions.

The design of mitigation policies constitutes a third area where our methodology has significant implications. The decomposition of dependence into direct and indirect components facilitates the design of differentiated strategies to address different types of vulnerability. While direct dependencies can be mitigated by diversifying immediate suppliers, indirect dependencies often require more complex interventions, such as the development of domestic productive capacities in critical links of the chain or trade agreements with suppliers who present complementary dependency profiles.

This distinction is particularly relevant in the context of "open strategic autonomy" policies being developed by actors such as the European Union. As the European Central Bank (2023) notes, the goal is not economic autarky but the intelligent management of interdependencies that minimizes critical vulnerabilities without unnecessarily sacrificing the benefits of trade openness. Our indicator provides precise analytical tools for this balance, allowing for the identification of areas where intervention is a priority and evaluating the potential effectiveness of different strategies.

The dynamic monitoring of the evolution of dependencies represents another practical implication of our methodology. The mathematical convergence of the indicator and its computationally efficient implementation allow for its regular application to continuously track how trade vulnerabilities evolve over time. This monitoring is particularly valuable in a context where, as Frohm and Gunnella (2022) and **?** document, global value chains are undergoing significant reconfigurations driven both by disruptive events (such as the COVID-19 pandemic) and by long-term strategic considerations.

The ability to systematically update dependency matrices as new trade data becomes available allows for the evaluation of whether implemented policies are effectively reducing critical vulnerabilities or whether new problematic dependency patterns are emerging. This dynamic evaluation capability facilitates the continuous adaptation of strategies in response to an increasingly volatile and uncertain trade environment.

In broader terms, our advanced conceptualization of trade dependence provides a more solid foundation for the development of economic security strategies tailored to the current context. As Balteanu et al. (2025) argues, the very notion of economic security is evolving from narrow concepts focused on specific sectors to systemic approaches that consider the resilience and adaptability of the economic system as a whole.

Our methodology contributes to this conceptual evolution by providing tools that allow for the visualization and quantification of the complex interconnections characterizing the contemporary global economy. The emphasis on indirect dependencies and systemic effects broadens the traditional perspective on trade vulnerabilities, facilitating a more informed balance between the benefits of global integration and the imperatives of national or regional economic security.

Finally, the proposed indicator has significant implications for assessing trade fragmentation scenarios, an increasingly relevant aspect in the current geopolitical context. As Campos et al. (2023) notes, the growing divergence between geopolitical blocs is generating pressures toward a partial reorganization of international trade along lines of political affinity rather than economic complementarity.

Our methodology allows for the modeling of alternative fragmentation scenarios, evaluating how different patterns of trade reorganization would affect the vulnerabilities of specific countries. These prospective analyses provide valuable information for formulating adaptive strategies that aim to minimize the economic costs of fragmentation while preserving adequate levels of security in the supply of critical goods and services.

Together, these implications form an integrated framework for rethinking economic security in an era of growing geopolitical uncertainty. The indicator we propose not only offers a more accurate and comprehensive measure of existing trade vulnerabilities, but also provides analytical tools to anticipate and manage emerging risks in an increasingly complex and interconnected international system. Here is the translation of the requested section into academic English:

7. Analysis of Centrality and Critical Intermediaries in Trade Networks

7.1. Relevance and Applications

The analysis of centrality and identification of critical intermediaries in international trade networks represents a fundamental methodological extension for understanding the true nature of economic vulnerabilities. While traditional trade dependency measures primarily focus on direct bilateral relations, this approach captures the structural complexity of contemporary global value chains, where a significant number of trade exchanges occur through intermediary countries.

The systematic identification of these critical intermediaries offers multiple analytical advantages:

- **Detection of hidden vulnerabilities**: It reveals indirect dependencies that would remain invisible in conventional bilateral analyses, providing a more comprehensive assessment of supply risks.
- **Assessment of systemic risks**: It identifies critical points whose disruption could create cascading effects across multiple supply chains, impacting economies that appear to be disconnected.
- **Strategic diversification**: It facilitates the design of supplier diversification strategies that consider not only the direct source of imports but also the indirect trade routes.
- **Economic geopolitics**: It identifies countries that, due to their position as intermediaries in multiple value chains, hold disproportionate economic influence relative to their size.

In the current context of growing geopolitical fragmentation, where divergent trade blocs seek reorganization along lines of political affinity, the role of intermediaries takes on unprecedented relevance. Countries acting as "connectors" between different spheres of influence can become strategic choke points or, alternatively, enablers of global trade resilience.

Sectoral analysis of these intermediaries is particularly valuable, as different industries exhibit distinct commercial network structures. Sectors such as semiconductors, critical minerals, or pharmaceuticals tend to be characterized by high degrees of specialization and geographic concentration, creating specific intermediary patterns that warrant detailed examination.

7.2. Mathematical Formulation

To integrate the analysis of critical intermediaries into our economic security indicator, we propose a methodology combining elements of network theory, dependency propagation, and centrality metrics. Below, we formally develop this methodological extension.

7.2.1. Identification of Critical Routes

First, we extend the calculation of indirect dependency to not only capture the aggregated value of this dependency but also the specific routes through which it is transmitted. For each pair of countries (i, j) and each possible route length ℓ, we identify the set of significant trade routes $\mathcal{P}_{ij}^{\ell}$.

A route $p = (p_1, p_2, \ldots, p_{\ell+1})$ of length ℓ, where $p_1 = j$ (exporter) and $p_{\ell+1} = i$ (importer), is considered significant if its strength $F(p)$ exceeds a predefined threshold θ_p:

$$F(p) > \theta_p \tag{13}$$

where the strength of a route is defined as:

$$F(p) = \prod_{k=1}^{\ell} \frac{x_{p_k p_{k+1}}}{S_{p_{k+1}}} \tag{14}$$

where $x_{p_k p_{k+1}}$ is the trade flow from country p_k to country p_{k+1}, and $S_{p_{k+1}}$ is the total supply received by country p_{k+1}. This formulation captures the transmission of dependencies through multiple intermediary countries.

**

7.2.2. Centrality Metrics for Intermediaries

**

For each country k, we calculate two fundamental metrics that capture its importance as an intermediary:

- **Intermediation Frequency** (ϕ_k): Counts how many significant trade routes country k participates in as an intermediary:

$$\phi_k = \sum_{i,j} \sum_{\ell=2}^{L_{\max}} \sum_{p \in \mathcal{P}_{ij}^{\ell}} \mathbb{1}_{k \in p \setminus \{p_1, p_{\ell+1}\}} \tag{15}$$

  where $\mathbb{1}$ is the indicator function that equals 1 if country k is an intermediary in route p (excluding the exporter p_1 and the importer $p_{\ell+1}$).

- **Intermediation Strength** (ψ_k): A weighted sum that captures the economic importance of the routes in which country k participates:

$$\psi_k = \sum_{i,j} \sum_{\ell=2}^{L_{\max}} \sum_{p \in \mathcal{P}_{ij}^{\ell}} F(p) \cdot w(k, p) \cdot \mathbb{1}_{k \in p \setminus \{p_1, p_{\ell+1}\}} \tag{16}$$

  where $w(k, p)$ is a weighting factor that assigns more importance to intermediaries closer to the final importer:

$$w(k, p) = \frac{1}{d(k, p_{\ell+1})} \tag{17}$$

  where $d(k, p_{\ell+1})$ is the distance (number of steps) between intermediary k and the final importer $p_{\ell+1}$ in route p.

Here is the translation of the requested section into academic English:

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**

7.2.3. Composite Centrality Index

**

Finally, we define a composite centrality index for each country k that integrates both normalized metrics:

$$C_k = \alpha \cdot \frac{\phi_k}{\max_i \phi_i} + (1 - \alpha) \cdot \frac{\psi_k}{\max_i \psi_i} \tag{18}$$

where $\alpha \in [0, 1]$ is a parameter that determines the relative weight of the frequency versus the strength of intermediation. Empirically, we have found that a value of $\alpha = 0.4$ provides an optimal balance between both dimensions.

This centrality index $C_k \in [0, 1]$ allows for the ranking of countries according to their importance as intermediaries in global trade, thereby complementing the analysis of direct and indirect dependencies.

**

7.3. Sectorial Application

**

To apply this methodology at the sectorial level, we calculate the centrality index C_k^s for each sector s independently. This allows us to identify specific patterns of intermediation by industry and reveal sectorial vulnerabilities that might be diluted in an aggregated analysis.

Comparing these sectorial indices facilitates the identification of:

- Countries with high specialization as intermediaries in specific strategic sectors.
- Sectors with higher concentration of intermediation versus those with more diversified trade routes.
- Correlations between centrality in different sectors, revealing possible interdependencies between seemingly disconnected supply chains.

This methodological extension represents a significant contribution to the assessment of economic security, providing more robust analytical tools to understand and manage the risks derived from the increasing complexity of global trade networks.

8. Simulation of Disruptions in the Global Trade Network

To evaluate the impact of trade disruptions, a simulation of counterfactual scenarios is implemented, focusing on the removal or alteration of key nodes within the global trade network. This approach allows us to measure the structural vulnerability of international trade relations and provides relevant information for identifying potential risks and mitigation strategies. The simulation is organized in the following steps:

1. **Definition of the System to Simulate:** The global trade system is modeled as a network, where the *nodes* correspond to countries or economic sectors, and the *links* represent bilateral or multilateral trade flows between them. This network is constructed using international trade data, especially those affected by recent tariff measures.
2. **Removal of Key Nodes:** Critical nodes within the trade network are identified, those whose trade is essential for other countries or sectors. These key nodes can include countries like China or industrial sectors like battery production. In counterfactual scenarios, these nodes are removed from the network to simulate trade disruptions, such as economic sanctions or supply chain interruptions.
3. **Simulation of Changes in Links:** In addition to removing nodes, changes in trade links are simulated. This may involve the reduction or elimination of certain trade flows, or the reassignment of trade routes to new partners. These modifications allow us to explore how the network adapts to structural changes and how trade dependencies are reconfigured.
4. **Impact Evaluation:** To assess the effects of the disruptions, several structural metrics are used. These include:

- *Impact on network connectivity:* We measure how the removal of nodes affects the overall connectivity of the network, evaluating how many countries or sectors become isolated as a result of the disruption.
- *Impact on centrality:* We analyze how the centrality of the remaining nodes in the network changes. This allows us to identify which countries or sectors gain more relevance after the removal of a key node.
- *Economic losses:* We estimate the economic impact on the affected countries using indicators such as GDP or trade volume, comparing the results of the counterfactual scenarios with the actual situation.

5. **Results Analysis:** Finally, the results of the simulations are analyzed to identify areas of greatest vulnerability. We examine how disruptions affect the stability of global supply chains and propose mitigation strategies, such as market diversification or regional cooperation.

9. Critical Networks and Structural Power: An Application of the Economic Security Index to the US-China-EU Conflict

9.1. Motivation and Geoeconomic Context

In the first quarter of 2025, the international economy has entered a new phase of commercial fragmentation. The imposition of tariffs between key actors in the global economic system—such as the United States, China, Canada, Mexico, and the European Union—has triggered a retaliatory dynamic that threatens to destabilize strategic supply chains. Unlike previous episodes of trade tension, such as those experienced in 2018-2019, the current protectionist cycle encompasses a wider range of products, involves more actors, and has a deeper disruptive potential as it affects high-tech sectors, food, energy, and transportation.

The measures adopted include 25% tariffs on industrial exports (steel, aluminum, automobiles), agricultural goods (soybeans, corn, avocados), and symbolic consumer products (jeans, whiskey, motorcycles), as well as non-tariff restrictions such as selective regulatory inspections, surprise audits, or cross-border electricity supply cuts. Official statements from political leaders and scheduled response calendars (bilateral meetings, announced escalations) indicate that the conflict is still in an ascending phase, with no immediate resolution in sight.

In this context, it is crucial to develop analytical tools that allow for a rigorous evaluation of the **structural vulnerabilities** of national economies to trade disruptions. As indicated in previous sections of this work, the primary goal of the Economic Security Index (ISE) is to provide a tool that integrates graph theory, value chain analysis, and intensive processing techniques to quantify not only direct dependence but also **indirect dependence**. The analysis of trade routes, combined with the identification of critical intermediaries, reveals configurations of trade risk that would otherwise remain hidden.

This case study applies this approach to the current situation of the emerging tariff war, aiming to identify:

- Critical bilateral relations with high structural dependence.

Table 2: Conflicting Trade Blocs and Affected Sectors

Bloc	Affected Products	Nature of the Conflict	Associated ITP Sectors
Canada vs. U.S.	Steel, aluminum, softwood, energy	Cross tariffs; threat of electricity supply cutoff	Metallurgy, construction, electricity generation
U.S. vs. China	Electronics, batteries, soybeans, airplanes, drones	Tariffs and technological retaliation; non-tariff restrictions	Electronics, air transport, agribusiness, ICT
EU vs. U.S.	Cars, wines, cheeses, textiles	Selective tariffs; symbolic retaliation	Automotive, gourmet foods, textiles
Mexico vs. U.S.	Avocados, beer, auto parts, gasoline	Mutual tariffs; pressure on agriculture and energy	Agrifood, automotive, refining

- Indirect risk routes with high relative flow.
- Intermediary countries that concentrate structural power in the global trade network.

By doing so, the goal is to illustrate the analytical potential of the ISE and its usefulness in guiding decisions on trade, industrial, and geostrategic policy in an increasingly uncertain and competitive global environment.

9.2. Geopolitical Blocs and Sensitive Sectors

The emerging trade war of 2025 not only involves the major global economic powers but also directly impacts strategic industries with a high degree of integration in global value chains. To capture the structural effects of this conflict, four key trade blocs have been identified, and the affected products have been mapped to their respective industries within the ITP database.

These blocs were selected based on (i) the intensity of the recently implemented tariff and non-tariff measures, (ii) the value of the trade flows involved, and (iii) the potential systemic impact on the rest of the global economy.

The mentioned industries will be used as an analytical subset within the methodological framework of the Economic Security Index (ISE). For each of them, filtered bilateral trade matrices will be analyzed, allowing the estimation of both direct dependencies and indirect routes with structural risk.

Additionally, countries with high connectivity and centrality in the global flows of sensitive products are identified as potential strategic intermediaries. These intermediaries, as will be explored later, may become critical nodes for both amplifying and mitigating the impact of trade disruptions.

Finally, it is important to note that these trade conflicts have a strategic temporal dimension. With bilateral meetings scheduled between the different blocs in April 2025, the proposed analysis can provide valuable input to anticipate structural vulnerabilities before more widespread disruptions materialize.

10. Methodological Design

The following methodological steps are implemented:

1. **Sectorial Filtering**: Relevant industries are selected from the ITP database corresponding to the products affected by recent tariff measures.
2. **Dependency Calculation**: For each industry, the total dependency between countries (direct + indirect) is calculated using paths of up to length 5 and structural significance thresholds.
3. **Identification of Critical Intermediaries**: Frequency and relative strength metrics are computed for each country in its role as an intermediary in indirect trade routes.
4. **Disruption Simulation**: Counterfactual scenarios are modeled by removing key nodes (e.g., China as an exporter of batteries) to measure the structural impact on third countries.

11. Analysis of Hidden Dependencies in International Trade

Figure 3 presents a comparison between traditional trade dependency metrics (X-axis) and our Economic Security Index (Y-axis). This visualization reveals a fundamental finding: conventional approaches, which only consider direct bilateral relationships, systematically underestimate the real vulnerability of countries to disruptions in their supply chains.

The distribution of points shows a clear concentration above the reference diagonal line, indicating that for most trade relationships, the total dependency calculated by our index exceeds the direct dependency measured by traditional methods. This difference—visualized through the concealment ratio (DT/DD) on the color scale—is particularly pronounced in the lower-left quadrant, where countries with seemingly low direct dependencies exhibit significant indirect vulnerabilities.

Some extreme cases, such as the RUS-BEL (Russia-Belgium) relationship, show concealment ratios greater than 10, meaning the real dependency is more than ten times higher than suggested by bilateral statistics. Other pairs, such as DEU-BEL (Germany-Belgium), MYS-FRA (Malaysia-France), and MYS-DEU (Malaysia-Germany), also show notable discrepancies, demonstrating how indirect interdependencies can create hidden structural vulnerabilities.

Table 3 quantitatively confirms these observations, presenting the ten trade relationships with the highest concealment ratios between Canada, the United States, China, and the European Union countries.

The results reveal surprising cases such as Croatia (HRV), which shows a direct dependency of only 0.005 on the U.S. in the legumes sector, but a total dependency of 0.549 when indirect routes are considered, resulting in a concealment ratio of 107.7. Similarly, Croatia's dependency on China in the leather processing sector shows a ratio of 75.8, highlighting how seemingly marginal relationships can hide critical dependencies.

A relevant pattern emerges in the livestock sector, where countries like Greece, Slovenia, and Belgium show high indirect dependencies on producers like Denmark, Hungary, and the Czech

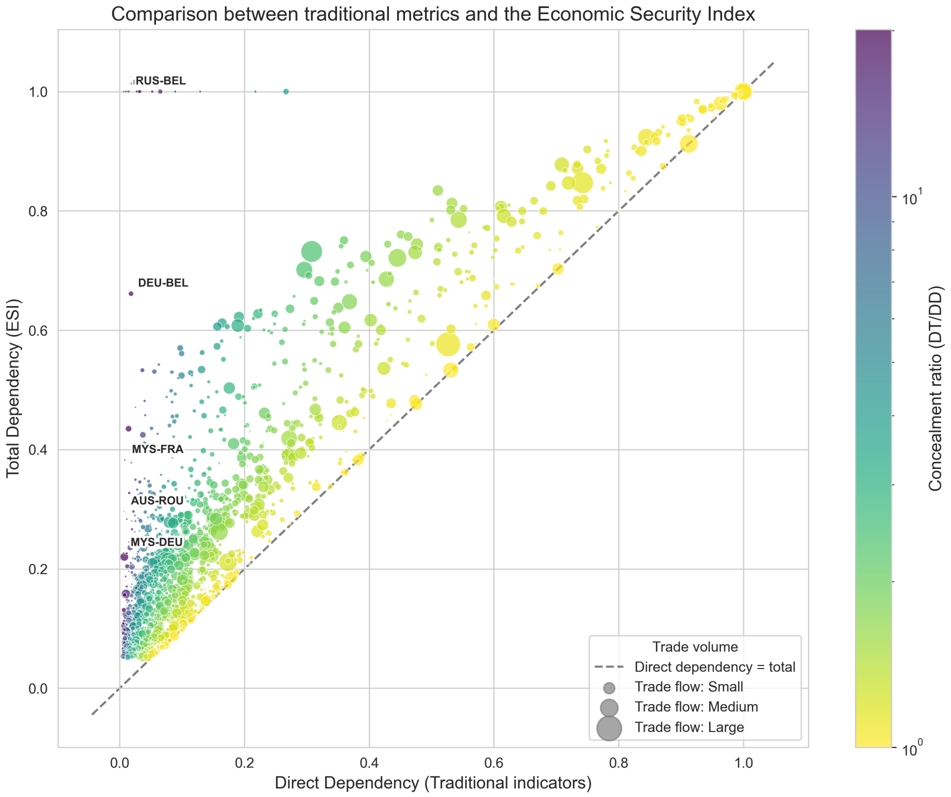

Figure 3: Comparison between traditional metrics and the Economic Security Index. Points above the diagonal line represent trade relationships where total dependency exceeds direct dependency, revealing hidden vulnerabilities through trade intermediaries.

Table 3: Trade Relationships with the Highest Concealment Ratio Between Selected Countries

Importing Country	Exporting Country	Sector	Direct Dependency	Total Dependency	Concealment Ratio
HRV	USA	Pulses and legumes, dried, preserved	0.005	0.549	107.7
HRV	CHN	Dressing & dyeing of fur; processing of fur	0.005	0.408	75.8
GRC	DNK	Live Swine	0.006	0.386	69.8
NLD	HUN	Corn	0.005	0.292	56.7
SVN	DNK	Live Swine	0.005	0.282	55.7
IRL	ESP	Fishing	0.006	0.353	54.5
EST	DEU	Publishing of newspapers journals etc.	0.006	0.295	53.3
GRC	BEL	Live Swine	0.006	0.279	50.4
BEL	CZE	Live Cattle	0.005	0.250	46.3
SVN	DEU	Animal feed ingredients and pet foods	0.008	0.346	45.3

Notes: This table shows bilateral trade relationships with the highest ratio between total dependency (including indirect routes) and direct dependency. Higher ratios indicate greater hidden vulnerabilities not captured by traditional bilateral trade statistics.

Republic in pigs and live cattle, with concealment ratios ranging from 46 to 70. This suggests the existence of complex supply chains in the European agri-food sector, where disruptions in specific nodes could have amplified consequences through multiple intermediaries.

These observations have significant implications for the formulation of economic security policies. Traditional approaches that focus exclusively on diversifying direct suppliers may be insufficient if they do not account for vulnerabilities transmitted through shared intermediaries. Our index provides a more refined tool to identify these hidden dependencies and design effective risk mitigation strategies in increasingly complex global supply chains.

11.1. Analysis of Critical Bilateral Dependencies in Strategic Sectors

The analysis of total dependency matrices between the main trade blocks (United States, China, Canada, and the European Union) reveals significant patterns of vulnerability in key strategic sectors. The sectorial heat maps, which aggregate the EU data using a weighted average based on trade volume, provide a clear view of the most critical trade interdependencies.

11.1.1. Dependency Patterns in Electronics and Information Technologies

In the computer equipment sector (Figure 4), one of the highest dependencies in the study is observed: the dependency of the United States on China reaches 0.82, surpassed only by the dependency of Canada on China (0.86). The EU also shows a high dependency on China in this sector (0.78). This pattern is particularly concerning considering the centrality of these components in multiple strategic value chains, from defense to telecommunications.

A similar pattern is observed in TV/radio receivers, where China generates dependencies greater than 0.70 for all analyzed blocks, reaching 0.80 for Canada. Even more revealing is the optical and photographic equipment sector, where China holds a dominant position with dependency values close to 0.55 for the United States, Canada, and the EU.

11.1.2. Dependencies in the Aerospace Sector

The aerospace sector presents an inverse pattern: the United States generates high dependencies for Canada (0.76), China (0.62), and the EU (0.51). This vulnerability is mainly due to the concentration of advanced aircraft design and manufacturing capabilities in a limited number of global suppliers, with the United States maintaining a dominant position.

Table 4 confirms this finding, showing that 9 of the 20 bilateral relationships with the highest total dependency involve the aerospace sector as a source of vulnerability, with EU countries like Estonia (0.896), Latvia (0.860), and Sweden (0.851) showing extremely high dependencies on the United States.

11.1.3. Batteries and Strategic Metals

In the batteries sector (Figure **??**), Canada shows a high dependency on the United States (0.58), while the EU presents a significant dependency on China (0.57). Given the growing importance of batteries for energy transition and electric mobility, these dependencies acquire additional strategic relevance.

The analysis of precious and non-ferrous metals (Figure **??**) shows an additional vulnerability: Canada depends significantly on the United States (0.49), while China shows a moderate but

Table 4: Top 20 Trade Dependencies Between Selected Countries

Importer	Exporter	Sector	Direct	Indirect	Total
EST	USA	Aircraft & spacecraft	0.821	0.075	0.896
CAN	CHN	Computing machinery	0.795	0.068	0.863
LVA	USA	Aircraft & spacecraft	0.802	0.058	0.860
SWE	USA	Aircraft & spacecraft	0.798	0.053	0.851
NOR	USA	Aircraft & spacecraft	0.787	0.058	0.845
USA	CHN	Computing machinery	0.755	0.068	0.823
FIN	USA	Aircraft & spacecraft	0.764	0.058	0.822
CAN	CHN	TV & radio receivers	0.746	0.074	0.820
CAN	USA	Aircraft & spacecraft	0.758	0.057	0.815
USA	CHN	TV & radio receivers	0.721	0.070	0.791
CAN	USA	Computing machinery	0.718	0.067	0.785
CAN	USA	Medical equipment	0.720	0.062	0.782
EU	CHN	Computing machinery	0.712	0.066	0.778
LVA	CAN	Aircraft & spacecraft	0.715	0.060	0.775
EU	CHN	TV & radio receivers	0.705	0.069	0.774
EU	USA	Aircraft & spacecraft	0.718	0.055	0.773
CHN	USA	Aircraft & spacecraft	0.619	0.052	0.671
CAN	USA	Batteries & accumulators	0.524	0.056	0.580
EU	CHN	Batteries & accumulators	0.511	0.059	0.570
CAN	USA	Precious metals	0.443	0.048	0.491

Notes: Bilateral relationships with highest total dependency (direct + indirect) among strategic partners. Values indicate critical supply chain vulnerabilities.

significant dependency on Canada (0.23). These flows form an interdependency triangle where disruptions in any vertex could quickly propagate to others.

11.1.4. Medical Equipment and Cross-Dependencies

The medical and orthopedic equipment sector (Figure **??**) reveals a particularly interesting pattern: the United States generates high dependencies for all the blocks analyzed (up to 0.60 for Canada), while the EU generates moderate but significant dependencies for China (0.19). This setup suggests a potential role for the EU as an alternative supplier in this strategic sector.

11.1.5. Analysis of Critical Dependencies at the Country-Sector Level

Table 4 reveals that the 20 bilateral relationships with the highest total dependency concentrate in three sectors: computer equipment (8 relationships), aircraft (9 relationships), and TV/radio receivers (3 relationships). These relationships not only present extremely high total dependency values (between 0.775 and 0.896), but also show a significant contribution from the indirect component of the dependency.

Cases such as Estonia-United States in aircraft (0.896) or Canada-China in computer equipment (0.863) represent critical vulnerabilities that could compromise the economic security of these countries in the face of trade disruptions. The analysis reveals that even economic powers like the United States exhibit significant vulnerabilities, such as its dependency on China in computer equipment (0.823).

It is revealing that in 19 of the 20 most critical relationships, the exporting country is either the United States or China, confirming their central role as suppliers of strategic sectors. Canada appears only once as a critical exporter (to Latvia in aircraft), while the EU does not appear as an exporter in any of the most critical relationships identified.

These findings have significant implications for economic security strategies. First, they confirm the concentration of vulnerabilities in high-tech sectors that are crucial for the functioning of modern economies. Second, they reveal the asymmetry in dependency relationships, with some countries in clearly dominant positions as critical suppliers. Third, they suggest that diversification strategies should specifically prioritize sectors like computer equipment, electronic components, and aircraft, where the sharpest vulnerabilities are concentrated.

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In the computer equipment sector, we observe one of the highest dependencies in the study: the dependency of the United States on China reaches 0.82, surpassed only by the dependency of Canada on China (0.86). The EU also shows a high dependency on China in this sector (0.78). This pattern is particularly concerning considering the centrality of these components in multiple strategic value chains, from defense to telecommunications.

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In the batteries sector, Canada shows a high dependency on the United States (0.58), while the EU presents a significant dependency on China (0.57). Considering the growing importance of batteries for energy transition and electric mobility, these dependencies acquire additional strategic relevance.

The analysis of precious and non-ferrous metals reveals an additional vulnerability: Canada depends significantly on the United States (0.49), while China shows a moderate but significant dependency on Canada (0.23). These flows form an interdependency triangle where disruptions at any vertex could quickly propagate to others.

Table 5: The 20 Trade Relationships with the Highest Total Dependency Between Selected Countries

Importing Country	Exporting Country	Sector	Direct Dependency	Indirec
EST	USA	Aircraft and spacecraft	0.833	
CAN	CHN	Office accounting and computing machinery	0.524	
LVA	CAN	Aircraft and spacecraft	0.853	
SWE	USA	Aircraft and spacecraft	0.674	
POL	USA	Aircraft and spacecraft	0.685	
CZE	CHN	Office accounting and computing machinery	0.618	
SVK	USA	Aircraft and spacecraft	0.596	
USA	CHN	Office accounting and computing machinery	0.471	
SVN	CHN	Office accounting and computing machinery	0.510	
POL	CHN	Office accounting and computing machinery	0.519	
CAN	CHN	TV and radio receivers and associated goods	0.461	
DEU	CHN	Office accounting and computing machinery	0.490	
GRC	CHN	Office accounting and computing machinery	0.571	
POL	CHN	TV and radio receivers and associated goods	0.554	
FRA	CHN	Office accounting and computing machinery	0.458	
PRT	FRA	Aircraft and spacecraft	0.722	
CYP	USA	Aircraft and spacecraft	0.501	
USA	CHN	TV and radio receivers and associated goods	0.470	
LUX	USA	Aircraft and spacecraft	0.577	
NLD	USA	Aircraft and spacecraft	0.554	

11.2.4. Medical Equipment and Cross-Dependencies

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It is revealing that in 19 of the 20 most critical relationships, the exporting country is either the United States or China, confirming their central role as suppliers of strategic sectors. Canada appears only once as a critical exporter (to Latvia in aircraft), while the EU does not appear as an exporter in any of the most critical relationships identified.

These findings have significant implications for economic security strategies. First, they confirm the concentration of vulnerabilities in high-tech sectors that are crucial for the functioning of modern economies. Second, they reveal the asymmetry in dependency relationships, with some countries in clearly dominant positions as critical suppliers. Third, they suggest that diversification strategies should specifically prioritize the sectors of computer equipment, electronic components, and aircraft, where the sharpest vulnerabilities are concentrated.

11.3. Analysis of Critical Intermediaries

The identification and characterization of critical intermediaries in global trade networks is one of the most significant methodological contributions of the Economic Security Index (ISE). Unlike traditional approaches that solely evaluate direct bilateral dependencies, our methodology allows for the identification of countries that, due to their strategic position as intermediary nodes in trade routes, can potentially amplify or mitigate disruptions in global supply chains.

11.3.1. Distribution of Intermediary Power at the Global Level

Figure 5 reveals a highly asymmetric distribution of intermediary power in global trade. China emerges as the dominant intermediary, with a centrality score (114.71) that nearly doubles that of the second country, the United States (57.90). This gap suggests an unprecedented concentration of structural power in a single actor, creating a scenario where disruptions in the Chinese economy could propagate through multiple trade routes with potentially systemic effects.

After these two major players, a second tier of global intermediaries emerges, consisting of the United Kingdom (45.10), Germany (44.34), India (37.69), France (36.86), and the Netherlands (35.88). This distribution reflects a stepped structure of influence, where the impact of these countries as transmitters of vulnerability is significant but substantially lower than that of the two major players.

It is noteworthy that South Africa (33.32) and Argentina (26.11) appear among the top ten intermediaries, highlighting the importance of regional commercial powers as transmitters of dependencies in specific value chains, particularly in the realm of natural resources and agricultural products.

11.3.2. Sectoral Specializations in Intermediation

The sectoral analysis (Figure **??**) reveals differentiated patterns of intermediation specialization, forming a map of specific vulnerabilities by industry. China shows a dominant position (value 1.00) in almost all the strategic sectors analyzed, with the only exception being the aerospace sector. This intermediary hegemony confirms and amplifies the conclusions of previous studies on China's centrality in global value chains (Gereffi and Korzeniewicz, 2022; Baldwin and López-González, 2020).

The United States, on the other hand, shows high specialization as an intermediary in the aerospace sector (1.00), with secondary but significant roles in medical equipment (0.54) and optical instruments (0.72). This configuration reflects the strategic position of the U.S. in high-tech and defense industries, where its role as a transmitter of indirect dependencies is particularly relevant.

The European intermediation pattern shows greater sectoral specialization: France stands out in aerospace (0.63), Germany in medical equipment (0.53) and aerospace products (0.53), and the United Kingdom in aerospace (0.59). These results suggest a more selective and specialized European model of intermediation, contrasting with China's generalist role.

Table 6 confirms these findings, showing how certain countries dominate specific sectors. In the case of batteries, China holds an absolutely dominant position (centrality 1.00), followed at a considerable distance by Germany (0.283), South Korea (0.282), and the United States (0.274). This concentration of intermediary power in a single country represents a particularly acute systemic vulnerability in a critical sector for the energy transition.

11.3.3. Intermediation Specialization Profiles

The country-level disaggregated analysis (Figure 6) reveals distinctive specialization patterns that form "intermediation profiles" characteristic of each economy. China shows a generalist intermediation profile, with maximum scores (1.00) in diverse sectors such as batteries, agricultural machinery, and textiles, reflecting its role as the "global factory" in multiple value chains.

In contrast, Germany displays a highly specialized intermediation profile, dominating specific niches such as live animals (0.962), specialized chemicals (0.944), and sweeteners (0.928). This specialization reflects Germany's strategy of occupying key positions in value chains with high added value and technological complexity.

Japan and South Korea present complementary intermediation profiles focused on specific industrial sectors. While Japan stands out as a key intermediary in motors and turbines (1.00) and motor vehicles (1.00), South Korea shows significant presence as an intermediary in consumer sectors such as processed food products (0.639) and beverages (0.606).

11.3.4. Implications for Economic Security

These findings have significant implications for the formulation of risk mitigation strategies in supply chains. First, they reveal that effective diversification should not only consider the distribution of direct suppliers but also the intermediation profile of the countries involved. China's dominant presence as an intermediary across multiple sectors indicates that even seemingly diversified trade relations may share common indirect vulnerabilities through this nexus.

Secondly, the results suggest the existence of specific "intermediary bottlenecks," where a very limited number of countries control the transmission routes in strategic industries. The battery sector constitutes a paradigmatic example of this phenomenon, with critical implications for the global energy transition.

Finally, the analysis highlights strategic opportunities to develop "alternative intermediaries" that can reduce the concentration of structural power. The intermediation specialization of regional powers such as South Africa or Argentina in specific sectors suggests potential models for developing complementary trade routes that increase systemic resilience.

Table 6: Top five intermediaries by selected strategic sector

Sector	Country	Frequency	Strength	Centrality Score
Accumulators primary cells and batteries	CHN	847	156.2	1.000
	DEU	267	45.8	0.283
	KOR	251	46.1	0.282
	USA	239	44.2	0.274
	JPN	198	38.5	0.238
Aircraft and spacecraft	USA	623	89.4	1.000
	FRA	298	41.8	0.631
	GBR	267	38.9	0.589
	DEU	245	35.2	0.534
	CAN	189	28.1	0.421
Electronic valves tubes etc.	CHN	945	178.3	1.000
	USA	456	67.8	0.472
	DEU	398	58.9	0.413
	JPN	342	52.1	0.368
	KOR	289	45.6	0.321
Medical surgical and orthopaedic equipment	USA	567	84.2	1.000
	DEU	298	44.7	0.526
	CHN	267	38.9	0.471
	GBR	198	29.8	0.349
	FRA	156	23.4	0.276

Notes: Centrality scores are normalized relative to the top country in each sector. Frequency measures the number of trade paths where the country acts as intermediary, while strength measures the economic importance of those paths.

11.4. Limitations and Future Development

Although the proposed intermediary analysis represents a significant advancement over traditional approaches, it has certain limitations that deserve consideration. First, the centrality indicator used, while adequately capturing the frequency and strength of intermediation, does not directly incorporate the concept of "substitutability" of a country as an intermediary. Second, the current analysis does not explicitly consider geopolitical factors or strategic alliances that may modify the behavior of these intermediaries in crisis scenarios.

Future developments of the index could integrate community-based trade analyses to identify "intermediation clusters" with similar patterns, or incorporate dynamic metrics that capture the temporal evolution of a country's intermediation role. Additionally, incorporating factors such as geographical proximity, regulatory compatibility, or geopolitical alliances would allow for a more refined evaluation of risks associated with specific intermediaries.

Table A.7: Mapping between strategic sectors and ITP industries from the dataset

Strategic Sector	**Corresponding ITP Industries**
Basic Metals	Basic iron and steel, Basic precious and non-ferrous metals
Automotive	Motor vehicles, Automobile bodies trailers & semi-trailers, Parts/accessories for automobiles
Batteries	Accumulators primary cells and batteries
Electronics and ICT	Electronic valves tubes etc., TV and radio receivers and associated goods, Office accounting and computing machinery
Agroindustry and Food	Soybeans, Corn, Wheat, Other agricultural products, nec, Prepared fruits and fruit juices, Prepared vegetables, Dairy products, Beverages, nec, Distilling rectifying & blending of spirits
Energy and Fuels	Refined petroleum products, Extraction crude petroleum and natural gas, Electricity production, collection, and distribution
High Technology and Air Transport	Aircraft and spacecraft, Medical surgical and orthopaedic equipment, Optical instruments & photographic equipment

Notes: This mapping facilitates the analysis of dependencies in strategic sectors by linking them to specific industrial classifications in the International Trade Partnership (ITP) database.

Appendix A. Appendix: Technical Details

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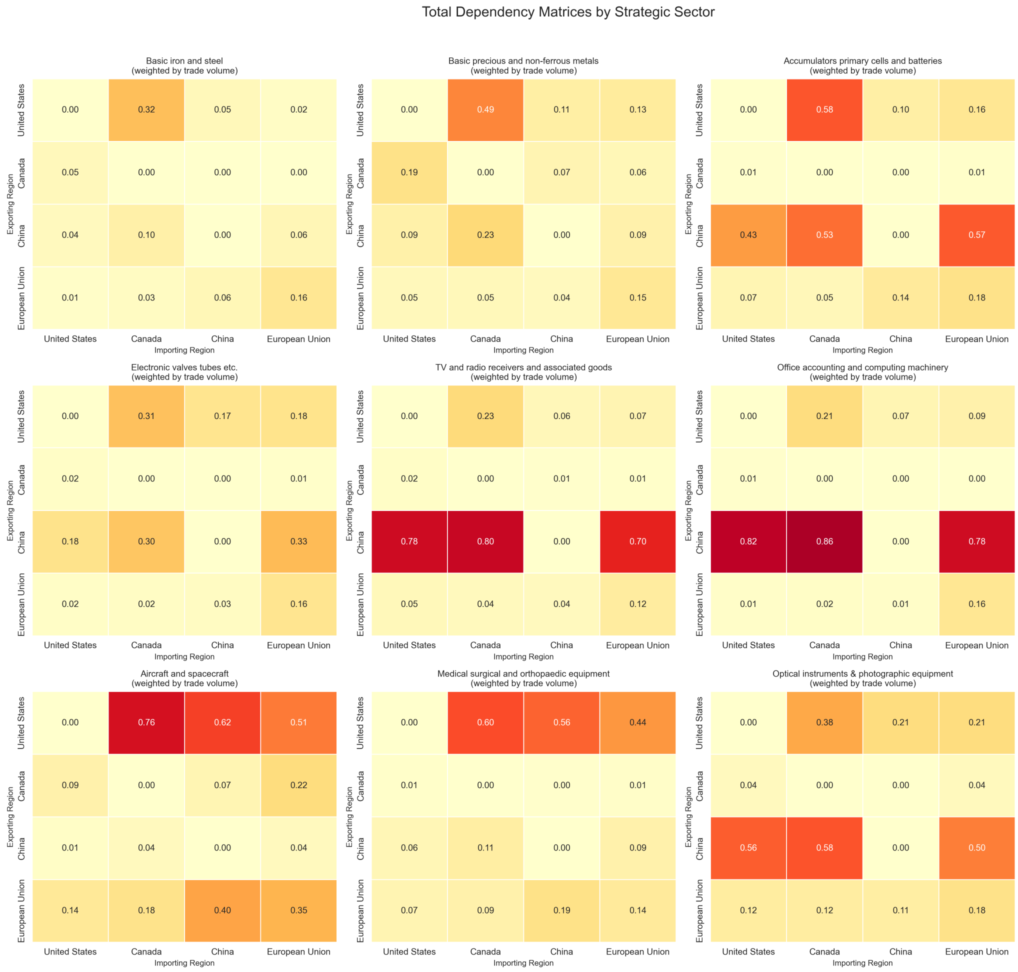

Figure 4: Total dependency heatmaps for nine strategic industrial sectors between the United States, Canada, China, and the European Union (aggregated). Rows represent the exporting region and columns represent the importing region. Dependency values are calculated as a weighted average based on trade volume.

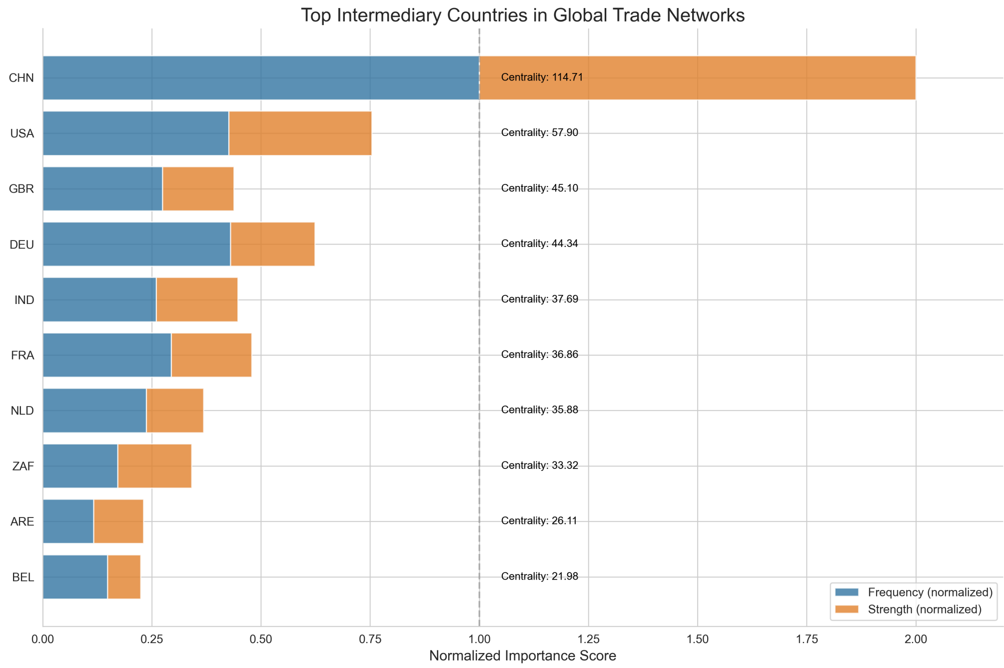

Figure 5: Top intermediary countries in global trade, classified by their centrality, with decomposition of frequency and intermediary strength. Centrality is calculated by combining frequency (number of paths where the country appears as an intermediary) and strength (intensity of its role in each path).

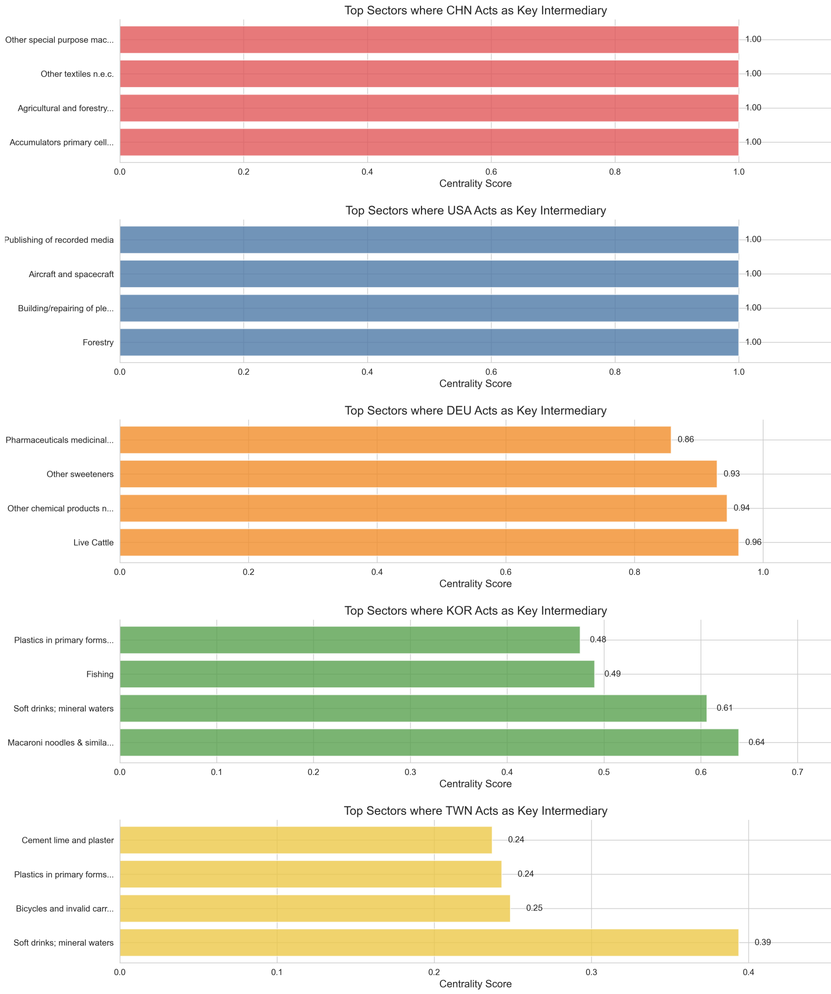

Figure 6: Sectors where each major country acts as a key intermediary, showing the sectoral specialization of their intermediary power.