Charles University

Faculty of Social Sciences
Institute of Economic Studies

MASTER'S THESIS

Production shifting from China to Vietnam: Implications for Global Value Chains

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Study program: **Economic Theory and Modelling**

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Academic Year: **2022/2023**

Declaration of Authorship

The author hereby declares that he compiled this thesis independently; using only the listed resources and literature, and the thesis has not been used to obtain a different or the same degree.

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Prague, August 1, 2023 Karolína Maderová

Acknowledgments

I am is deeply grateful to my supervisor, Ing. Vilém Semerák, M.A., Ph.D., for all his help and support, I would never finish this work without him. I would also like to thank my friends and family for their support and their patience with me, especially during the last few weeks.

Abstract

This thesis analyzes the importance of China within the global economy and assesses the potential of Vietnam to serve as its replacement, or at least for some industries. Using the network analysis and the hypothetical extraction method (HEM), the most influential sectors of the Chinese economy were identified and an increasing trend of reliance of the Westen countries on China's supply and demand was found. Next, using the trade decomposition method, the participation in GVC for Vietnam and China was calculated. Although Vietnam is increasing its participation and other countries are increasing their demand for inputs from Vietnam, based on the available data, it was not possible to determine whether these changes could mean that Vietnam can replace China in the future.

JEL Classification	C67, D57, F18, F52
Keywords	Input-output model, HEM, network analysis, GVC
Title	Production shifting from China to Vietnam: Implications for Global Value Chains

Abstrakt

Tato práce analyzuje význam Číny v rámci světové ekonomiky a vyhodnocuje, zda je Vietnam potenciálně schopný ji nahradit, alespoň v určitých Pomocí síťové analýzy a metody hypotetické extrakce (HEM) byly identifikovány nejvlivnější sektory čínské ekonomiky a byl zjištěn rostoucí trend závislosti západních zemí na čínské nabídce a poptávce. Dále bylo pomocí metody rozkladu obchodu vypočteno zapojení Vietnamu a Číny v globálních hodnotových řetězcích. Přestože Vietnam zvyšuje své zapojení a ostatní země zvyšují svou poptávku po vstupech z Vietnamu, na základě dostupných dat nebylo možné určit, zda tyto změny mohou znamenat, že Vietnam by mohl v budoucnu nahradit Čínu.

Klasifikace	C67, D57, F18. F52
Klíčová slova	Input-output model, metoda hypotetické extrakce, síťová analýza, globální hodnotové řetezce
Název práce	Přesun výroby z ČLR do Vietnamu: dopady na globální hodnotové řetězce

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List of Abbreviations

ADB	Asian Development Bank
CESEE	Central, East and Southeast Europe
DAVAX	Directly absorbed value-added in exports
DC	Domestic content
DCC	Domestic double counted
DTAA	Double tax (taxation) avoidance agreement
DVA	Domestic value added
EU	European Union
FC	Foreign content
FCC	Foreign double counted
FDI	Foreign direct investment
FIGARO	Full International and Global Accounts for Research in input-Output analysis
FTA	Free trade agreement
FVA	Foreign value added
GDP	Gross domestic output
GEM	Global (hypothetical) extraction method
GSC	Global supply chain
GTAP	Global Trade Analysis Project
GVC	Global value chain
HEM	Hypothetical extraction method
ICIO	Inter-Country Input-Output
ICT	Information and communications technology
I-O	Input-Output
JETRO	Japanese External Trade Organization
KWW	Koopman, Wang, Wei
MRIO	Multiregional Input-Output
OECD	Organisation for Economic Co-operation and Development
PTF	Pass-through frequency
RTA	Regional trade agreement
USA	United States of America
VAX	Value-added export
VS	Vertical specialization
WIOD	World Input Output Database
WTO	World Trade Organization

Master's Thesis Proposal

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Specialization:	ET&M	Defense Planned:	June 2023

Proposed Topic:

Production shifting from China to Vietnam: Implications for Global Value Chains

Motivation:

In the recent years, Vietnam has been becoming an attractive production destination for many global businesses due to low wages, location, and relative stability. Simultaneously, many big companies have opted for relocation from China to other regions due to increase in labor costs and political tensions, mainly between China and the US. In 2019, these tensions resulted in global value chain (GVC) disruption after the US imposed high tariffs on certain goods imported from China, prompting China to retaliate with tariffs on US goods. According to Chor and Li (2021), the tariffs eventually affected 14.2% and 5.6% of the total value of China's exports and imports, respectively, in 2017. Moreover, when the Covid-19 pandemic hit, GVCs experienced yet another shock when production in China was suddenly paused. Businesses then saw just how much they had been relying on Chinese manufacturing. However, attempts at relocation had been made even before these shocks. Due to data limitations, I will focus on relocation prior to 2018.

The lower costs and geographical proximity between the two countries, as well as potentially more stable manufacturing environment, resulting in more stable GVCs, made Vietnam a good alternative location for companies to shift their location to. Apple Inc. is one of the companies seizing this opportunity. In addition, Japanese government even started financially supporting businesses to move out of China.

China's share in volume of the world's manufacturing is large and therefore any disturbance to Chinese market can have and has had great consequences to GVCs. Relocation or at least diversification of production locations is a supposed step towards an increase in GVC resilience of Western countries. In my thesis, I will study this production shift and attempt to estimate the effect on GVCs and whether we may observe a decrease in GVC vulnerability.

Hypotheses:

1. Hypothesis #1: There are sectors of the global economy in which the world is considerably dependent on China
2. Hypothesis #2: Empirical data already showed that, following the shift, relative changes in the position of Vietnam and China in GVC had already been taking place
3. Hypothesis #3: These changes were correlated with changes in FDIs

4. Hypothesis #4: These changes had real impact on GVC resilience of other countries

Methodology:

In my thesis, I will be relying on OECD's Inter-Country Input-Output (ICIO) Tables (2021 edition). These table are time series from 1995 to 2018 and they cover 45 unique industries for 66 countries. Firstly, I will use this unique time series to identify and describe the complex dependencies of the rest of the world on Chinese production in certain sectors. For such analysis, I will attempt to apply methodology of global hypothetical extraction introduced by Dietzenbacher et al. (2019). Next, I will determine both China's and Vietnam's position in GVCs and will look at the trends that the two countries followed (for example, whether one followed the other or whether they showed rather complementary patterns). This analysis will help us determine how the position of the two countries in GVCs changed and identify the most significant sectors. To do so, I will be using an approach laid out by Koopman et al. (2014), later complemented by Borin and Mancini (2017). The authors propose a framework that is used to break down country's gross exports into value-added and double-counted components by accounting for multiple border crossing of intermediate goods. This approach explains the gap between official trade statistics and national accounts.

Next, I will use data by World Bank and Ministry of Planning and Investment of Vietnam on foreign direct investment (FDI) to inspect if and how they related to these changes. In other words, if a certain country was more exposed to China, did it change its FDIs to Vietnam. Unfortunately, the structure and level of detail of the available FDI and FDI-related data seem to allow only relatively basic regression-based tests of their relationship with the previously identified trends. This part of the results is therefore expected to be of a rather illustrative and complementary nature.

Next, using the same ICIO Tables, I will evaluate the impact on GVC resilience. I intend to focus on economies of Europe and the US and their exposure to China. For this part of analysis, I will use the methodological approach suggested by Inomata & Hanaka (2021). The authors put forward new referential statistics to improve existing methods of risk analysis on geographical concentration of global supply chains. In addition to the conventional volume-based approach, they measure concentration risk in term of frequency – how many times a given chain passes through a given region.

Contribution to literature:

Geographic relocation has been recognized as a tool for improving GVC vulnerability in the literature. There exist several studies bringing out the importance of geographical reconfiguration and optimization (Smorodinskaya et al., 2021) However, studies on relocating production from one specific country to another specific country, in this case China and Vietnam, respectively, ae not common in academic literature

Another contribution of this thesis to existing literature is practical application of the assessment of supply chain geographical concentration laid out by Inomata & Hanaka (2021), as mentioned above. The authors illustrate their approach on the very same data (ICIO tables) that I will be using. Their paper was published simultaneously with the release of the data with the aim to show how they can be exploited. However, the authors provide only a few examples, therefore, we do not know what the results for other countries will look like. This gives us a great opportunity to expand upon their work and test the usefulness of the proposed indicators for applied analytical work as many policymakers have been searching for robust tools that could measure the dependencies.

Expected Contribution:

As China is the leader in world’s manufacturing output with many large economies depending on their imports, any disruption to its economy (be it natural disasters, pandemic, political tensions) can be expected to have grave consequences for the rest of the world. To protect themselves, some companies are choosing to relocate their production to other regions. It is crucial to understand whether these shifts can help solving the issues that arise from geographical concentration of manufacturing. If relocating to Vietnam proved to have positive impact on GVC resilience, more companies may decide to follow to protect themselves from exposure to China. Whether these relocation attempts were successful can potentially influence future recommendations for governments to support national companies in further relocation to Vietnam or other South Asian countries.

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1 Introduction

China is the second largest economy in the world (after the Unites States) and is often referred to as the “factory of the world” due to for example its manufacturing capacity (after all, it is the most populous country in the world), relatively low labor costs (at least historically) or the diversity of the products. It is also the largest exporter of goods and services in the world with 3.71 trillion US$ in 2022. Therefore any disturbance to the Chinese market can have and has had great consequences for GVCs. Naturally, Western countries have been getting progressively wary of China’s influence and are now attempting to find ways to decrease its dependence on China. This process is referred to as “decoupling”. One part of decoupling is finding alternative locations that could in some way substitute for the inputs from China. One of these locations frequently discussed is Vietnam – for multiple reasons such as its geographic proximity to China, lower wages, and stability of the business environment, among others. Many big companies perceive Vietnam as a good alternative, or at least supplement, to China, and have decided to move parts of their production there (Apple, for example) to also diversify their supply chains. The relocation talks were accelerated by two major events of the past years – the US-China trade war (and geo-political tensions in general) which brought additional tariffs on both imports from China and exports to China, and the Covid-19 pandemic which greatly disrupted many value chains.

This thesis studies the position of China and Vietnam within the global production network and attempts to determine whether the structure of Vietnam’s economy makes it a feasible alternative production location. Since many of the relocating attempts are very recent or still in the planning stages, this thesis should not be understood as an ex-post analysis. This thesis employs multiple methodologies. Firstly, the network analysis which is becoming a popular method for identifying key sectors within economies. Secondly, the hypothetical extraction method and its extension, the global hypothetical extraction method, which is also used to identify key sectors and sectoral linkages but from a different perspective than network analysis. Lastly, the comprehensive trade decomposition that can isolate the components is used to study the value added in exports and participation in the structure of value chains.

The rest of this thesis is organized as follows: Chapter 2 provides background to GVC shock and the possibilities and advantages of relocating to Vietnam, Chapter 3 reviews relevant literature, including some methodologies, Chapter 4 describes data, Chapter 5 presents the methodologies and research questions, Chapter 6 summarizes all results, and Chapter 7 concludes.

2 Background

This chapter describes in more depth the motivation for this thesis and explains why the research topic should be of interest. The first section talks about events that can cause problems for Global Value Chains and what makes some value chains more exposed to these events. The second section first introduces different types of relocation strategies firms employ and the reasons behind them. Then, it highlights the main motivations of companies to relocate to Vietnam.

2.1 Shocks and Disruptions to Global Value Chains

A shock to Global Value Chains is an unexpected event that causes disruption. One must mention the obvious example of the Covid-19 pandemic that the world is yet to fully recover from. Of course, a pandemic is not the only source of a shock to the economy. In their report, Lund et al. (2020) identify four types of disruptions that can affect GVCs: force majeure (such as natural disasters or pandemics), macropolitical (e.g., financial crisis, military conflict, terrorism), malicious actor (e.g., cyberattack, theft) and idiosyncratic shock (e.g., IT outage, supplier bankruptcies).

The world trade has become more interconnected and the value of intermediate goods in trade flows has increased. For illustration, between 2000 and 2020 the export and imports of intermediate goods rose by roughly 20% more than the overall exports and imports.[1] This means that the value chains are becoming more complex and production is separated into more stages. Although some shocks, such as natural disasters, have always existed and had the ability to affect the economy and production, now due to the interconnectedness, shocks can cause ripple effects throughout industries.

The severity of a shock is determined by multiple factors. Firstly, the elasticity of finding a suitable substitute for the affected point is crucial – lower availability of alternative suppliers magnifies the impact of a shock. Then, there is the so-called lead time which indicates how foreseeable the shock is. For example, a military conflict is usually a result of prolonged tensions and thus can be anticipated in

[1] Source: World Bank (World Integrated Trade Solution)

advance. On the other hand, an event like a cyberattack or terrorist attack is much more difficult to predict. How long the disruption lasts and how “contagious” it is also crucial. For example, a hypothetical global military conflict is expected to last for a long time as well as spread across countries and industries. Conversely, a trade dispute (such as the US-China trade war) can also last for a long time but does not necessarily embroil the rest of the world directly into the conflict. Lastly, the severity depends on what part of the economy is affected by the shock – demand, supply, or both. For example, the Covid-19 pandemic affected both simultaneously, but an economic crisis would mostly only hit the demand side. (Lund et al., 2020)

A value chain risk can be thought of as a product of its exposure to shock and its vulnerability. Some value chains are more susceptible to shocks than others – this is referred to as *vulnerability* or *resilience* of value chains. How vulnerable some chains are can be due to the particular industry characteristics or decision-making of firms. Lund et al. (2020) identify five areas of vulnerability: demand planning and inventory management, supplier networks, product complexity, transportation and logistics, and financial fragility. For illustration, these are supplier network structures that can create vulnerability: lack of alternative suppliers, highly interconnected suppliers, multiple layers of suppliers (depth of supplier chain), lack of transparency in deeper layers, suppliers dependent on a small number of customers, and concentration on few or geographically close suppliers.

As mentioned above, one potential issue for GVC resilience arises from geographical concentration. It may sound counterintuitive but globalization led to geographical diversification in some industries (such as aerospace) but to concentration in others (such as communication equipment)[2]. Geographical concentration is largely due to industry clusters being formed which increases the economies of scale of firms. Of course, this is a profitable undertaking but it can lead to so-called bottlenecks if the area of clusters is affected by a shock and production at multiple stages is hindered. (Lund et al., 2020)

One apparent measure that can help shield the production from potential shocks is relocation – more on that in the next section.

[2] Identified by change in Herfindahl-Hirschman index

2.2 Relocation of Production

This section introduces four different types of relocation strategies that businesses can implement. Yet, relocating production is in no way an easy decision-making process for companies as the existing global value chain structure is very complex. Moreover, some value chains are difficult or even impossible to move, for example, industries with high capital investment or industries that rely on natural resources.

Nevertheless, in light of the recent events (Covid-19 pandemic, Russian invasion of Ukraine) production shifting is something to consider. The initial practice is called *offshoring*[3] which is simply transferring activities to a foreign country. Historically, offshoring has been carried out mostly to decrease the cost of labor and access skilled labor.[4] A similar concept is *nearshoring* which is, as the name suggests, relocation to a geographically close country.[5] The advantage of nearshoring for a company is more control, lower coordination costs, and time-to-market reduction. (Piatanesi & Arauzo-Carod, 2019)

The two remaining types of relocation may be considered value-chain risk-reducing practices. *Reshoring* (also *onshoring*, *inshoring*, or *backshoring*) is the transfer of production back to the company's home country (therefore, it is essentially the opposite of offshoring). The Covid-19 pandemic prompted debates about reshoring and, by extension, an increase in self-sustainability as many companies experienced extreme exposure to supply chain disruptions. (Barbieri et al., 2020) Lastly, *friendshoring* is relocating activities to countries or sourcing from countries that share the home country's political and economic values. Like onshoring, friendshoring became a hot topic of debate in response to the pandemic and later to Russia's invasion of Ukraine.

However, some studies warn about the potential downsides of reshoring and friendshoring. Triggs and Hardwick (2022) claim that enhancing supply chain resiliency through reshoring (or as they refer to it – onshoring) is a misbelief since supply chains cannot realistically be fully onshore and will still have inputs from other countries. The authors concede that friendshoring may be an economically

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[3] Not to be confused with *outsourcing* which is a delegation of the production process to an external company.
[4] An example of offshoring is German and Austrian firms moving their production to Eastern Europe in the 1990s (Marin, 2006)
[5] For example, Mexico is an attractive nearshoring destination for the US (Piatanesi & Arauzo-Carod, 2019)

reasonable alternative but they warn that it may forestall regional growth and heighten divisions between countries. Smarzynska Javorcik et al. (2022) estimate that friendshoring could lead to up to a 4.6% loss in global GDP.

Relocating Production from China to Vietnam

At the beginning of 2018, President Trump's administration announced the imposition of tariffs on some imports from China. The retaliation from the Chinese side did not take long and the two largest world economies found themselves amidst a "tariff war". At its most critical point, in September 2019, the imposed US tariffs on Chinese goods covered 93% of Harmonized System products, while tariffs on US imports affected 84.3% of products. (Chor & Li, 2021)

As mentioned above, the Covid-19 crisis was another hit to supply chains and China's manufacturing sector suffered greatly due to the zero-Covid policy strategy which shut down many factories and caused logistical issues in transportation and ports which resulted in significant delays.

In response, some companies, have gone public with their plans for moving part of their production from China to other countries, especially Vietnam, as is reflected in the name of this thesis. For example, in a recent article, Forbes informs about Apple's intention of diversifying their supply chains by producing MacBooks in Vietnam[6]. (Q.ai - Powering a Personal Wealth Movement, 2023) According to the article, Apple has for a long time relied solely on Chinese manufacturing which led to several supply chain disruptions during the Covid-19 pandemic.

Samsung is another tech company that has taken a great interest in Vietnam's manufacturing possibilities. In recent years, Samsung has already shifted a large portion of its electronics manufacturing from China to Vietnam and is one of the biggest FDI sources for Vietnam's economy. (Sheldon & Kwon, 2023)

Japanese firms have also invested in producing in Vietnam, partially due to government subsidies aimed at reducing dependence on China. According to a survey by the Japanese External Trade Organization (JETRO), Vietnam is a top target region for Japanese businesses for expansion. (Hoang, 2023)

[6] This is following a recent partial relocation of iPhone production to India.

Apart from supply chain diversification and decreasing dependence on China, relocation to Vietnam has other potential advantages. An overview in Vietnam Briefing identifies multiple drivers for relocation to Vietnam. Firstly, Vietnam exhibits relatively high and stable GDP growth. In the five years before the pandemic, the GDP grew annually by roughly 7%[7]. Of course, it slowed down during the pandemic but recovered quickly – according to World Bank, Vietnam's GDP grew by 8% in 2022. Secondly, Vietnam has a large working-age population and very high female labor force participation[8]. Thirdly, Vietnam has a one-party political regime that can facilitate a stable business environment[9]. Lastly, since Vietnam acceded to the World Trade Organization (WTO) in 2007, it has entered many Free Trade Agreements (FTAs) and Double Taxation Avoidance Agreements (DTAAs). (Pritesh, n.d.)

The cost of labor is another factor to consider. According to Statista[10], in 2020, the manufacturing cost of labor per hour for China was $6.5, while for Vietnam, it was only $2.99.

It is worth mentioning that while China and Vietnam share the same political ideology (they are both communist regimes), their present-day relations are not ruled by a sense of camaraderie but rather an economic pragmatism, as their worldviews have diverged significantly. Despite maintaining economic interdependence, Vietnam is very cautious of its sovereignty due to historical conflicts. (Thanh Hai, 2021) Therefore, it is reasonable to assert that Vietnam can indeed potentially serve as a counterweight to China.

[7] Source: World Bank
[8] 69.1% according to World Bank (higher than China, Japan or South Korea)
[9] In 1986, Vietnam's communist party abandoned the central planning model typical for socialist regimes and decided to adopt a reform called *Doi Moi*. Its objective was to create a "market-oriented socialist economy under state guidance". (Beresford, 2008)
[10] https://www.statista.com/statistics/744071/manufacturing-labor-costs-per-hour-china-vietnam-mexico/

3 Literature review

The first part of this chapter introduces the concept of global value chains and how they emerged, as well as their governance and industrial upgrading. The subsequent sections focus on literature relevant to the empirical part of this thesis. The second section discusses the construction and mathematical logic of the input-output model, covering both the traditional Leontief model and its alternative – the Ghosh model. The third section is devoted to the analysis of sectoral linkages and the identification of key sectors through hypothetical extraction and tools from network analysis. Lastly, section 3.4 talks about the approach to the decomposition of global value chains. Throughout this chapter, the notation is kept as presented by original authors, unless specified otherwise.

3.1 Global Value and Global Supply Chains

Value-added chain (or simply *value chain*) describes a journey of a product or service throughout all production stages at which value is added to it. The term value chain was first used in business management by Michael Porter in 1985 which was later translated also into the field of economics. Porter (1985) believed that businesses should focus on production stages in which they had a comparative advantage and preferably outsource other activities. Gereffi and Kaplinsky (2001) coined the term *global* value chains (GVCs) and also define an important distinction between GVCs and another closely related concept, global *supply* chains (GSCs). GSCs describe the input-output structure of all the processes leading to the final creation of products and how they are eventually brought to a customer, while GVCs determine the relative value that each process adds to the intermediate good in order to satisfy the end consumer. In theory, the terms global value chain and global supply chain should not be used completely interchangeably but in reality, many authors use them essentially as synonymous, as their activities overlap to a large extent.

Investigating GVCs has been an integral part of world trade research in recent years with the increase in globalization. Many important organizations such as OECD, World Trade Organization (WTO), and World Bank have been investing in research and contributing to the literature with various reports and analyses (e.g., the exhaustive Global Value Chain Development Report series by WTO).

3.1.1 The Emergence of Global Supply Chains

Baldwin (2012) describes two main stages of economic globalization which led to the evolution of global supply chains. The author calls them the first and second unbundling[11]. Before world globalization, transporting goods was a risky and costly process, and therefore communities would mostly only consume what they produced.

The beginning of the first unbundling is associated with advancements in steam power and the production of iron and steel which facilitated the transportation of goods over greater distances. Baldwin (2012) identifies five circumstances that characterize this period. First, Europe, North America, and Japan (the "North") became more industrialized while the countries like China and India (the "South") de-industrialized. Second, steam power had a great impact on trade costs making production at larger scales profitable which led to further innovation. Third, due to innovation and the scales of production, the incomes of the North and South diverged dramatically. Fourth, the world saw expansion in international trade and migration due to the low costs of transportation. Last, because coordinating large-scale production entails additional costs, the production became, paradoxically, more concentrated due to its complexity.

The second unbundling has to do with the advancement in information and communications technology (ICT) in the mid-1980s. ICT made it possible for the complex processes to be coordinated from anywhere in the world and due to the income differences mentioned above, it became profitable to move production to lower-income areas. Again, Baldwin (2012) connects five facts to the second unbundling. First, the divergence of income was reversed when emerging economies industrialized. Second, the trend of industrialization was also reversed – the North became less industrialized and the South more. Third, there was a significant increase in trade in components, international investment, coordination of production, and the international flow of know-how. Fourth, countries were no longer forced to build their own supply chains as they could simply join the

[11] In this context unbundling is to be understood as separation of production processes and consumption.

established structure. Last, the world economy became more liberalized in terms of trade and investment policies which led to expansion in regional trade agreements (RTAs)[12].

3.1.2 Global Value Chains Governance and Upgrading

The GVC framework is used to analyze the economy from two points of view: top-down and bottom-up. The top-down approach relates to the *governance* of global value chains and the bottom-down approach uses the concept of *upgrading*. (Gereffi, 2011)

Governance of global value chains focuses on large firms with industry power and how they can affect global production and the activities of other actors within the chain. Gereffi et al. (2005) establish five forms of global value chain governance that describe how these firms exercise their power. The type with the lowest degree of explicit coordination and power asymmetry is called *market* governance in which suppliers make goods without too much coordination with buyers (switching to a new partner is relatively easy) and the governance mechanism is the price of goods. The other extreme with the highest degree of coordination and power asymmetry is called *hierarchical* governance with full vertical integration where lead firms produce their goods in-house and the governance mechanism is managerial control. The types between these two extremes are *modular*, *relational,* and *captive* governance. For a complete overview, see Gereffi et al. (2005). It is important to note that the type of governance in the market is not identical across all value chains or even the stage of the value chain, it depends on the distribution of power among the firms at a given point. (Gereffi & Lee, 2012)

Industrial upgrading is a process "by which economic actors – nations, firms, and workers – move from low-value to relatively high-value activities in global production networks" (Gereffi, 2011, p. 45) and it is a direct consequence of global outsourcing (a process combining outsourcing and offshoring that began in the 1970s). Humphrey and Schmitz (2002) identify four types of upgrading: *process upgrading* (organizing the production in a more efficient way), *product upgrading* (switching to more sophisticated products within the same industry), *functional upgrading* (finding new functions to improve activities), and *inter-sectoral*

[12] To put this information into perspective, there were 22 RTAs in force in 1990 and there are 360 currently. (source: https://rtais.wto.org/UI/PublicMaintainRTAHome.aspx)

upgrading (switching to more productive but related industries). If a firm engages in intersectoral upgrading, it can contribute to the creation of new (global) value chains. If this is executed in the early stages, the firm can gain an advantageous position within the chain that provides it with a significant proportion of the overall value added.

3.2 Input-output analysis

Years before Wassily Leontief[13] developed his input-output analysis framework used so extensively nowadays, an 18th-century French economist, Francois Quesnay[14], introduced the idea of circular flows of income and output among sectors in the economy. He depicted this notion in what he called Tableau Économique – a diagram through which one can trace the expenditures in the economy. Although his work did not include mathematical formalization and did not take into account the idea of value being added throughout the production stages, it inspired others to further build upon his ideas. Notably, Achille-Nicolas Isnard[15] found a way to represent this circular flow as a system of algebraic equations and denoted the surplus as “disposable wealth”. Nearly a century later, influenced by Isnard’s work, León Walras[16] developed the basics of general equilibrium theory. Building upon Quesnay and Walras, Leontief presented his own input-output framework in 1936. (Miller & Blair, 2009)

3.2.1 Leontief Input-Output Model and Matrix

The input-output model comprises data for a given area (usually a country) whose economic activity is separated into sectors (or industries, henceforth used interchangeably). These data must include the flows (usually in monetary terms) of goods between all sector pairs in a given time period (typically a year). (Miller & Blair, 2009)

The values of transactions from sector i to sector j are commonly denoted as z_{ij} and they represent the intermediate demand. Intuitively, the demand of sector j for the input from sector i is related to the output of sector j. Additionally, sectors also produce goods to meet the demand of external buyers, for example, households, and

[13] W. Leontief was awarded the Nobel Prize in Economics for the development of the model.
[14] In 1758
[15] In 1781
[16] In 1874

these goods are then typically used as such and not as inputs for further production. Therefore, it is denoted as a final demand. Now, let x_i be the total sectoral output of i and f_i the final demand for its product. Then we can write the equation summarizing the output of sector i in an n-sector economy as:

$$x_i = \sum_{j=1}^{n} z_{ij} + f_i \tag{3.1}$$

The equation can be also expressed using matrix notation. Let **x** and **f** be column vectors of output and final demand for sectors 1 to n, respectively, **Z** a matrix of intermediate demands (or intersectoral trade flows), and **i** is a $(n \times 1)$ a column vector (oftentimes referred to as summation vector):

$$\mathbf{x} = \begin{bmatrix} x_1 \\ \vdots \\ x_n \end{bmatrix}, \mathbf{Z} = \begin{bmatrix} z_{11} & \cdots & z_{1n} \\ \vdots & \ddots & \vdots \\ z_{n1} & \cdots & z_{nn} \end{bmatrix} \text{ and } \mathbf{f} = \begin{bmatrix} f_1 \\ \vdots \\ f_n \end{bmatrix} \tag{3.2}$$

Then Equation (3.1) in matrix notation is specified as

$$\mathbf{x} = \mathbf{Zi} + \mathbf{f} \tag{3.3}$$

A generalized form of an interindustry input-output table is presented in Table 3.1. The columns and rows represent the sector's inputs and outputs, respectively. Hence the name "input-output table". (Miller & Blair, 2009)

Table 3.1: Input-Output Table of Interindustry Flows

		Buying Sector				
		1	$\cdots$	j	$\cdots$	n
Selling Sector	1	z_{11}	$\cdots$	z_{1j}	$\cdots$	z_{1n}
	$\vdots$	$\vdots$		$\vdots$		$\vdots$
	i	z_{i1}	$\cdots$	z_{ij}	$\cdots$	z_{in}
	$\vdots$	$\vdots$		$\vdots$		$\vdots$
	n	z_{n1}	$\cdots$	z_{nj}	$\cdots$	z_{nn}

Source: Miller and Blair (2009)

To get to a full specification of the Leontief model, the exact relationship between the inputs and outputs must be specified. In other words, we want to know how much of an input is needed to produce one unit of output. Essentially, it is a ratio of the input of sector i bought by sector j to the output of sector j, and it is denoted as a_{ij}:

$$a_{ij} = \frac{z_{ij}}{x_j} \tag{3.4}$$

This ratio is called the technical (or input) coefficient and it is implicitly constant (Leontief model assumes constant returns to scale). Therefore, the proportions of inputs are also fixed. (Miller & Blair, 2009)

With the understanding of technical coefficients, Equation (3.1) can be rewritten as

$$x_i = \sum_{j=1}^{n} a_{ij}x_j + f_i \tag{3.5}$$

To express Equation (3.5) in matrix form, the summation needs to be disintegrated and all the x terms are brought to the left side of the equation. Then, the x_i the term is factored out for the i-th equation:

$$\begin{aligned}
&(1 - a_{11})x_1 - \cdots - a_{1i}x_i - \cdots - a_{1n}x_n = f_1 \\
&\quad\vdots \\
&- a_{i1}x_1 - \cdots + (1 - a_{ii})x_i - \cdots a_{in}x_n = f_i \\
&\quad\vdots \\
&- a_{n1}x_1 - \cdots a_{ni}x_i - \cdots + (1 - a_{nn})x_n = f_n
\end{aligned} \tag{3.6}$$

The vector $\mathbf{x}$ can be expressed in matrix form as $\hat{\mathbf{x}} = \begin{bmatrix} x_1 & \cdots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \cdots & x_n \end{bmatrix}$. Using the definition of the inverse matrix, $(\hat{\mathbf{x}})(\hat{\mathbf{x}})^{-1} = \mathbf{I}$, therefore $(\hat{\mathbf{x}})^{-1} = \begin{bmatrix} \frac{1}{x_1} & \cdots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \cdots & \frac{1}{x_n} \end{bmatrix}$.

Now, the technical (or input) coefficient $(n \times n)$ matrix is defined as

$$\mathbf{A} = \mathbf{Z}(\hat{\mathbf{x}})^{-1} \tag{3.7}$$

The Equation (3.5) can be expressed in matrix form by combining (3.2) and (3.7) as

$$\mathbf{x} = \mathbf{A}\mathbf{x} + \mathbf{f} \quad (3.8)$$

Let $\mathbf{I}$ be an $(n \times n)$ identity matrix. Then the system of Equations (3.8) is also expressed as

$$(\mathbf{I} - \mathbf{A})\mathbf{x} = \mathbf{f} \quad (3.9)$$

If $|\mathbf{I} - \mathbf{A}| \neq 0$, then $(\mathbf{I} - \mathbf{A})^{-1}$ exists and

$$\mathbf{x} = (\mathbf{I} - \mathbf{A})^{-1}\mathbf{f} = \mathbf{L}\mathbf{f} \quad (3.10)$$

where $\mathbf{L}$ is the *Leontief inverse* matrix and it embodies how much output must be produced in order to meet the final demand. (Raa, 2005)

The final step towards understanding the full structure of real-world I-O databases is incorporating the idea of multiple regions whose sectors can interact with each other.

To illustrate the composition, we assume that the I-O table represents two regions (r and s) with sectors i and j in each[17], as presented by Miller and Blair (2009). However, it can be easily extended to any number of regions and sectors. For the construction of the table, one needs information about intraregional (from r to r) and interregional (from r to s) flows of goods to fill the $\mathbf{Z}$ matrix. In the case of multiple regions, this matrix consists of four sub-matrices: $\mathbf{Z}^{rr} = [z_{ij}^{rr}]$, $\mathbf{Z}^{ss} = [z_{ij}^{ss}]$, $\mathbf{Z}^{rs} = [z_{ij}^{rs}]$ and $\mathbf{Z}^{sr} = [z_{ij}^{sr}]$. The full intersectoral flows matrix can then be expressed as

$$\mathbf{Z} = \begin{bmatrix} \mathbf{Z}^{rr} & \mathbf{Z}^{rs} \\ \mathbf{Z}^{sr} & \mathbf{Z}^{ss} \end{bmatrix} \quad (3.11)$$

Assuming, the information about the gross outputs of sectors ($\mathbf{x}^r = [x_i^r]$ and $\mathbf{x}^s = [x_i^s]$) is also available, the technical coefficients can be derived:

$$a_{ij}^{rr} = \frac{z_{ij}^{rr}}{x_j^r}, a_{ij}^{ss} = \frac{z_{ij}^{ss}}{x_j^s}, a_{ij}^{rs} = \frac{z_{ij}^{rs}}{x_j^s}, a_{ij}^{sr} = \frac{z_{ij}^{sr}}{x_j^r} \quad (3.12)$$

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[17] Similar example is briefly presented in Chapter Data to illustrate the structure of OECD ICIO database.

where a_{ij}^{rr} and a_{ij}^{ss} represent the intraregional technical coefficients, and a_{ij}^{rs} and a_{ij}^{sr} the interregional input coefficients. Similar to the flows matrix $\mathbf{Z}$, the full technical coefficient matrix is then given by

$$\mathbf{A} = \begin{bmatrix} \mathbf{A}^{rr} & \mathbf{A}^{rs} \\ \mathbf{A}^{sr} & \mathbf{A}^{ss} \end{bmatrix} \tag{3.13}$$

Therefore, using the same mathematical operations described by Equations (3.6) to (3.9), the system is expressed as

$$\mathbf{x} = (\mathbf{I} - \mathbf{A})^{-1}\mathbf{f} \tag{3.14}$$

where $\mathbf{x} = \begin{bmatrix} \mathbf{x}^r \\ \mathbf{x}^s \end{bmatrix}$, $\mathbf{f} = \begin{bmatrix} \mathbf{f}^r \\ \mathbf{f}^s \end{bmatrix}$ and $\mathbf{I} = \begin{bmatrix} \mathbf{I} & \mathbf{0} \\ \mathbf{0} & \mathbf{I} \end{bmatrix}$.

3.2.2 Ghosh Input-Output Model

The previous section described the Leontief model which is sometimes referred to as the demand-driven I-O model since the Leontief inverse matrix provides information about the amount of output needed to satisfy the final demand.

In 1958, Ghosh developed an alternative to the demand-driven model which can be applied to the same data but instead of relating the output with final demand, it looks at the connection between output and primary inputs. Miller and Blair (2009) define it as transposed Leontief model. The following section derives the model according to Miller and Blair (2009).

The output of sector j in an n-sector economy can be written as

$$x_j = \sum_{i=1}^{n} z_{ij} + v_j \tag{3.15}$$

Then, the transposed form or Equation (3.3) is

$$\mathbf{x}' = \mathbf{Zi}' + \mathbf{v}' \tag{3.16}$$

where $\mathbf{v}'$ is a row vector of total value-added expenditures for all sectors. In the Leontief model, the matrix $\mathbf{Z}$ of interindustry flows was used to calculate the technical coefficients by diving its columns by output. Since the Ghosh model can be thought of as transposed Leontief, it is now the *rows* of $\mathbf{Z}$ that are divided by output, not columns. The coefficients obtained from this division are no longer called technical coefficients, but *direct-output* or *allocation* coefficients, b_{ij}. The result is direct-output (allocation) coefficient matrix $\mathbf{B} = \left[b_{ij}\right]$. In a simplified two-sector economy:

$$\mathbf{B} = \begin{bmatrix} z_{11}/x_1 & z_{12}/x_1 \\ z_{21}/x_2 & z_{22}/x_2 \end{bmatrix} = \begin{bmatrix} 1/x_1 & 0 \\ 0 & 1/x_n \end{bmatrix} \begin{bmatrix} z_{11} & z_{12} \\ z_{21} & z_{22} \end{bmatrix} = (\hat{\mathbf{x}})^{-1}\mathbf{Z} \qquad (3.17)$$

Now, combing Equations (3.16) and (3.17) gives

$$\mathbf{x}' = \mathbf{x}'\mathbf{B} + \mathbf{v}' \qquad (3.18)$$

since $\mathbf{Z} = \hat{\mathbf{x}}\mathbf{B}$ and $\mathbf{i}'\hat{\mathbf{x}} = \mathbf{x}'$.

Then

$$\mathbf{x}' = \mathbf{v}'(\mathbf{I} - \mathbf{B})^{-1} = \mathbf{v}'\mathbf{G} \qquad (3.19)$$

where $\mathbf{G}$ is the *Ghosh inverse* (or *output inverse*) matrix.

Similar to the Leontief model, where the technical coefficients were assumed to be constant, the allocation coefficients in the Ghosh model are subject to the same assumption.

The Ghosh model was subjected to a lot of criticism. Most notably, Oosterhaven (1988) questions the model's plausibility by pointing out that if the value added in sector i increases, the output of all other sectors is automatically increased as well but without any increases in primary inputs.

Dietzenbacher (1997) proposes an alternative interpretation of the Ghosh model as a *price* model (instead of a *quantity* model) that can overcome the criticism. A price model extends the traditional model by incorporating the prices of inputs and outputs. Therefore, the model becomes plausible since if the value added in sector i increases, all prices, and hence, output values will increase as well. An input-output price model is used for analyzing cost pushes, such as changes in input prices.

3.2.3 Relationship between Leontief and Ghosh models

This subsection shortly introduces the relations between the coefficient matrices, **A** and **B**, and, by extension, the relations between the two models. As above, this section follows Miller and Blair (2009).

The relationship between **A** and **B** is obtained by combing Equations (3.7) and (3.17):

$$\mathbf{A} = \hat{\mathbf{x}}\mathbf{B}\hat{\mathbf{x}}^{-1} \text{ or } \mathbf{B} = \hat{\mathbf{x}}^{-1}\mathbf{A}\hat{\mathbf{x}}^{18} \quad (3.20)$$

Incorporating the identity matrix, we get

$$(\mathbf{I} - \mathbf{A}) = \mathbf{I} - \hat{\mathbf{x}}\mathbf{B}\hat{\mathbf{x}}^{-1} \quad (3.21)$$

which can be rearranged to

$$(\mathbf{I} - \mathbf{A}) = \hat{\mathbf{x}}(\mathbf{I} - \mathbf{B})\hat{\mathbf{x}}^{-1} \quad (3.22)$$

since $\mathbf{I} = \hat{\mathbf{x}}\mathbf{I}\hat{\mathbf{x}}^{-1}$.

Inversing[19] both sides of Equation (3.22):

$$(\mathbf{I} - \mathbf{A})^{-1} = \hat{\mathbf{x}}(\mathbf{I} - \mathbf{B})^{-1}\hat{\mathbf{x}}^{-1} \quad (3.23)$$

And finally substituting **L** and **G:**

$$\mathbf{L} = \hat{\mathbf{x}}\mathbf{G}\hat{\mathbf{x}}^{-1} \text{ or } \mathbf{G} = \hat{\mathbf{x}}^{-1}\mathbf{L}\hat{\mathbf{x}} \quad (3.24)$$

Although one intuitively understands that the Leontief and the Ghosh models are two sides of the same coin, this section proves it mathematically.

3.3 Industry Linkages and Key Sector Analysis

Identifying key sectors and measuring industry linkages has been a focus for many researchers, especially with the increasing availability and coverage of Input-Output

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[18] Note that $\hat{\mathbf{x}}$ is a matrix, not a vector. See page … for full specification.
[19] The inverse of product of three matrices is defined as $(\mathbf{ABC})^{-1} = \mathbf{C}^{-1}\mathbf{B}^{-1}\mathbf{A}^{-1}$

tables[20]. This section introduces the idea of sectoral linkages which constitute the traditional approach to identifying key sectors. Next, the hypothetical extraction method is introduced in which a sector is artificially removed from the economy and the overall loss in output is evaluated. Lastly, this section talks about network centrality and how this framework can be applied to identify key sectors of the economy.

3.3.1 Linkages in I-O models

The previous section explains that the sectors in the economy are connected through flows of inputs and outputs. Therefore, a given sector j influences other sectors if its demand for inputs or supply of outputs changes. The connections from sector j to sectors that provide it with inputs (upstream sectors) are called backward linkages and they appear in the demand-driven model. Conversely, in a supply-driven model, sector j provides inputs to other sectors (downstream sectors) through forward linkages. It should now be apparent that the elements of the Leontief model presented in section 3.2.1 are better suited for calculating the backward linkages, while the Ghosh model from section 3.2.2 is more appropriate for studying the forward linkages (Miller & Blair, 2009)

The total backward linkage indicator for sector j in an n-sector economy is defined as

$$BL(t)_j = \sum_{j=1}^{n} l_{ij} \quad (3.25)$$

where l_{ij} are the elements of $\mathbf{L}$ matrix.

Similarly, the total forward linkage indicator is

$$FL(t)_j = \sum_{j=1}^{n} g_{ij} \quad (3.26)$$

where g_{ij} are the elements of $\mathbf{G}$ matrix.

[20] More details in Chapter Data

Generally, the indicators are calculated in a normalized form – a value smaller than 1 indicates a low connection to other sectors, and vice versa for values higher than 1. Once both backward and forward linkages of sector j are calculated, conclusions about its interconnectedness can be drawn: it can be independent of other sectors (both linkages smaller than 1), dependent on other sectors (both linkages higher than 1), dependent on supply (backward linkage higher than 1) and dependent on demand (forward linkage higher than one).

Although more sophisticated frameworks have been developed, this traditional linkage method is still used in literature. For example, Ali et al. (2019) study the performance of the construction industry in developing economies and use the backward and forward linkages to examine the demand push a supply pull effects. They also use HEM, which is described in the next section, in their analysis.

3.3.2 Hypothetical Extraction Method

The hypothetical extraction method (HEM) was first proposed by Paelnick et al. (1965) to measure the effect on the total output of the economy if a given sector was extracted from it. In an I-O model, this is done by deleting the row and column, say j, from the technical coefficient matrix $\mathbf{A}$, resulting in a new $(n-1) \times (n-1)$ coefficient matrix $\bar{\mathbf{A}}_{(j)}$, and a new final demand vector $\bar{\mathbf{f}}_{(j)}$. Then the output of the reduced economy is $\bar{\mathbf{x}}_{(j)} = \left[\mathbf{I} - \bar{\mathbf{A}}_{(j)}\right]^{-1}\bar{\mathbf{f}}_{(j)}$. The loss in output generated by the removal of sector j is found as $T_j = \mathbf{i}'\mathbf{x} - \mathbf{i}'\bar{\mathbf{x}}_{(\mathbf{j})}$ and it is the total linkage of sector j. The same logic can be applied to calculate the backward and forward linkages. For backward linkages, only the column j is extracted from $\mathbf{A}$, and for forward linkages, the row j is extracted from matrix **B.**

HEM is a popular method for identifying key sectors and industry linkages and has been used to answer a variety of research questions. For example, Duarte et al. (2002) exploit HEM for their environmental analysis of water use by Spanish production sectors. Similarly, Sajid et al. (2019), studied inter-sectoral carbon linkages in the Turkish economy using the demand-driven model for backward linkages and the supply-driven model for forward linkages. Song and Liu (2006) measure the linkages of the construction sector to other sectors in national economies using OECD input-output database and they, too, focus on both backward and forward linkages.

3.3.3 Global Hypothetical Extraction Method

All studies mentioned in the previous section explore the linkages on a national level. This reflects one great disadvantage of HEM – it can only be applied to national input-output tables with the assumption[21] that the extracted sector would be substituted by additional imports from other economies. (Miller & Lahr, 2001) This logic cannot be translated into a global setting since there are no "outside" economies available anymore. Similarly, it is not feasible to assume that if country A stops exporting, then country B, which previously imported from country A, will be able to miraculously produce the same amount of output as before the disruption in supply. As a remedy, Dietzenbacher et al. (2019) propose an alternative to HEM, calling it the global extraction method (GEM), in which the extracted sector is to be replaced by the rest of the system itself, i.e., other countries that previously exported will export proportionally more.

Dietzenbacher et al. (2019) present a scenario with *N* countries and *n* industries (sectors)[22]. The model is defined by

$$\mathbf{Z} = \begin{bmatrix} \mathbf{Z}^{11} & \cdots & \mathbf{Z}^{1N} \\ \vdots & \ddots & \vdots \\ \mathbf{Z}^{N1} & \cdots & \mathbf{Z}^{NN} \end{bmatrix}, \mathbf{F} = \begin{bmatrix} \mathbf{f}^{11} & \cdots & \mathbf{f}^{1N} \\ \vdots & \ddots & \vdots \\ \mathbf{f}^{N1} & \cdots & \mathbf{f}^{NN} \end{bmatrix}, \mathbf{x} = \begin{bmatrix} \mathbf{x}^{1} \\ \vdots \\ \mathbf{x}^{N} \end{bmatrix}, \mathbf{v} = \begin{bmatrix} \mathbf{v}^{1} \\ \vdots \\ \mathbf{v}^{N} \end{bmatrix} \quad (3.27)$$

where $\mathbf{Z}$ is $Nn \times Nn$ matrix of intersectoral flows, $\mathbf{F}$ is $Nn \times N$ matrix of final demands, $\mathbf{x}$ and $\mathbf{v}$ are Nn-element vectors of output and value added, respectively.

The technical coefficient matrix $\mathbf{A}$ is obtained in the same way as in Equation (3.7). Therefore, $\mathbf{A}^{RS} = \mathbf{Z}^{RS}(\hat{\mathbf{x}}^{\boldsymbol{S}})^{-\mathbf{1}}$ contains the technical coefficients for transactions from country R to country S. The final demand Nn-element vector is given by $\mathbf{f} = \mathbf{Fi}$ ($\mathbf{f}^{\mathrm{R}} = \sum_{S=1}^{N} \mathbf{f}^{\mathrm{RS}}$).

Now, assume that an industry *k* of country *H* (*k-H*) is extracted:

$$\bar{a}_{kj}^{HS} = \bar{a}_{ik}^{TH} = 0 \ \forall i, j, \forall S, T \quad (3.28)$$

$$\bar{f}_{k}^{HS} = 0 \ \forall S \quad (3.29)$$

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[21] This assumption was applied for example by Song, Y., Liu, C., & Langston, C. (2006). Linkage measures of the construction sector using the hypothetical extraction method. Construction management and Economics, 24(6), 579-589.

[22] In this scenario, an industry *n* within a country *N* is denoted as *n-N.* All other combinations of lowercase and capital letters are analogous.

Following this logic, *k-H* does not buy or sell, therefore both the industries and final users that previously purchased from *k-H* now need to find another source of *k*. In the case that purchasing industry is also from country *H*, the solution is to buy more *k* from the remaining sources, proportionally to the original distribution. For example, suppose that industry *m* in country *H* (*m-H*) was purchasing 50%, 25%, and 25% of *k* from *k-H* and two other sources, respectively. According to GEM, once the *k-H* industry is extracted, *m-H* will buy double (50% and 50%) from the other two sources in order to get 100% of inputs. Nevertheless, if the purchasing industry is from a country other than *H*, say *F*, it is not possible to redistribute in the same way since there is a logical assumption that *k-F* is already selling to industry *m* in country *F* at full capacity and therefore the redistribution must happen among the rest of the sources. Again, to give an example, suppose *m-F* was purchasing 50% of inputs from *k-F*, 25% from *k-H*, and 25% from other sources, then following the extraction of *k-H*, *m-F* will adjust (double) only its purchases from the other source and get 100% of inputs. The same logic is applied to replace the final demand.

These assumptions expressed mathematically are

$$\bar{a}_{kj}^{TS} = a_{kj}^{TS} + a_{kj}^{HS} \frac{a_{kj}^{TS}}{\sum_{R \neq H,S} a_{kj}^{RS}} \;\; \forall j, \forall S, \forall T \neq H, S \tag{3.30}$$

$$\bar{f}_k^{TS} = f_k^{TS} + f_k^{HS} \frac{f_k^{TS}}{\sum_{R \neq H,S} f_k^{RS}} \;\; \forall S, \forall T \neq H, S \tag{3.31}$$

The calculation of the extraction effect in GEM is equivalent to HEM. The output loss for country *T* is given by $\mathbf{i}'\mathbf{x}^T - \mathbf{i}'\bar{\mathbf{x}}^T$.

GEM is a relatively new concept and the present writer did not find many studies that exploit it. However, Reiter and Stehrer (2021) employ GEM in their analysis of vulnerable sectors in the context of the Covid-19 pandemic to evaluate the effect of the EU's re-shoring of risky imports along global value chains. Maeno et al. (2022) extend the framework to extract sectors with high CO_2 emissions from the automotive supply chain to analyze possibilities of CO_2 mitigation.

3.3.4 Network Analysis and Centrality Measures

Network analysis, oftentimes referred to as structural analysis, is a tool used to examine and visualize the structure of a certain network. This network can be any type of dataset in which the actors interact with each other, for example, social media networks. Structural analysis has been used in many fields to study various problems, such as the spread of Covid-19 or the cryptocurrency market.

Every network is comprised of nodes and edges. The nodes represent the actors, and the edges show how interconnected they are. Such a network can also be represented by an adjacency matrix $\mathbf{A} = (a_{ij}) \in \{0;1\}^{n \times n}$ where a_{ij} is the edge (linkage) between nodes i and j, and $a_{ij} = 1$ if node i and j are linked, and 0 otherwise. (Landherr et al., 2010)

Visualizing the network itself and identifying important nodes are the two main purposes of structural analysis. The position of a node within the network can be determined by so-called centrality measures.

There are several measures that help us determine the importance of a given node, for example, it can be even directly observed from the graph (if it is simple enough) – the more edges a node has, the more integral it is in the network. This measure is called *degree centrality* and it is very easy to calculate and interpret, however, it may not provide accurate information about how central a node is since it does not take into account the topological distances from other nodes. (Sikos & Meirmanova, 2020)

Formally, normalized degree centrality can be expressed as

$$C_D(i) = \frac{d(i)}{n-1} \tag{3.32}$$

where $d(i)$ is the degree of a node i and it holds that $d(i) = \sum_{j \neq i} a_{ij}$.

One important characterization for the networks is whether they are undirected, i.e. any link between two nodes is taken into account, or directed in which only outward or inward linkages are considered. For such cases, we must further specify the components of the adjacency matrix as ${a_{ij}}^{in}$ and ${a_{ij}}^{out}$. It is also important to distinguish between unweighted networks which simply inform about a (non)existence of an edge, and weighted networks which also measure the significance of an edge. Therefore, it is no longer possible to simply use the adjacency matrix in Equation (3.32); we must use a weighted matrix w_{ij} which contains information about the strength of the edges.

Since the structure of the input-output tables can be understood as weighted (the amount of intermediate goods in $ transferred among the sectors) and directed (goods imported vs goods exported) GVC networks, weighted *total degree*, *in-degree* and *out-degree centralities* can be calculated.

Another centrality measure is *closeness centrality* which indicates how a node can be reached by all other nodes. (Golbeck, 2013) Therefore, this closeness centrality takes into account all nodes in the network, as opposed to degree centrality which only accounts for neighboring nodes.

It can be expressed as

$$C_C(i) = \frac{n-1}{\sum_{j \neq i} d_{ij}} \tag{3.33}$$

where d_{ij} is the length of the shortest path between nodes i and j.

To examine the importance of a node in connecting other nodes, i.e. how many shortest paths connecting two nodes are going through it, *betweenness centrality* is to be applied.

The betweenness centrality of a node i can be expressed as

$$C_B(i) = \sum_{j \neq i \neq k} \frac{p_{jk}(i)}{p_{jk}} \tag{3.34}$$

where $\sum_{j \neq i \neq k} p_{jk}(i)$ is the number of shortest paths passing through node i, and $\sum_{j \neq i \neq k} p_{jk}$ is the total number of all shortest paths. Dijkstra (1959) proposed an algorithm to find the shortest path which accounts for the weights of shortest paths and can also be applied to directed networks. For more information about Dijkstra's algorithm, see Newman (2008), Chapter 10.

Lastly, we turn to eigenvalue-based centralities. *Eigenvector centrality* is a concept similar to degree centrality but it takes into account the importance of connected nodes – the more significant connections a node has, the higher its eigenvector centrality. (Newman, 2008) Therefore, it may be the case that a node has a high degree centrality but low eigenvector centrality if it has a high number of less significant connections.

However, eigenvector centrality is not ideal for directed networks since the adjacency matrix is not symmetric and therefore yields two sets of eigenvectors (left and right) and neither provides accurate results unless the matrix is strongly connected. This issue can be addressed by *Katz centrality* which gives each node a small, constant centrality guaranteeing that nodes with zero in-degree do not cause the connected nodes to have zero centrality. Unfortunately, even Katz centrality is not completely infallible since a large number of nodes may be connected to one very "central" node which assigns them a very high centrality also. Their relative importance is then amplified. (Newman, 2010) For these reasons, this thesis opts for a variation of Katz centrality called *PageRank centrality*.

PageRank which was originally developed by Google to estimate the importance of a website by the number of other webpages linked to it. Brin and Page (1998) define the PageRank centrality of a node (website) i as an algorithm[23]:

$$PR(i) = (1-d) + d\left(\sum_{j=1}^{n} \frac{{a_{ji}}^{out} PR(j)}{C(j)}\right) \tag{3.35}$$

where ${a_{ji}}^{out}$ equals 1 whenever there is an outward linkage from node j to node i, 0 otherwise, and $PR(j)$ represents the PageRank centrality of a node j. The reason why PageRank is preferred to Katz is the variable $C(j)$ - the number of outward linkages (out-degree) of node j – which ensures that only a portion of the node's centrality is passed down to other nodes. Parameter d is called a damping factor and it ensures that the algorithm does not terminate when a node with no outward linkages is reached.

Cerina et al. (2015) find that PageRank centrality is a robust method for accurately identifying key sectors in the economy. PageRank centrality is somewhat less intuitive than the previous centrality measures. Adarov (2021) explains that:

> PageRank centrality conveys the probability that a random shock originating anywhere in the network and traveling through the network from one node to another via adjacent linkages (with the higher probability of choosing the linkage with a higher weight), will arrive at a given node in a given time. (p. 24)

[23] Partially redefined by author to better fit previously used notation.

There are multiple recent studies applying network analysis to I-O tables since their structure can be understood as GVC networks in which the country-sectors represent the nodes and intermediate inputs represent the edges. Adarov (2021) uses network analysis, in particular degree centrality and PageRank centrality, to examine the position of CESEE[24] countries and their sectors in GVCs. Similarly, Wang et al. (2021) apply PageRank to Chinese regional input-output tables to rank province-sectors by their influence. Zhang et. al (2022) propose an extended PageRank centrality for weighted, directed networks (WPR) and found that it outperformed the traditional PageRank.

Sikos and Meirmanova (2020) use network analysis (combining degree, closeness, and betweenness centralities) to scrutinize the structure of international wheat trade. Closeness and betweenness centralities often come hand in hand in literature - Xu and Liang (2019) use WIOD[25] from 2009 to identify sectors in the global GVC network with the highest betweenness and closeness centrality. They argue that the heterogenous structure of an input-output database makes it a good candidate for such network analysis.

Liang et al. (2016) propose a framework for identifying important "transmission" sectors by combining structural path analysis and betweenness centrality. Their betweenness-based method calculates the betweenness of sectors by the supply chain paths passing through them. They manage to rank sectors in the Chinese economy by CO2 emissions and argue that their method of betweenness structural centrality performs better than other traditional methods.

Interestingly, Tokito et al. (2022) study how sectors contributed to CO2 emissions through GVCs by using both the hypothetical extraction method and the betweenness structural centrality method, showing that they can be used as complements. They found that betweenness centrality performs better at identifying the key sectors.

Building upon Liang et al. (2016) and their structural betweenness centrality, Inomata and Hanaka (2021) develop an indicator called Pass-through frequency (PTF) which calculates the number of times a given supply chain passes through a certain point (sector). Using an input-output table, it can calculate the PTF value for

[24] Central, East and Southeast European
[25] World Input Output Database

any supply chain that connects two sectors. Therefore, as opposed to the more traditional methods, such as HEM, which focus on volume impact, their proposed referential statistic focuses on the impact of frequency. The authors advocate for the complementary use of both metrics. Using this proposed framework, the authors set Japan and China as target regions and identify sectors in the global supply chain network with the highest PTF, i.e., those that interact with sectors in the Chinese and Japanese economies the most.

3.4 Trade Decomposition

The share of intermediate goods in total trade[26] has been somewhat stable in the last years averaging at 50%[27]. These intermediate inputs are crossing the borders multiple times and at each production stage, a value is added to them. This creates a problem since the traditional trade statistics no longer provide reliable information about the value added produced by each country. (Koopman et al., 2014)

In the past, there have been multiple attempts at a robust approach to trade decomposition. Hummels et al. (2001) suggest a framework for calculating the use of imported intermediate goods, calling it the vertical specialization (VS) of countries. Using the input-output OECD database for 10 countries and four emerging markets, they measure the vertical specialization of exports through the foreign value added. Their findings include: smaller countries have a higher share of vertical specialization in their exports, between 1970 and 1990 the overall share of vertical specialization grew by 30% and this growth resulted in a 30% increase in the export/GDP ratio. They also propose another measure, VS1, to calculate intermediate exports embodied in exports of third countries. Daudin et al. (2011) propose an additional measure, VS1*, complementary to Hummels et al. (2001), which is a part of VS1 that is shipped back to the country of origin. Johnson and Noguera (2012) define their measure of value-added content as a ratio of value-added exports to gross exports, calling it the VAX ratio. The value-added exports describe the value added produced in the source country and absorbed in the destination country. The authors use the GTAP database to report the countries' VAX ratios.

[26] Excluding fuel
[27] WTO (https://www.wto.org/english/news_e/news23_e/stat_01feb23_e.htm)

However, Koopman et al. (2014) (henceforth abbreviated to KWW[28]) point out that the measures proposed in the abovementioned studies cannot be considered equal for most cases. They provide a framework that decomposes a country's gross exports into the sum of various components and show that VS, VS1, and VS1* are all simply linear combinations of them. KWW framework explains the differences between the official trade statistics and national accounts by taking into account *double-counted* flows. If an intermediate good crosses international borders multiple times, the official trade statics also count its value more than once which causes discrepancies.

Furthermore, KWW demonstrate how to break up the value added embedded in a country's exports while taking into account where it is ultimately absorbed. They also highlight the fact that double-counted terms are diverse, and it is important to understand their structure since it contains information about where a country stands in global production chains. For full specification of the generalized form of the gross exports accounting equation, see Appendix A.

Borin and Mancini (2017) extend the KWW framework by scrutinizing *bilateral* trade flows which can identify countries' upstream and downstream trade partners and can provide valuable information about a country's participation in the global value chains. Since the structure of value added is assumed to be constant, such analysis can provide significant policy implications, such as the future development of gross trade.

Borin and Mancini (2017) follow the work of Nagengast and Stehrer (2014) who propose two approaches to bilateral trade decomposition: A source-based approach, where a commodity is considered as "value added" the first time it crosses a border and as "double counted" thereafter. And a sink-based approach, where a commodity is considered as "value added" the last time it crosses the border and as "double counted" beforehand. In other words, the source-based approach assigns the value added flows to the country of production while the sink-based approach assigns it to the country of final absorption. Nagengast and Stehrer (2014) also note that a variation of the source-based approach is used by KWW.

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[28] This abbreviation is used in most literature that is based on their work.

The complete decomposition of bilateral exports as presented in Borin and Mancini (2017) is provided in Appendix A, along with a comparison to the original KKW decomposition.

This methodology can be used to study various empirical questions (such as measuring GVC-related trade), each demanding a different approach. To ease the computation, the authors together with Belotti developed a Stata command, icio, which they comprehensively describe in their paper for World Bank (Belotti et al., 2020). Furthermore, Borin and Mancini (2023) provide a complex overview of the evolution of decomposition and a toolkit for proper value-added accounting. They cover multiple empirical questions along with methodologies suitable to address them.

4 Data

This thesis relies on the 2022 edition of the OECD Inter-Country Input-Output (ICIO) Tables published in November 2022. This unique database covers 45 industries and 76 countries for the years 1995 to 2020. Originally, the present writer assumed they would be using the 2021 edition, as mentioned in the thesis proposal, which only covered the years 1995 to 2018 and fewer non-OECD economies[29]. The lack of data for more recent years was the greatest possible limitation of the analysis and the conclusiveness of its findings the present writer was aware of. Additionally, more developing countries were included in the latest release which will help to better analyze the role of China in the world's economy. A full overview of the countries and industries included in the database is provided in Appendix B.

The following sections provide an overview of available input-output tables and describe the main features of the data used in this thesis.

4.1 Overview of Existing Input-Output Tables

Many organizations have in the recent year taken to the construction of multiregional Input-Output (IO) tables. Besides the ICIO database, there exist three other databases that are worth mentioning: World Input-Output Database (WIOD), Asian Development Bank (ADB) Database, and the EU's Full International and Global Accounts for Research in input-Output analysis (FIGARO). Also, the Global Trade Analysis Project (GTAP) is often mentioned although it is not technically an IO database but rather a collection of national tables and trade flows which can then be used for further calculations.

WIOD was a project funded by European Commission and it provides very similar type of data as the OECD ICIO Tables. However, it is no longer an ongoing project – the latest release was in 2016 in which the last year covered was 2014. It used supply-use tables from each country's national statistics and transformed them into final I-O tables. (Jones et al., 2014)

[29] The 2021 and 2022 edition presented data for 28 and 38 non-OECD economies, respectively.

ADB developed its Multiregional Input-Output (MRIO) Tables to extend the WIOD by including statistics for more Asian economies. (Mancini et al., 2023) The latest 2021 release of ABD MRIO covers 35 sectors in 62[30] countries, mainly focusing on and providing the most detailed statistics for 25 Asian economies.

Figaro tables are annually released trade data for all EU Member States and 18 additional countries (EU's largest trade partners) and as of now[31], they are available for the years 2010-2020. These tables are a direct source for the OECD ICIO Tables for the EU countries.[32] The reason the OECD database was prioritized for this thesis is because of better country coverage (unfortunately, Figaro tables do not include data for Vietnam).

Lastly, GTAP is a paid database that offers somewhat better sectoral and country coverage compared to the OECD database but is much more lacking in time period coverage – the latest version (2019) only provides 4 reference years and is not as up-to-date (last year for which data was published is 2014). Additional problems with the GTAP database are the discrepancies with national account statistics and the lack of distinction between intermediate and final goods. (Jones et al., 2014)

4.2 OECD ICIO Tables description

The ICIO tables are part of an ongoing project by the Organisation for Economic Co-operation and Development (OECD) since 2011 when the first ICIO edition was issued. The 2022 edition is the 8th release and the most comprehensive one. OECD constructs the tables based on the official national statistics of involved countries and is therefore regarded as highly reliable. (Inomata & Hanaka, 2021)

The database contains an exhaustive annual report of inter-country inter-industry trade flows. The data structure for a simplified case of three countries and two sectors is outlined in Table 4.1.

[30] In addition, it includes statistics for aggregated Rest of the World. Source: https://www.adb.org/what-we-do/data/regional-input-output-tables
[31] July 2023
[32] Source: https://ec.europa.eu/eurostat/web/esa-supply-use-input-tables/figaro

Table 4.1: Simplified structure of OECD ICIO Tables

at basic prices		Intermediate demand						Final demand			Output
		Country 1		Country 2		Country 3		Country 1	Country 2	Country 3	
		Indy 1	Indy 2	Indy 1	Indy 2	Indy 1	Indy 2				
Country 1	Industry 1	z_{11}^{11}			$\cdots$		z_{12}^{13}	f_1^{11}	$\cdots$	f_1^{31}	x_1^1
	Industry 2										
Country 2	Industry 1	$\vdots$			$\ddots$		$\vdots$	$\vdots$	$\ddots$	$\vdots$	$\vdots$
	Industry 2										
Country 3	Industry 1										
	Industry 2	z_{21}^{31}			$\cdots$		z_{22}^{33}	f_2^{31}	$\cdots$	f_2^{33}	x_2^3
Value added		w_1^1			$\cdots$		w_2^3				
Output		x_1^1			$\cdots$		x_2^3				

The industry supply is represented by rows in the upper part of Table 2, and the demand is represented by columns. Let $r, s = 1, 2, 3$ and $i, j = 1, 2$, the supply of industry i in country r to industry j in country s (intermediate demand) is denoted as z_{ij}^{rs}, while the supply of industry i in country r to country s (final demand) is denoted as f_i^{rs}. Lastly, the value added by industry i in country r and the total output of industry i in country r are represented in the table by w_i^r and x_i^r, respectively. All values presented in ICIO tables are at basic prices.

5 Methodology

This chapter overviews the relevant methodologies used in the thesis for hypotheses testing. It is important to note that this thesis does not rely on traditional econometric approaches and therefore does not provide any information about the statistical significance (e.g., p-values) of the results. However, all of the methods used are recognized in academic literature and are able to produce robust findings. The sections of this chapter describe the network analysis, then the trade decomposition, and lastly the hypothetical extraction.

The following is an overview of hypotheses, together with the methodology applied to them:

1. *Sectors of China's economy are gaining significant positions within the structure of the global productions network*
   - **Network analysis method**
2.
   a) *Western countries (USA, EU) are becoming more dependent on Chinese demand (exports to China)*
      - **Hypothetical extraction method**

   b) *Western countries (USA, EU) are becoming more dependent on imports from China*
      - **Trade decomposition method**
3. *There is a decrease in the role of China in the global value chain network and it is simultaneously being replaced by Vietnam*
   - **Trade decomposition method**
4. *Other countries are increasing their reliance on inputs from Vietnam*
   - **Trade decomposition method**

Also note that, as mentioned above, these hypotheses are not tested by econometric tools. They should be understood rather as research questions. Therefore, in the section Results, they are either rejected or confirmed[33].

[33] As opposed to traditional "cannot be rejected".

5.1 Network analysis method

The network centrality measures were theoretically introduced in the Chapter Literature but a quick overview including more appropriate notation is provided below.

The focus in this section is on the intermediate demands which are represented by the matrix **Z** in the OECD Tables. This matrix can be understood as a weighted directed network where the elements z_{ij}^{rs}[34] represent the weights of edges and the nodes are country-sector pairs. Therefore, the following centrality measures may be applied:

Weighted in-degree centrality of sector i in country r:

$$C_{in-degree}(i,r) = \sum_{j}\sum_{s} z_{ji}^{sr} \tag{5.1}$$

Weighted out-degree centrality of sector i in country r:

$$C_{out-degree}(i,r) = \sum_{j}\sum_{s} z_{ij}^{rs} \tag{5.2}$$

Then the degree centrality can be expressed as the sum of in- and out-degree centrality:

$$C_{degree}(i,r) = C_{in-degree}(i,r) + C_{out-degree}(i,r) \tag{5.3}$$

If one wants to calculate unweighted degree centrality, the z_{ij}^{rs} are simply replaced by 0 if there is no connection (no trade flow) and by 1 otherwise.

The closeness centrality of sector i in country r:

[34] r, s represent countries, while i, j represent sectors. See Chapters Literature and Data for more information.

$$C_{closeness}(i,r) = \frac{1}{\sum_j \sum_s d_{ij}^{rs}} \tag{5.4}$$

where d_{ij}^{rs} is the length of the shortest path between sector i in country r to sector j s. Of course, the sector i in country r is excluded from the summation[35].

The betweenness centrality of sector i in country r:

$$C_{betweenness}(i,r) = \sum_{j \neq k} \sum_{s \neq t} \frac{p_{jk}^{st}(i,r)}{p_{jk}^{st}} \tag{5.5}$$

where $\sum_{j \neq k} p_{jk}(i,r)$ is the number of shortest paths that pass through the sector i in country r, and $\sum_{j \neq k} p_{jk}$ is the number of all shortest paths that exist within the network. Again, the sector i in country r is excluded from the summation.

Lastly, the PageRank centrality of sector i in country r:

$$PR(i,r) = (1-d) + d\left(\sum_{j=1} \sum_{s=1} \frac{z_{ji}^{sr} PR(j,s)}{C(j,s)}\right) \tag{5.6}$$

where d is the damping factor which is often set to 0.85 (as seen in Wang et al., 2021; Zhang et al., 2022) and it is also the default value suggested by Gephi. Therefore this thesis adheres to this recommendation. z_{ji}^{sr} represents the weighted outdegree of sector j in country s, $PR(j,s)$ is the PageRank centrality of sector j in country s, and $C(j,s)$ is the number of outward connections of sector j in country s (or the unweighted out-degree).

During the calculation of centrality measures, an issue regarding the large size of the matrix was encountered. After all, the original matrix of intermediate flows, **Z**, has 3645 rows and columns (45 sectors multiplied by 81 regions[36]), resulting in over 13 million elements. To reduce the size and ease the computations, two alterations

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[35] It cannot be explicitly expressed in the equation as $j \neq i$ as that would exclude sectors i in all countries which is not desirable.

[36] The OCED database provides data for 76 countries, the Rest of the World, and split tables for China (CN1, CN2) and Mexico (MX1, MX2)

were performed on the data. Firstly, the elements for China and split tables for China were aggregated, and the same was done for Mexico. Then, all EU countries were aggregated. These aggregations decreased the number of regions to 51 and therefore also the number of rows and columns to 2295, resulting in less than half of the number of original elements. Note, that with this aggregation, no data is being disregarded. Conversely, in the second alteration, trade flows smaller than 10% of the average value of all trade flows were set to zero, and therefore disregarded, decreasing the number of rows and columns by an additional 158. Therefore, in the end, there were 2137 nodes, the country-sector pairs, whose centralities were measured.

5.2 Trade decomposition method

Value-added in exports

As mentioned in Chapter Literature, Belotti et al. (2020) developed their Stata icio command which is used for the computations described below. The authors note that for value-added measures both sink and source-based approaches can be utilized[37]. For the purposes of this thesis, both approaches were tested and the results produced by Stata were identical. Therefore, this section will only cover the source-based approach since it is also used later for the GVC-related trade measures. The source-based accounting framework is provided in Appendix A (Equation (A.2)) and the following computations are linked to it.

The Stata icio command provides two types of results of the exports breakdown – the total value in millions of $ and as a % share of the exports. Since this thesis compares two economies of different sizes (China and Vietnam), most results will be provided as shares.

According to Borin and Mancini (2019), the gross exports of a country can be decomposed into domestic (DC) and foreign content (FC). Each of these contents is then further decomposed into domestic/foreign value-added (DVA/FVA) and domestic/foreign double-counted (DDC/FDC) components. For a full scheme of this decomposition, see Appendix A.

[37] See section Trade Decomposition in Chapter 2 for the distinction between sink- and source-based approaches.

In this section, the focus is on the value-added measures. The domestic value added is an indicator of the amount of input a country has in its own exports. On the other hand, the foreign value added represents the inputs from other countries in a country's exports.

In an input-output model with G countries and N sectors, let $\mathbf{V}_s$ and $\mathbf{V}_t$ be row vectors of direct value-added coefficients for countries s and t, respectively, $\mathbf{Y}_{sr}$ the demand vector of final goods from s in r, $\mathbf{A}$ the technical coefficients matrix, $\mathbf{B}$ the inverse Leontief matrix[38], $\mathbf{E}_{sr}$ a vector of the gross exports from s to r. Then, in the source-based approach, the domestic and foreign value added embedded in total exports from country s to country r are defined as (Borin & Mancini, 2019)

$$DVAsource_{sr} = \mathbf{V}_s(\mathbf{I} - \mathbf{A}_{ss})^{-1}\mathbf{E}_{sr} \tag{5.7}$$

and

$$FVAsource_{sr} = \sum_{t \neq s}^{G} \mathbf{V}_t \mathbf{B}_{ts}^{s} \, \mathbf{E}_{sr} \tag{5.8}$$

where $(\mathbf{I} - \mathbf{A}_{ss})^{-1}$ is the *local* inverse Leontief matrix which excludes the backward linkages of country s and $\mathbf{B}_{ts}^{s}$ is a modified inverse Leontief matrix which is obtained from a technical coefficient matrix $\mathbf{A}^{s}$ where $\mathbf{A}_{ts} = 0$.

Borin and Mancini (2019) then split the gross exports of country s to country r, $\mathbf{E}_{sr}$, into multiple components[39] and derive the comprehensive source-based decomposition of DVA and FVA:

[38] Although, the Leontief inverse matrix was previously denoted as L, this methodology opts for different notation. To avoid confusion, this thesis mostly follows the notation used by the authors from whom it derives.

[39] For full decomposition, see Borin and Mancini (2019), p. 15-17

$$DVAsource_{sr} = \mathbf{V}_s(\mathbf{I}-\mathbf{A}_{ss})^{-1}\left[\mathbf{Y}_{sr} + \mathbf{A}_{sr}(\mathbf{I}-\mathbf{A}_{rr})^{-1}\mathbf{Y}_{rr} + \mathbf{A}_{sr}(\mathbf{I}-\mathbf{A}_{rr})^{-1}\sum_{j\neq r}^{G}\mathbf{Y}_{rj} + \mathbf{A}_{sr}(\mathbf{I}-\mathbf{A}_{rr})^{-1}\sum_{j\neq r}^{G}\mathbf{A}_{rj}\sum_{k}^{G}\sum_{l}^{G}\mathbf{B}_{jk}\mathbf{Y}_{kl}\right] \tag{5.9}$$

and

$$FVAsource_{sr} = \sum_{t\neq s}^{G}\mathbf{V}_t\mathbf{B}_{ts}^{s}\left[\mathbf{Y}_{sr} + \mathbf{A}_{sr}(\mathbf{I}-\mathbf{A}_{rr})^{-1}\mathbf{Y}_{rr} + \mathbf{A}_{sr}(\mathbf{I}-\mathbf{A}_{rr})^{-1}\sum_{j\neq r}^{G}\mathbf{Y}_{rj} + \mathbf{A}_{sr}(\mathbf{I}-\mathbf{A}_{rr})^{-1}\sum_{j\neq r}^{G}\mathbf{A}_{rj}\sum_{k}^{G}\sum_{l}^{G}\mathbf{B}_{jk}\mathbf{Y}_{kl}\right] \tag{5.10}$$

The bilateral exports are decomposed in square brackets. For illustration, they account for (from left to right): the final demand in country r for goods from s, processing stages in r that produce final goods for domestic consumption, the final demand in countries j for goods from r (whose inputs can be traced to s) and the intermediate inputs from country j to country k where they are processed for final consumption in country l.

Besides the DVA and FVA in bilateral exports, as presented above, the DVA and FVA embedded in a country's overall exports, $\mathbf{u}_N\mathbf{E}_{s*}$, is also of interest. This share of DVA and DVA can be easily obtained from Equations (5.9) and (5.10), respectively, by summing them over all importing countries, r.

Additionally, in the bilateral scenario, it is also possible to obtain the FVA originating in a third country – it is the country t in Equation (5.10). One must simply remove the summation. Specifically, say we are interested in the value added from Vietnam in China's exports to the US, then Vietnam is country t, China is the country s and the US is country r. Conversely, if the country of final absorption (consumption) is of interest, or l in Equations (5.9) and (5.10), the summation is removed for the very last term in the equations.

Lastly, it is possible to extend all the above-mentioned decompositions to a sectoral level. The logic remains the same, only additional indexing to distinguish the country-sectors is needed.

GVC-related trade

GVC-related trade is an indicator of participation in the structure of global value chains. In contrast to "traditional" trade which measures flows that solely cross one border, GVC-related trade measures the flows that cross multiple borders. (Borin et al., 2021) GVC-related trade can only be computed by a source-based approach proposed by Borin and Mancini (2017) because it allows for isolation of the domestic value added exported only once and absorbed directly by the importers.

The directly absorbed value-added in exports of country s, or $DAVAX_s$, is contained in the first two terms of Equation (A.2) summed across all bilateral flows[40]:

$$\begin{aligned} DAVAX_s &= \sum_{r\neq s} 1a^* + \sum_{r\neq s} 2a^* \\ &= \mathbf{V}_s(\mathbf{I}-\mathbf{A}_{ss})^{-1}\sum_{r\neq s}^{G}\mathbf{Y}_{sr} \\ &+ \mathbf{V}_s(\mathbf{I}-\mathbf{A}_{ss})^{-1}\sum_{r\neq s}^{G}\mathbf{A}_{sr}(\mathbf{I}-\mathbf{A}_{rr})^{-1}\mathbf{Y}_{rr} \end{aligned} \tag{5.11}$$

The bilateral version of Equation (5.11) is the same, only without the summation operators.

Then the GVC-related trade *share* in total exports of country s, $\mathbf{u}_N\mathbf{E}_{s*}$, can be calculated as

[40] The Equation (A.2) is the decomposition of bilateral exports from country s to country r.

$$GVC_s = \frac{\mathbf{u}_N \mathbf{E}_{s*} - DAVAX_s}{\mathbf{u}_N \mathbf{E}_{s*}} \tag{5.12}$$

where $\mathbf{u}_N$ is $(1 \times N)$ unit row vector.

Similarly, the GVC-related trade share of the total export of country s to country r, $u_N E_{sr}$, is given as

$$GVC_{sr} = \frac{\mathbf{u}_N \mathbf{E}_{sr} - DAVAX_{sr}}{\mathbf{u}_N \mathbf{E}_{sr}} \tag{5.13}$$

The overall GVC indicator described above can be further decomposed into *backward* and *forward* components:

$$GVC_{sr} = GVCbackward_{sr} + GVCforward_{sr} \tag{5.14}$$

The backward component relates to the import portion, or backward linkages, of exports and its bilateral form can be expressed as

$$GVCbackward_{sr} = \frac{\mathbf{V}_s(\mathbf{I} - \mathbf{A}_{ss})^{-1} \sum_{j \neq s}^{G} \mathbf{A}_{sj} \mathbf{B}_{js} \mathbf{E}_{sr} + \sum_{t \neq s}^{G} \mathbf{V}_t \mathbf{B}_{ts} \mathbf{E}_{sr}}{\mathbf{u}_N \mathbf{E}_{sr}} \tag{5.15}$$

The first part of the numerator in Equation (5.15) is the domestic double-counted component (DDC) of exports and the second part is the foreign content (FC) of exports.

The forward component of GVC participation expresses the portion of domestic production which is supplied to the importing country for further processing and is consequently re-exported. These forward linkages can be expressed as

$$GVCforward_{sr} = \frac{\mathbf{V}_s(\mathbf{I} - \mathbf{A}_{ss})^{-1} \mathbf{A}_{sr} (\mathbf{I} - \mathbf{A}_{rr})^{-1} \left(\sum_{j \neq r}^{G} \mathbf{Y}_{rj} + \sum_{j \neq r}^{G} \mathbf{A}_{rj} \sum_{k}^{G} \sum_{l \neq s}^{G} \mathbf{B}_{jk} \mathbf{Y}_{kl} \right)}{\mathbf{u}_N \mathbf{E}_{sr}} \tag{5.16}$$

where the numerator is the difference between the domestic value added ($DVAsource_{sr}$) and $DAVAX_{sr}$.

5.3 Hypothetical extraction method

The hypothetical extraction method was in detail presented in Chapter Literature. Using the Leontief inverse matrix, it can determine the effect on output if one component is extracted from the economy. It is best suited for studying the forward linkages in the economy. In this thesis, two types of forward linkages are studied – on the sectoral level and the country level. In both cases, not only the effect on the output is estimated but also on the final demand and value added.

To study the effect of extracting sectors, classical HEM, without the redistribution (GEM) suggested by Dietzenbacher (2019), was used. This should not pose significant limitations as the effects of extracting a single sector are quite small and the differences between HEM and GEM would be marginal.

Conversely, on the country level, the redistribution is much more relevant since the extracted component is now much greater. Therefore, to study the impact of a whole country being extracted from the system, this thesis opts for global hypothetical extraction (GEM). For a full explanation of how GEM works, see Chapter Literature.

6 Results

6.1 Network analysis

Centrality measures were computed for the years 2000, 2010, and 2020 to see how the centrality of sectors in China changed over time. The reported centrality measures are weighted degree, closeness, betweenness, and PageRank. They are all presented in the same logic in Figures 6.1, 6.2, 6.3, and 6.4: for every centrality measure, these figures represent the sector's change in position[41] (ranking) within the whole network over the reported years. It can be readily observed that the centralities of Chinese sectors follow an upward trend, suggesting their increasing importance. For the sake of clarity, only 10 sectors with the highest centrality in the year 2020 are shown in the figures.

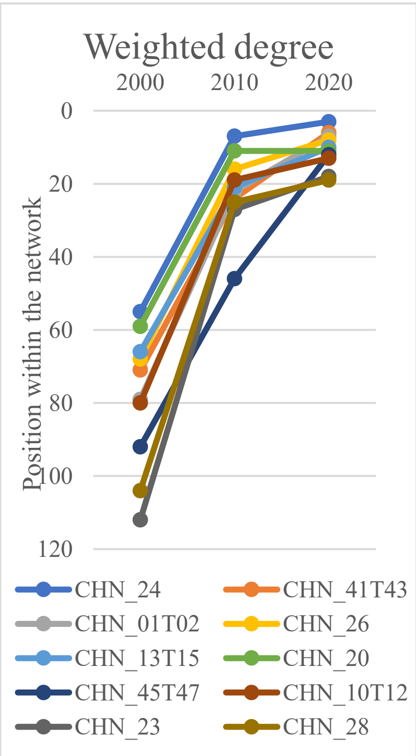

Figure 6.1: Change in position of the top 10 sectors by weighted degree

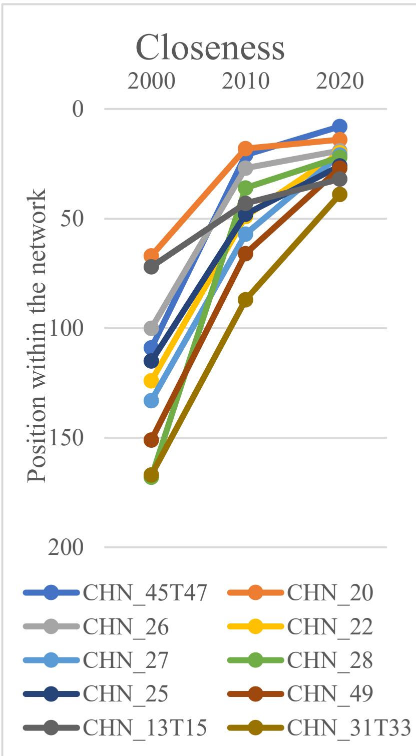

Figure 6.2: Change in position of the top 10 sectors by closeness

[41] Note that there are 2127 country-sectors in this sample.

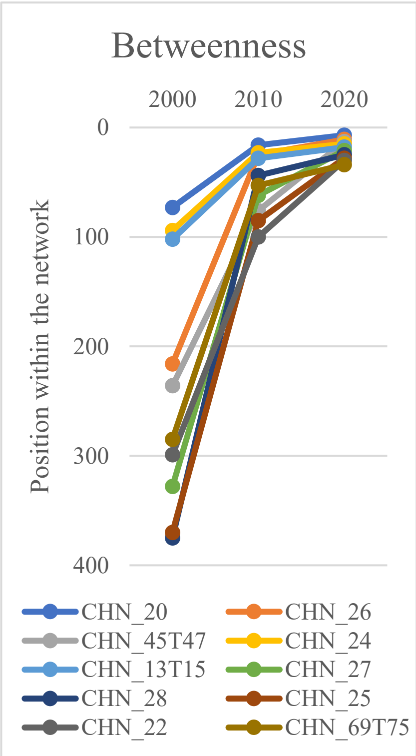

Figure 6.3: Changes in the position of the top 10 sectors by betweenness

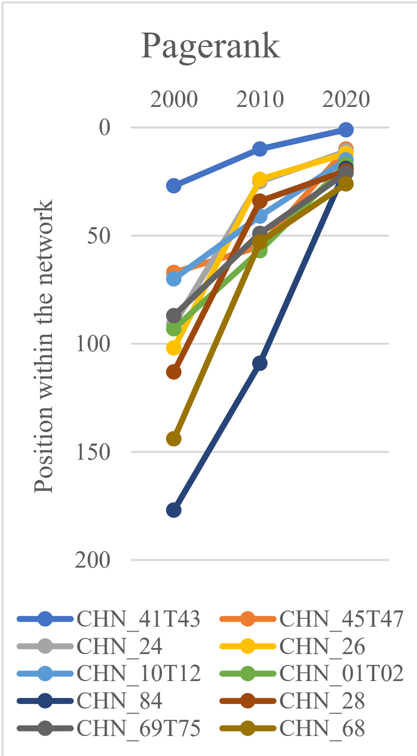

Figure 6.4: Changes in the position of the top 19 sectors by PageRank

Weighted degree

The weighted degree for a sector represents the amount of trade flow that this sector imports (in-degree) and exports (out-degree). In other words, how much the sector engages with the rest of the network in terms of dollars.

The top 3[42] sectors identified as the most influential by weighted degree are basic metals (24), wholesale and retail trade; repair of motor vehicles (45T47), and agriculture, hunting, forestry (01T02).

For all sectors, a significant upward shift can be observed over the years. For example, take sector 24 In Figure 6.1 representing basic metals. It was in the 55th, 7th, and 3rd position in the global economy network in 2000, 2010, and 2020, respectively.

[42] Appendix B provides a full overview of the sector notation, therefore the rest of the sectors can be easily identified.

Now, from a slightly different point of view, in 2000, there were only 10 Chinese sectors present in the top 100 sectors (out of 2137), while there were 22 and 28 in 2010 and 2020, respectively. It seems that a similar pattern can be observed for the change in sector position over time and the number of top sectors over time. Clearly, the size of these Chinese sectors is increasing relative to other sectors, however, the trend seems to be decelerating.

Closeness centrality

The closeness centrality of a sector expresses how accessible it is. A high closeness centrality indicates that the sector can quickly and easily reach other sectors. From the definition in Equation (E for closeness), the fewer steps in the shortest path, the higher the closeness centrality.

The top 3 sectors identified as the most influential by closeness are wholesale and retail trade; repair of motor vehicles (45T47), chemical and chemical products (20), and computer, electronic and optical equipment (27).

Although only some sectors are represented in both Figure 6.1 and 6.2, the overall pattern is alike – a big “jump” from 2000 to 2010 and a smaller one from 2010 to 2020. Similarly, the number of sectors in the top 100 was 2, 13, and 16 in 2000, 2010, and 2020, respectively.

Betweenness centrality

The betweenness centrality of a sector measures how important it is in terms of connecting other sectors in the economy. From the specification in Equation (for betweenness), the higher the number of shortest paths that pass through a sector, the more it connects other sectors.

The top 3 sectors identified as the most influential by betweenness are the same as by closeness, only in a different order (20, 27, 45T47). The pattern of change in position again follows what was already mentioned above for weighted degree and closeness. Similarly, the number of sectors in the top 100 was 2, 10, and 16 in 2000, 2010, and 2020, respectively.

The sectors in China’s economy are becoming more central and also more sectors are passing through them but at a slower pace.

PageRank centrality

PageRank centrality of a sector is perhaps the most comprehensive one as it assigns a value to a sector based on the importance of its connections. A sector's PageRank is essentially a sum of Pagerank centralities for the connected nodes.

The top 3 sectors identified as the most influential by PageRank are construction (41T43), wholesale and retail trade; repair of motor vehicles (45T47), and basic metal (24).

Interestingly, the above-mentioned pattern of the number of top sectors cannot be observed for PageRank centralities. The number of sectors in the top 100 was 7, 14, and 26 in 2000, 2010, and 2020, respectively. Therefore, it seems that sectors in China's economy are steadily becoming more central when measured by PageRank.

For almost all sectors, including those not mentioned in the top 10, their position within the structure of global production networks grew. This confirms the first hypothesis. However, as already noted above, this upward trend seems to be decelerating in most cases.

Table 6.1 provides an overview of six sectors in China's economy that were among the top 10 identified as the most central by all four or three centrality measures.

Table 6.1: The most central sectors in China's economy

sector	CHN_26[43]	CHN_45T47[44]	CHN_28[45]	CHN_24[46]	CHN_13T15[47]	CHN_20[48]
identified by	all	all	all	weighted degree	weighted degree	weighted degree
				betweenness	betweenness	betweenness
				PageRank	closeness	closeness

These findings are consistent with the fact that these industries are often mentioned when dependence on China is discussed.

[43] Computer, electronic and optical equipment
[44] Wholesale and retail trade; repair of motor vehicles
[45] Machinery and equipment
[46] Basic metals
[47] Textiles, textile products, leather, footwear
[48] Chemical and chemical products

6.2 Forward linkages by HEM and GEM

To understand the dependence on demand from China, the (global) hypothetical extraction method was employed. Simply put, the research question here is: What happens to the output/value added if China ceases to import? USA and EU were chosen as representative exporters of the Westen countries.

Sectoral HEM

For the sake of clarity, the results are provided for only three years – 2000, 2010, and 2020 - which should provide sufficient information about the evolution of these effects over time. All results are provided as a percentage change.

The shock to output and VA of extracting each one of the 45 sectors was calculated. Figure 6.5 summarizes the average effect of these shocks for years 2000, 2010, and 2020. An increase can be observed for all variables. This means that, on average, the sectors of both the US and the EU are becoming more dependent on exporting to China. Clearly, the average dependence is not only higher for the EU but it also increases more significantly in the second time period. Of course, this can also be seen on the aggregate level.

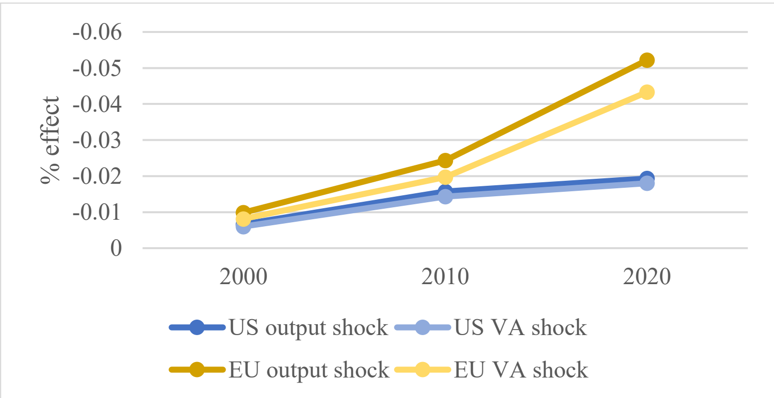

Figure 6.5: Average effect of shocks on sectors

Naturally, one is more interested in those sectors that would suffer the most if China stopped buying from them. Ten such sectors for the latest year, 2020, are identified in Table (6.2) for the US and Table (6.3) for the EU.

Table 6.2: US sectors with the highest forward linkages to China

sector	% effect on output	sector	% effect on VA
45T47	-0.1367	**45T47**	-0.1355
26	-0.0692	**26**	-0.0837
20	-0.0683	**20**	-0.0571
1	-0.0618	**1**	-0.0526
29	-0.0460	**69T75**	-0.0416
28	-0.0432	**28**	-0.0353
38	-0.0381	**41**	-0.0321
30	-0.0320	**30**	-0.0302
55T56	-0.0267	**29**	-0.0297
49	-0.0264	**55T56**	-0.0257

Table 6.3: EU sectors with the highest forward linkages to China

sector	% effect on output	sector	% effect on VA
29	-0.2876	**45T47**	-0.2521
28	-0.2524	**29**	-0.2080
45T47	-0.2396	**28**	-0.2033
20	-0.1618	**20**	-0.1187
26	-0.1330	**26**	-0.1160
27	-0.1183	**27**	-0.0937
24	-0.0910	**69T75**	-0.0774
10T12	-0.0900	**77T82**	-0.0770
30	-0.0775	**10T12**	-0.0674
69T75	-0.0740	**31T33**	-0.0585

Clearly, it can be observed from both tables that the effects seem to be larger for the EU. This is consistent with the trends in Figure 6.5. This indicates that the forward linkages between the US and China are weaker, and therefore, the US would be less exposed to potential interruptions in China's demand.

From the output perspective, the sectors in the EU with the largest dependence on China's demand are 29, motor vehicles, trailers and semi-trailers, and 28, machinery and equipment. It seems quite logical considering that vehicles and machinery are two of the largest components in the EU's exports[49]. The % effects indicate that if China ceased importing from sectors 29 and 29, the overall output of the EU economy would decline by 0.14% and 0.07%, respectively.

Sector 45T47 (wholesale and retail trade; repair of motor vehicles) has a high position in both effects on output and value added in the EU, as well as the US. Since similar or the same sectors usually have higher linkages, this result is quite consistent with the findings from network analysis where this sector was identified by all centrality measures as one of the most important within China's economy.

GEM

In this section, the focus is solely on the effects of shocks on output as it can be seen from the sectoral analysis that they go mostly hand-in-hand. Figure 6.6 shows how affected would the output of the US and EU be if China stopped importing from all sectors. Note that GEM accounts for redistribution. The differences between the

[49] Source: Trading Economics

result from GEM and HEM are, however, very small. To give an example, the effect on the EU in 2020 was estimated to be 2.295% and 2.28% loss in output by HEM and GEM, respectively. Therefore, it seems that HEM somewhat overstates the effects of shock but it is negligible, at least in the context of this thesis.

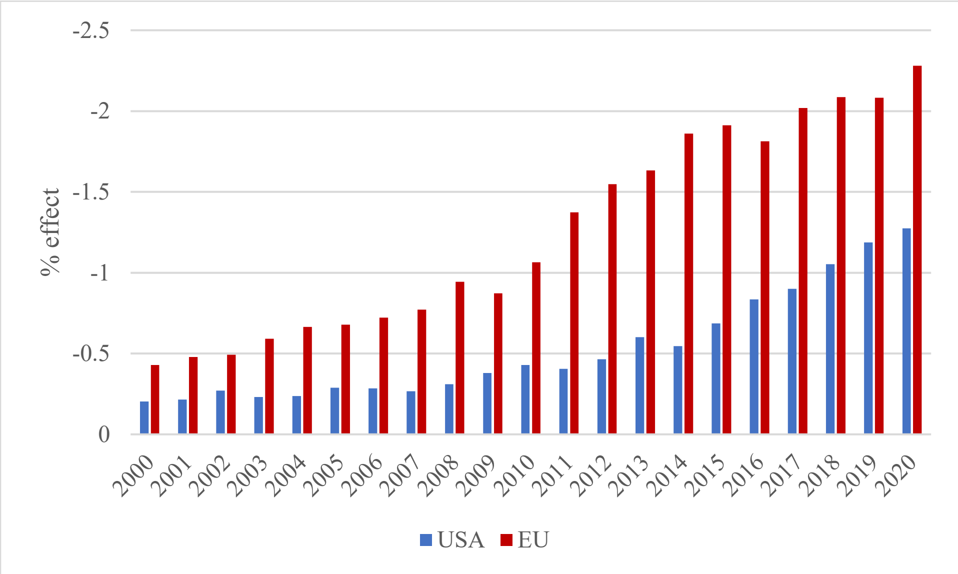

Figure 6.6: Percentage loss in output if China stops importing, with redistribution

Figure 6.6 supports the findings from Figure 6.5 and Tables 6.2 and 6.3 – the forward linkages are stronger for the EU than for the US. However, there is a clear upward trend in these linkages for both economies. In other words, both the US and the EU are increasing their dependence on China at both sectoral and aggregate levels. Therefore, the hypothesis 2a is confirmed.

6.3 Backward linkages by trade decomposition

Originally, the backward linkages were to be estimated by the Ghosh pricing model. Unfortunately, at the last minute, some issues with the code were encountered and the results produced would not be credible. Therefore, the method of trade decomposition is employed instead. Although it is not ideal, this thesis does not focus on the concrete numbers but more on the overall trends which can still be obtained by the trade decomposition method.

Again, the US and the EU were chosen to represent the backward linkages of the Western world to China. Simply put, the focus is now on the dependence on inputs *from* China which can be estimated by the domestic value added embedded in China's exports. The DVA in exports of Chinese sectors to both the EU and the US was calculated for years 2000, 2010, and 2020. There were four sectors (same for the EU and the US) whose DVA was zero, therefore they were disregarded.

The overall trend of DVA in China's exports to the EU and the US increase slightly between 2000 and 2010 – an overview is provided in Table 6.4. Interestingly, a decrease in the share of DVA is observed for the first time period.

Table 6.4: Share of DVA in Chinese exports

importer	2000	2010	2020	change (2000-2020)
US	86.58%	86.08%	88.5%	1.92%
EU	86.63%	86.07%	88.46%	1.83%

The sectoral level shall provide more interesting insights. Five Chinese sectors with the highest DVA (in $) in their exports for the latest year, 2020, are identified in Table (6.5) for the US and Table (6.6) for the EU, together with the % change in DVA.

From these tables, it can be concluded that both the US and the EU are becoming more dependent on Chinese inputs. Therefore, hypothesis 2b can be confirmed.

Table 6.5: Chinese sectors with the highest DVA in exports to the US

sector	Δ% 2000-2010	Δ% 2010-2020	overall change
26	1.2653	4.4891	5.7543
13T15	6.5696	3.3433	9.9129
31T33	2.0646	1.4285	3.4931
45T47	3.4723	0.0461	3.5184
27	-3.2161	4.8056	1.5896

Table 6.6: Chinese sectors with the highest DVA in exports to the EU

sector	Δ% 2000-2010	Δ% 2010-2020	overall change
26	1.2602	4.4898	5.7500
13T15	6.4080	3.3320	9.7400
45T47	3.4723	0.0461	3.5184
27	-3.2199	4.8076	1.5876
31T33	1.9289	1.4353	3.3642

It is evident from Tables 6.5 and 6.6 that both economies are most dependent on the same Chinese inputs (sectors).

6.4 Changes in GVC and VA in China and Vietnam

DVA and FVA in exports of China and Vietnam

Figure 6.7 shows the development over the last ten years[50] of DVA and FVA's share in gross exports of China and Vietnam. It can be seen from the graph that the sum of these two measures almost fully exhausts the gross exports decomposition - that is because the domestic and foreign double-counted terms are very small in comparison. These findings are consistent with the examples provided by Belotti et al. (2020).

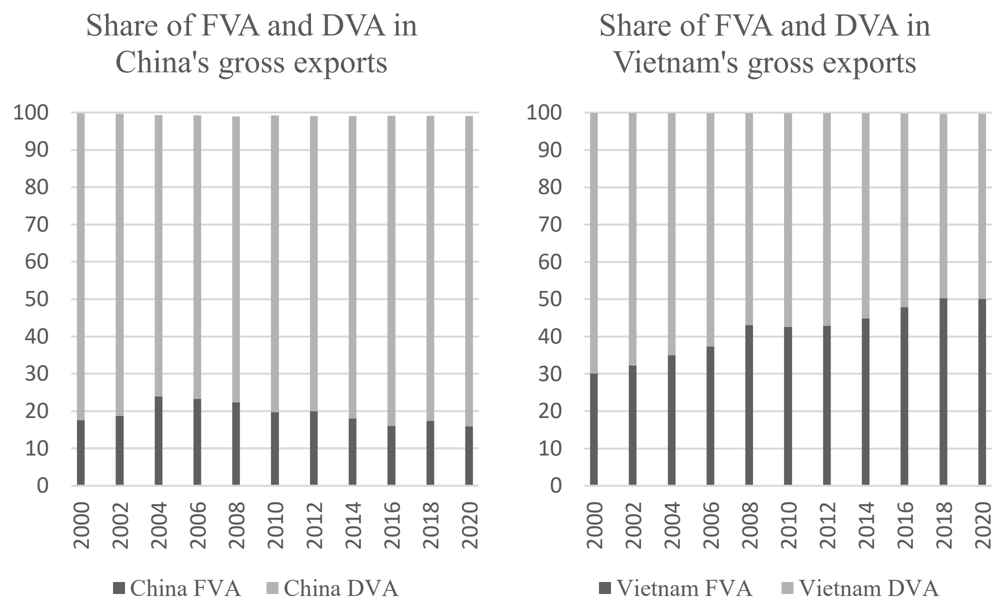

Figure 6.7: DVA and FVA in gross exports of China and Vietnam (2000-2020)

Clearly, the DVA share for China has always been higher than for Vietnam which seems intuitive based on the difference in manufacturing possibilities and the size of the two countries. There is a peak in the FVA in China's exports between the years 2004 and 2006 which is consistent with the fact that China's openness to trade was the highest in this exact time period.[51]

Furthermore, over the last ten years, there was a 3.8% decrease and a 7.5% increase in FVA in Chinese and Vietnamese exports, respectively. This is consistent with Dollar et al. (2019) who also note that while for most countries the trend in FVA

[50] The available data cover years 1995-2020, however, more recent years are of interest.
[51] Source World Bank – Trade (% of GDP)

share was upward in recent years, China managed to keep its DVA high as a result of technological advances and possibly intentional policy measures, such as investments to human capital improvement. Interestingly, although the FVA in Vietnam's exports exhibits an upward trend, it seems to have reached its peak around the year 2018 at around 50%.

GVC participation

In the Chapter Methodology, it was established that GVC-related trade is calculated using DAVAX (note that it was *subtracted* from the exports) which is a subcomponent of DVA. Therefore, the trend in overall GVC participation virtually follows the trend in FVA share in gross exports which can be observed in Figure 6.8 – it is represented by the two lines.

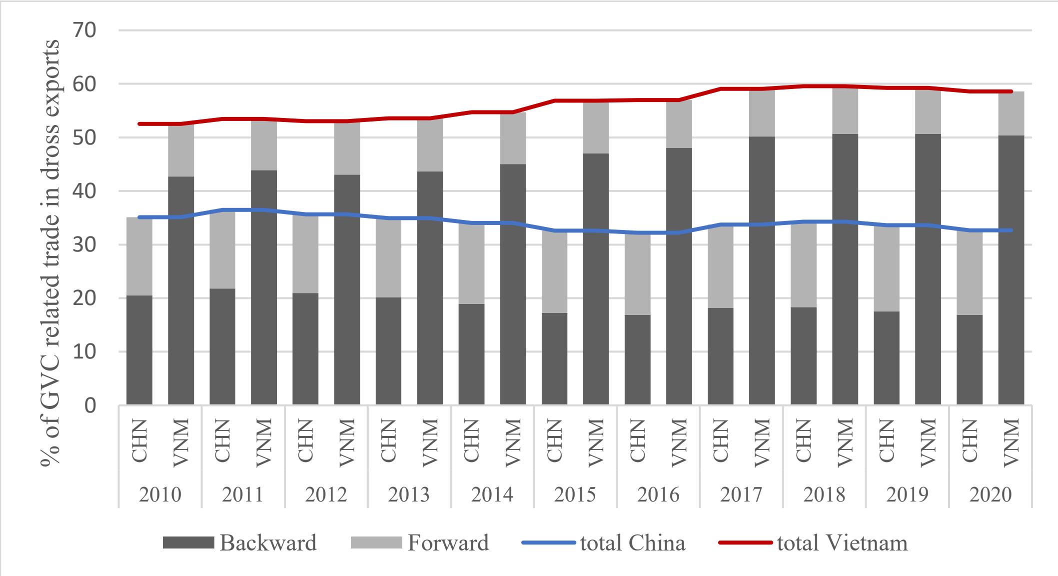

Figure 6.8: GVC-related trade as a share of gross exports

The GVC participation can be divided into forward and backward participation which can further explain the changes in GVC participation (see Figure 6.8). In the time period 2010-2020, the backward participation of Vietnam increased by approximately 7.7 percentage points (pp), while the forward participation decreased by 1.7pp, resulting in an overall increase in GVC participation by 6pp. This suggests that there was a shift in Vietnam's production towards later stages, such as the final assembly of products.

In contrast, over the same time period, the backward participation of China decreased by 3.7pp and the forward increased by 1.2pp, resulting in an overall decrease in GVC participation by 2.5pp.

All results from estimations of GVC-related trade are provided in Appendix C.

GVC participation - bilateral perspective

To scrutinize the changes in GVC participation, it might be useful to look at the bilateral trades of China and Vietnam since they can provide insights into the driving factors of these changes. The USA, EU, Japan, and South Korea were chosen since they represent the biggest trade partners for both countries. Moreover, Vietnam and China are each other's significant trade partners, therefore they were also included. For simplicity, the changes between the years 2010 and 2020 are reported and summarized in Figure 6.9. An overview of all results is provided in Appendix C.

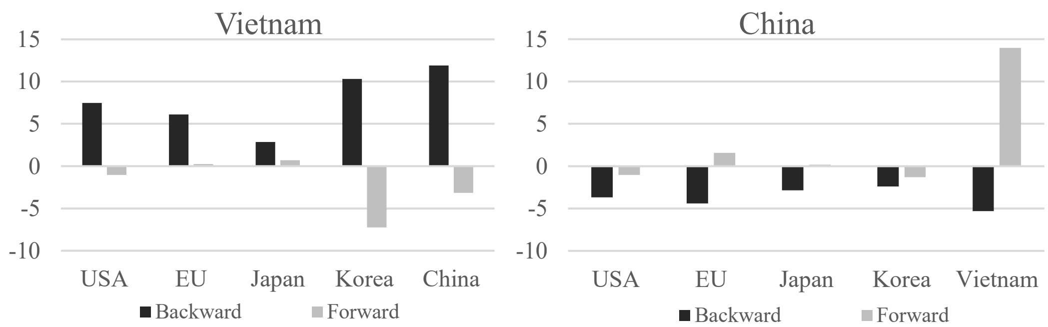

Figure 6.9: Change in share of backward and forward GVC-related bilateral trade between 2010 and 2020

For Vietnam, most findings are consistent with the GVC participation on the world level. The backward participation rose for all reported bilateral exports, most notably in exports to China and South Korea. Interestingly, also the forward participation in exports to Japan and EU increased slightly which corresponds to an increase in the exports of domestically produced inputs to these countries for downstream stages of production.

Similarly to the world level, the backward participation of China decreased for all bilateral exports, most significantly for exports to Vietnam. On the other hand, the forward participation in exports to Vietnam increased substantially, by almost 14pp. For the rest of the bilateral exports, the forward participation either decreased or increased by a small percentage.

To summarize, the most significant changes are observed in the bilateral flows of China and Vietnam. They suggest a shift in the position in production stages – Vietnam seems to be moving "up" in the production stages *partially* at the expense of China. However, this does not necessarily indicate an economic loss for China, in fact, it may be an intentional delegation (a traditional division of labor) of activities by Chinese firms to Vietnam. This can be supported by the fact that the flows of FDIs from China to Vietnam have more than tripled from 2015 to 2020[52]. For China, it is undoubtedly desirable to increase Vietnam's dependence. If that were the case, it would lower the prospects of other countries relying on Vietnam as an alternative manufacturing location that is not dependent on China.

From the observed data, it cannot be definitively confirmed that this growth in Vietnam is because it is becoming a realistic alternative to China or if it is evolving into an extension of China. It is likely a combination of both. Therefore, based on GVC participation results, the fourth hypothesis is rejected even though there are some patterns that could potentially support it.

Origin of value added in exports

Next, the value added in exports was scrutinized to see how much countries rely on inputs from China and Vietnam. The calculations are summarized in Table 6.7.

Table 6.7: Value added originating in China and Vietnam in countries' exports (share)

year	USA		EU		Japan		South Korea		China		Vietnam	
	CHN	VNM	CHN	VNM	CHN	VNM	CHN	VNM	CHN	VNM	CHN	VNM
2010	1.07	0.03	1.24	0.03	1.55	0.07	4.31	0.19	DVA	0.09	8.64	DVA
2011	1.18	0.03	1.29	0.03	1.66	0.09	5.24	0.21	DVA	0.10	9.05	DVA
2012	1.24	0.03	1.32	0.05	1.70	0.11	5.09	0.21	DVA	0.14	8.98	DVA
2013	1.32	0.04	1.31	0.04	1.91	0.15	4.94	0.27	DVA	0.15	10.21	DVA
2014	1.44	0.04	1.45	0.05	2.24	0.16	5.09	0.22	DVA	0.16	11.48	DVA
2015	1.47	0.04	1.61	0.06	2.35	0.18	5.73	0.28	DVA	0.18	12.63	DVA
2016	1.31	0.05	1.49	0.06	1.96	0.16	5.35	0.31	DVA	0.23	11.95	DVA
2017	1.34	0.05	1.56	0.06	2.11	0.19	5.58	0.33	DVA	0.25	12.79	DVA
2018	1.38	0.05	1.61	0.06	2.25	0.19	5.73	0.36	DVA	0.27	13.38	DVA
2019	1.18	0.05	1.70	0.06	2.20	0.19	5.79	0.40	DVA	0.28	15.00	DVA
2020	1.18	0.06	1.95	0.06	2.47	0.20	6.40	0.34	DVA	0.30	15.68	DVA
% change	10.15	96.75	57.16	92.51	59.85	183.68	48.30	78.19		250.56	81.61	

52 From 560 million to 1875 million of US$ (source: https://www.statista.com/statistics/720408/china-outward-fdi-flows-to-vietnam/)

Besides China, countries like the USA or Japan also have a very high share of DVA in their exports, therefore the value added originating in other countries is rather low. For the US, it seems that there were no big changes, except for a slight decrease in value added from China after the year 2018 which could be a result of the US-China trade war and the decoupling attempts that were discussed during this period. An increase in value added originating in both China and Vietnam can be seen in Japan's exports – the values are of course higher for China but the increase was steeper for Vietnam. While the shares are overall higher in South Korea's exports, the pattern is similar to Japan's.

For China and Vietnam[53], it can be seen in Table 6.7 that they both increased their reliance on each other. Again, the values are significantly higher for China's VA in Vietnam's exports than vice versa but the percentage change is much more noticeable for Vietnam's VA in China's exports. In other words, China is increasing its dependence on intermediate inputs from Vietnam at a much higher rate (81% vs 250% increase).

China remains a larger source of value added in the exports of other countries than Vietnam which is certainly to be expected due to the difference in the size of the two economies. These differences confirm that at this point in time, Vietnam cannot serve as a complete alternative to China.

However, it appears that the reported countries are increasing their reliance on Vietnam's inputs faster which confirms the last hypothesis. These findings are also consistent with the increase in GVC participation of Vietnam.

To gain additional insights into the value added of Vietnam in China's export and vice versa, more estimations at the bilateral level were carried out, specifically for exports to the US, Japan, South Korea, and the EU. In other words, when China/Vietnam exports to one of these economies, what is the share of value added from Vietnam/China?

The results are summarized in Figure C.1 in Appendix C. The value added originating in Vietnam in China's bilateral exports mirrors the trends observed in the overall exports. The same conclusion can be drawn for the role of China in Vietnam's bilateral exports. It is worth mentioning that in both instances the share

[53] Note that the value added of China and Vietnam in their respective exports are not reported since they simply represent the domestic value added which is discussed at the beginning of this section.

of value added was the highest for exports to the US for the entirety of the time period[54].

[54] 2010-2020

7 Conclusion

The main objective of this work was to understand the role of China in the global economy and use this knowledge to assess whether Vietnam has the capacity to, at least partially, serve as a potential replacement.

Using the network analysis – the weighted degree, closeness, betweenness, and PageRank centralities, the most important sectors of China's economy were identified and ranked. Within the global production network, these sectors occupy very high positions, while the sectors of Vietnam's economy are far behind. For example, for the weighted degree centralities of the 2020 network, China's top sector was in the third position, meanwhile, Vietnam's top sector was 209th. Clearly, as of now, Vietnam's importance within the global production network is nowhere near China's.

This paper also finds that, despite efforts to decouple from China, the Western world is still increasing its dependence on China in terms of both supply and demand. Using HEM and GEM, the forward linkages between the West (represented by the US and the EU) and China were assessed. These linkages measure the effects on overall output if a sector or an entire country stops importing. A clear increase was observed, indicating the rising reliance of the West on China. The backward linkages were measured by changes in domestic value added in Chinese exports and it was also apparent that the West is becoming increasingly dependent on Chinese inputs.

Nevertheless, it seems that economies like the US, the EU, Japan, and South Korea are also sourcing more and more inputs from Vietnam and at a faster rate than they are sourcing from China. Additionally, these findings are supported by an increase in Vietnam's participation in the GVC network which was also observed.

While these findings suggest that there might be a possibility in the future for Vietnam to compete with China, at least in certain industries, further research on future data will be required to see if that can be the case. From the data observed in this thesis, it was not possible to confirm this hypothesis.

The overall findings of this thesis should alert policymakers to continue monitoring the increasing role of China and look for ways to decrease the dependence. Not only because potential shocks to the Chinese economy can easily cause ripple effects to the rest of the world (as we saw during the Covid-19 pandemic), but also because the Western world could potentially be held hostage if China continues expanding its influence.

Future research should also focus more on the resilience of global value chains or investigate other economies beyond Vietnam to evaluate their capacities to compete with China. While it might not be feasible for a single economy to replace China in the top position in the global economy, strategic measures could be taken to assist multiple countries at once. Together with Vietnam, other emerging economies, such as Indonesia or the Philippines, could play an important role in decreasing the world's overreliance on China and diversifying GVCs.

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Appendix A: Trade Decomposition

KKW decomposition

The essential decomposition of total exports of country s ($\mathbf{u}_N \mathbf{E}_{s*}$) formulized by KKW (Borin & Mancini, 2017):

$$\begin{aligned}
\mathbf{u}_N \mathbf{E}_{s*} = & \left\{ \mathbf{V}_s \sum_{r \neq s}^{G} \mathbf{B}_{ss} \mathbf{Y}_{sr} + \mathbf{V}_s \sum_{r \neq s}^{G} \mathbf{B}_{sr} \mathbf{Y}_{rr} + \mathbf{V}_s \sum_{r \neq s}^{G} \sum_{t \neq s,r}^{G} \mathbf{B}_{sr} \mathbf{Y}_{rt} \right\} \\
+ & \left\{ \mathbf{V}_s \sum_{r \neq s}^{G} \mathbf{B}_{sr} \mathbf{Y}_{rs} + \mathbf{V}_s \sum_{r \neq s}^{G} \mathbf{B}_{sr} \mathbf{A}_{rs} (\mathbf{I} - \mathbf{A}_{ss})^{-1} \mathbf{Y}_{ss} \right\} \\
+ & \mathbf{V}_s \sum_{r \neq s}^{G} \mathbf{B}_{sr} \mathbf{A}_{rs} (\mathbf{I} - \mathbf{A}_{ss})^{-1} \mathbf{E}_{s*} \\
+ & \left\{ \sum_{t \neq s}^{G} \sum_{r \neq s}^{G} \mathbf{V}_t \mathbf{B}_{ts} \mathbf{Y}_{sr} + \sum_{t \neq s}^{G} \sum_{r \neq s}^{G} \mathbf{V}_t \mathbf{B}_{ts} \mathbf{A}_{sr} (\mathbf{I} - \mathbf{A}_{rr})^{-1} \mathbf{Y}_{rr} \right\} \\
+ & \sum_{t \neq s}^{G} \sum_{r \neq s}^{G} \mathbf{V}_t \mathbf{B}_{ts} \mathbf{A}_{sr} (\mathbf{I} - \mathbf{A}_{rr})^{-1} \mathbf{E}_{r*}
\end{aligned} \tag{A.1}$$

Chronologically, the terms in Equation (A.1) are defined as:

1 DVA in direct final goods exports
2 DVA in intermediate exports absorbed by direct importers
3 DVA in intermediate exports absorbed by direct importers
4 DVA in intermediate exports re-imported as final goods
5 DVA in intermediate inputs re-imported as intermediate goods and finally absorbed at home
6 double-counted intermediate exports originally produced at home
7 FVA in exports of final goods
8 FVA in exports of intermediate goods
9 double-counted intermediate exports of intermediate goods

Source-based bilateral decomposition

The source-based decomposition of bilateral exports from country s to country r presented by Borin and Mancini (2017):

$$
\begin{aligned}
u_N E_{sr} = {} & \overset{\textbf{1a*}}{V_s(I - A_{ss})^{-1} Y_{sr}} \\
& + V_s(I - A_{ss})^{-1} A_{sr}(I - A_{rr})^{-1} \Bigg[\overset{\textbf{1b*}}{\sum_{j \neq r}^{G} A_{rj} B_{js} Y_{sr}} + \overset{\textbf{1c*}}{\sum_{j \neq r}^{G} A_{rj} \sum_{k \neq s,r}^{G} B_{js} Y_{sk}} \Bigg] \\
& + V_s(I - A_{ss})^{-1} A_{sr}(I - A_{rr})^{-1} \Bigg[\overset{\textbf{2a*}}{Y_{rr}} + \overset{\textbf{2b*}}{\sum_{j \neq r}^{G} A_{rj} B_{jr} Y_{rr}} + \overset{\textbf{2c*}}{\sum_{j \neq r}^{G} A_{rj} \sum_{k \neq s,r}^{G} B_{jk} Y_{kk}} \Bigg] \\
& + V_s(I - A_{ss})^{-1} A_{sr}(I - A_{rr})^{-1} \Bigg[\overset{\textbf{3a*}}{\sum_{j \neq r,s}^{G} Y_{rj}} + \overset{\textbf{3b*}}{\sum_{j \neq r}^{G} A_{rj} \sum_{l \neq s,r}^{G} B_{jr} Y_{rl}} \\
& \qquad + \overset{\textbf{3c*}}{\sum_{j \neq r}^{G} A_{rj} \sum_{k \neq s,r}^{G} B_{jk} Y_{kr}} + \overset{\textbf{3d*}}{\sum_{j \neq r}^{G} A_{rj} \sum_{k \neq s,r,l}^{G} \sum_{l \neq s,r}^{G} B_{jk} Y_{kl}} \Bigg] \\
& + V_s(I - A_{ss})^{-1} A_{sr}(I - A_{rr})^{-1} \Bigg[\overset{\textbf{4a*}}{Y_{rs}} + \overset{\textbf{4b*}}{\sum_{j \neq r}^{G} A_{rj} B_{jr} Y_{rs}} + \overset{\textbf{4c*}}{\sum_{j \neq r}^{G} A_{rj} \sum_{k \neq s,r}^{G} B_{jk} Y_{ks}} \Bigg] \\
& + \overset{\textbf{5*}}{V_s(I - A_{ss})^{-1} A_{sr}(I - A_{rr})^{-1} \sum_{j \neq r}^{G} A_{rj} B_{js} Y_{ss}} \\
& + \overset{\textbf{6*}}{V_s(I - A_{ss})^{-1} \sum_{t \neq s}^{G} A_{rt} B_{ts} E_{sr}} \\
& + \overset{\textbf{7}}{\sum_{t \neq s}^{G} V_t B_{ts} Y_{sr}} + \overset{\textbf{8}}{\sum_{t \neq s}^{G} V_t B_{ts} A_{sr}(I - A_{rr})^{-1} Y_{rr}} \\
& + \overset{\textbf{9}}{\sum_{t \neq s}^{G} V_t B_{ts} A_{sr}(I - A_{rr})^{-1} E_{r*}}
\end{aligned}
\tag{A.2}
$$

The terms are defined as:

1a* DVA in final good exports directly absorbed by bilateral importers

1b* DVA in intermediate exports absorbed by bilateral importers as domestic final goods after additional processing stages

1c* DVA in intermediate exports absorbed by third countries as domestic final goods after additional processing stages

2a* DVA in intermediate exports absorbed by direct importers as local final goods

2b* DVA in intermediate exports absorbed by direct importers as local final goods only after further processing stages

2c* DVA in intermediate exports absorbed by third countries as local final goods

3a* DVA in intermediate exports absorbed by third countries as final goods from direct bilateral importers

3b* DVA in intermediate exports absorbed by third countries as final goods from direct bilateral importers only after further processing stages

3c* DVA in intermediate exports absorbed by direct importers as final goods from third countries

3d* DVA in intermediate exports absorbed by third countries as final goods from other third countries

4a* DVA in intermediate exports absorbed at home as final goods of the bilateral importers

4b* DVA in intermediate exports absorbed at home as final goods of the bilateral importers after further processing stages

4c* DVA in intermediate exports absorbed at home as final goods of a third country

5* DVA in intermediate exports absorbed at home as domestic final goods

6* double-counted intermediate exports originally produced at home

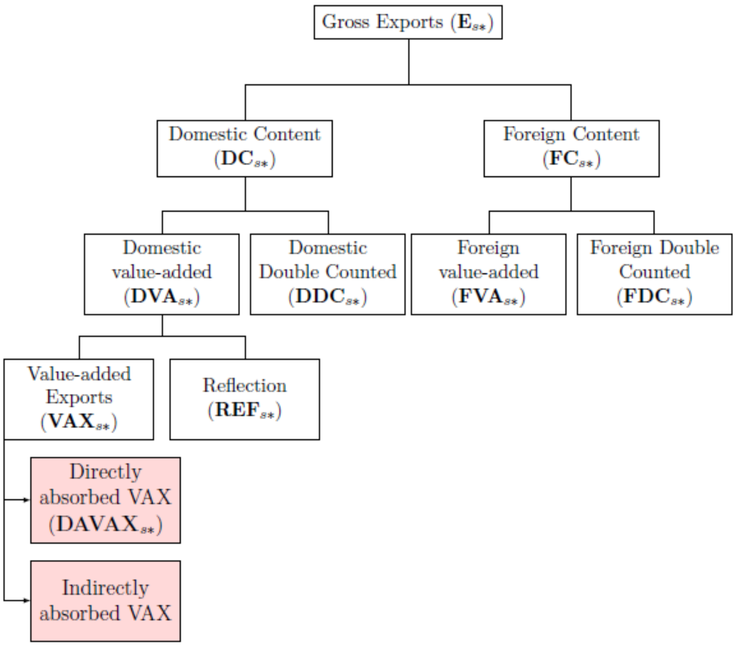
7 FVA in export of final goods

8 FVA in exports of intermediate goods

9 double-counted intermediate exports originally produced abroad

Borin and Mancini (2017) show that the components are equal to those in KWW (A.1) when summed up, e.g. $2a^* + 2b^* + 2c^*$(in A.2) = 2 (in A.1).

Figure A.1: A scheme of value-added decomposition of total exports based on Koopman et al. (2014), extended by Borin and Mancini (2019)



Source: Belotti et al. (2020)

Appendix B: OECD ICIO Tables

Countries included in OECD ICIO Tables 2022

OECD countries: Australia, Austria, Belgium, Canada, Chile, Colombia, Costa Rica, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Israel, Italy, Japan, Korea, Latvia, Lithuania, Luxembourg, Mexico, Netherlands, New Zealand, Norway, Poland, Portugal, Slovak Republic, Slovenia, Spain, Sweden, Switzerland, Turkey, United Kingdom, United States

Non-OECD countries: Argentina, Bangladesh, Belarus, Brazil, Brunei, Bulgaria, Cambodia, Cameroon, China, Côte d'Ivoire, Croatia, Cyprus, Egypt, Hong Kong, India, Indonesia, Jordan, Kazakhstan, Laos, Malaysia, Malta, Morocco, Myanmar, Nigeria, Pakistan, Peru, Philippines, Romania, Russian Federation, Saudi Arabia, Senegal, Singapore, South Africa, Chinese Taipei, Thailand, Tunisia, Ukraine, Vietnam

Also, trade data for Rest of the World are included, as well as split tables for Mexico and China.

Industries included in OECD ICIO Tables 2022

Industry	ISIC Rev.4[55]
Agriculture, hunting, forestry	01, 02
Fishing and aquaculture	03
Mining and quarrying, energy producing products	05, 06
Mining and quarrying, non-energy producing products	07, 08
Mining support service activities	09
Food products, beverages and tobacco	10, 11, 12
Textiles, textile products, leather and footwear	13, 14, 15
Wood and products of wood and cork	16
Paper products and printing	17, 18
Coke and refined petroleum products	19
Chemical and chemical products	20
Pharmaceuticals, medicinal chemical and botanical products	21
Rubber and plastics products	22
Other non-metallic mineral products	23

[55]International Standard Industrial Classification of All Economic Activities (Rev.4 is the latest version)

Basic metals	24
Fabricated metal products	25
Computer, electronic and optical equipment	26
Electrical equipment	27
Machinery and equipment, n.e.c.[56]	28
Motor vehicles, trailers and semi-trailers	29
Other transport equipment	30
Manufacturing n.e.c.; repair and installation of machinery and equipment	31, 32, 33
Electricity, gas, steam and air conditioning supply	35
Water supply; sewerage, waste management and remediation activities	36, 37, 38, 39
Construction	41, 42, 43
Wholesale and retail trade; repair of motor vehicles	45, 46, 47
Land transport and transport via pipelines	49
Water transport	50
Air transport	51
Warehousing and support activities for transportation	52
Postal and courier activities	53
Accommodation and food service activities	55, 56
Publishing, audiovisual and broadcasting activities	58, 59, 60
Telecommunications	61
IT and other information services	62, 63
Financial and insurance activities	64, 65, 66
Real estate activities	68
Professional, scientific and technical activities	69 to 75
Administrative and support services	77 to 82
Public administration and defence; compulsory social security	84
Education	85
Human health and social work activities	86, 87, 88
Arts, entertainment and recreation	90, 91, 92, 93
Other service activities	94,95, 96
Activities of households as employers; undifferentiated goods- and services-producing activities of households for own use	97, 98

Source: OECD

[56] not elsewhere specified

Appendix C Supplementary results: Trade Decomposition

Table C.1: GVC-related trade results

	China			Vietnam		
year	Backward	Forward	Total	Backward	Forward	Total
1995	15.57	11.75	27.32	23.45	10.65	34.10
1996	15.41	11.61	27.02	26.82	10.42	37.24
1997	16.17	12.25	28.42	26.97	11.31	38.28
1998	14.42	13.07	27.49	27.17	11.71	38.88
1999	15.73	12.92	28.66	27.89	12.09	39.99
2000	17.86	13.20	31.06	30.20	11.67	41.87
2001	17.71	12.74	30.45	30.36	12.08	42.45
2002	19.08	12.54	31.62	32.36	12.38	44.74
2003	22.23	12.55	34.77	34.49	12.07	46.56
2004	24.59	13.06	37.64	35.12	13.47	48.58
2005	24.84	13.29	38.13	35.76	13.87	49.63
2006	24.08	13.58	37.66	37.49	12.97	50.46
2007	23.53	14.07	37.61	40.60	12.33	52.93
2008	23.42	14.85	38.27	43.21	10.76	53.97
2009	18.60	13.59	32.19	40.16	10.60	50.75
2010	20.55	14.57	35.13	42.67	9.86	52.53
2011	21.79	14.69	36.48	43.88	9.56	53.44
2012	20.94	14.70	35.64	43.05	9.98	53.04
2013	20.16	14.76	34.92	43.63	9.96	53.60
2014	18.95	15.08	34.03	45.06	9.63	54.69
2015	17.23	15.38	32.60	47.02	9.81	56.83
2016	16.88	15.33	32.21	48.10	8.88	56.98
2017	18.21	15.52	33.73	50.19	8.90	59.09
2018	18.30	15.98	34.28	50.63	8.94	59.57
2019	17.53	16.11	33.63	50.63	8.64	59.27
2020	16.89	15.79	32.68	50.42	8.20	58.61

Table C.2: GVC-related trade in bilateral exports of China results

year	USA		EU		Japan		Korea		Vietnam	
	Backward	Forward	Backward	Forward	Backward	Forward	Backward	Forward	Backward	Forward
1996	17.54	4.77	16.62	7.02	15.00	3.99	14.02	19.83	14.44	15.90
1997	17.88	5.36	17.15	7.79	15.54	4.96	14.91	23.84	14.52	18.34
1998	16.16	5.56	15.35	7.96	13.71	5.27	14.19	33.72	12.66	20.47
1999	17.63	5.25	16.87	7.95	14.82	4.79	14.88	27.70	12.67	20.53
2000	20.02	5.24	18.85	9.68	16.99	5.19	16.55	21.91	15.67	21.71
2001	18.87	4.91	19.11	9.12	16.73	5.49	16.86	22.53	15.75	24.92
2002	20.49	4.56	20.29	8.86	18.22	5.71	17.24	19.85	16.91	26.05
2003	23.14	4.25	23.86	8.31	21.06	6.23	20.35	21.44	19.97	27.38
2004	25.55	4.53	26.14	8.63	23.17	7.14	22.83	24.15	22.36	27.45
2005	26.34	4.72	25.69	9.04	23.48	8.82	23.33	22.49	23.75	29.32
2006	25.52	4.91	24.96	9.50	22.61	9.62	22.69	22.68	22.39	30.03
2007	24.83	5.22	24.26	9.81	22.05	10.18	22.53	23.49	21.90	25.64
2008	24.29	5.72	23.79	9.98	22.10	10.22	22.76	27.54	21.95	29.81
2009	19.40	4.85	18.66	9.17	17.06	7.44	18.65	27.59	19.12	30.43
2010	20.96	5.09	20.67	10.29	19.62	8.86	20.17	27.16	21.73	33.71
2011	22.21	5.52	21.73	10.57	20.54	7.91	21.89	28.73	23.43	36.22
2012	21.49	5.42	20.72	11.46	19.92	7.43	20.44	28.85	22.84	37.92
2013	20.64	5.57	19.58	11.47	19.45	7.62	19.71	28.25	21.64	39.42
2014	19.38	5.72	18.22	11.79	18.52	8.65	18.58	28.51	20.50	40.96
2015	17.75	5.55	16.78	12.85	16.81	9.12	17.08	30.05	17.29	44.21
2016	17.58	5.19	16.49	12.23	16.40	8.57	16.56	28.59	16.16	46.04
2017	18.94	5.21	17.43	12.38	17.55	9.28	18.00	28.05	17.46	47.62
2018	18.67	5.26	17.44	12.26	17.57	9.71	18.24	28.57	19.33	47.49
2019	17.53	4.93	16.97	12.31	17.03	9.28	18.00	26.20	18.16	47.89
2020	17.28	4.08	16.26	11.86	16.77	9.05	17.79	25.86	16.43	47.67

Table C.3: GVC-related trade in bilateral exports of Vietnam results

year	USA		EU		Japan		Korea		China	
	Backward	Forward	Backward	Forward	Backward	Forward	Backward	Forward	Backward	Forward
1996	22.58	4.89	28.99	5.01	24.77	3.38	25.94	13.35	17.29	12.08
1997	24.29	4.26	31.70	4.92	25.18	3.96	27.19	13.07	18.88	14.78
1998	22.50	5.22	31.70	4.96	26.72	3.97	26.27	22.62	21.07	11.70
1999	25.53	4.16	31.25	5.15	28.96	3.24	28.86	16.23	19.10	12.44
2000	27.21	3.74	34.10	5.51	33.00	3.30	29.80	12.12	18.67	12.91
2001	28.12	3.40	32.60	6.07	32.92	4.01	31.16	12.69	20.17	13.01
2002	32.93	2.33	35.80	6.84	34.75	4.63	31.91	11.58	21.22	15.40
2003	35.55	2.37	36.75	6.31	35.88	5.22	33.66	11.85	24.44	17.90
2004	35.77	2.55	37.86	6.39	36.67	5.79	32.89	13.88	22.69	22.44
2005	36.80	2.61	37.54	7.08	37.65	6.32	34.99	11.24	25.53	22.00
2006	37.47	2.95	39.55	6.29	39.75	7.43	36.48	10.78	31.27	18.72
2007	41.60	2.95	41.42	6.53	42.00	7.89	39.51	11.98	35.91	16.87
2008	43.68	2.93	42.14	5.92	43.64	7.87	42.41	14.44	41.50	15.85
2009	41.08	2.78	39.64	5.42	42.89	5.75	39.05	18.98	37.43	13.40
2010	43.97	2.78	42.79	5.31	45.13	5.80	39.98	18.81	41.33	13.91
2011	45.31	2.85	44.63	5.47	43.78	6.25	41.40	18.33	42.20	13.57
2012	44.40	2.63	42.93	6.90	42.24	6.26	41.55	17.29	43.26	14.77
2013	44.32	2.80	44.03	6.28	42.22	7.32	41.85	18.44	43.90	13.74
2014	45.75	2.74	45.23	6.27	43.98	7.64	43.57	15.32	45.48	13.24
2015	48.27	2.27	46.73	6.73	46.28	7.51	46.61	15.94	48.48	12.33
2016	49.01	2.16	47.87	6.19	47.50	6.61	48.44	14.69	48.28	11.60
2017	50.45	2.12	49.47	5.88	48.36	7.00	50.06	13.53	52.77	11.85
2018	51.07	1.95	49.80	5.72	49.32	7.04	50.68	13.65	53.23	11.13
2019	51.84	1.84	49.51	5.80	49.00	6.82	50.72	13.51	52.67	10.98
2020	51.47	1.74	48.91	5.57	47.99	6.50	50.28	11.57	53.22	10.74

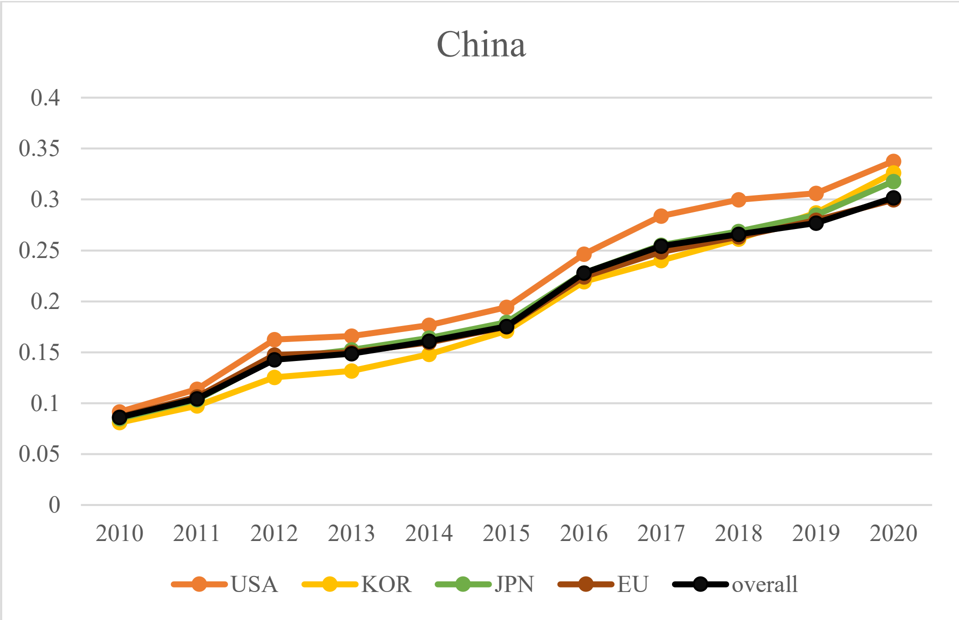


Figure C.1: Value added originating in Vietnam in China's bilateral exports

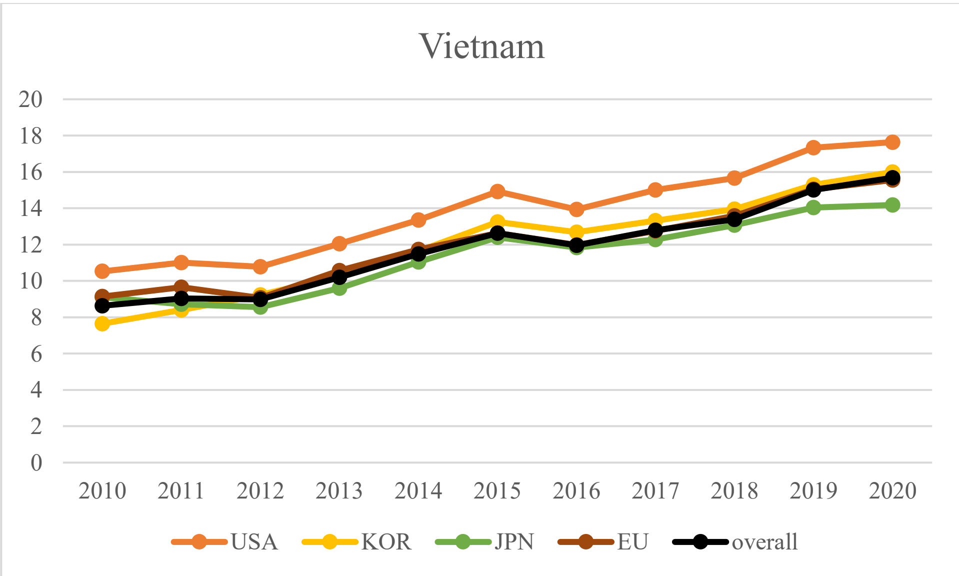


Figure C.2: Value added originating in China in Vietnam's bilateral exports