Production Networks and Rules of Origin: Moving From NAFTA to USMCA

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Abstract

Free Trade Agreements (FTAs) give firms within the member countries duty-free access to each other's markets. But with a catch. Non-bloc workers and capitalists are the primary beneficiaries if these firms rely heavily on suppliers outside the bloc for their upstream inputs. So to limit this diversion of factor demand, FTAs include elaborate rules—known as Rules of origin (RoOs)—that dictate how much of a product's value must be created within the bloc for it to be "in compliance," i.e., enjoy duty-free access to member country markets.

Because value chains are often lengthy, it is difficult to discern which firms RoOs favor, which firms they penalize, and by how much. I use comprehensive value-added tax records from Mexico to shed new light on these issues. In particular, I study the effects of the North American Free Trade Agreement (NAFTA) and its replacement, the United States-Mexico-Canada Agreement (USMCA), on the Mexican automotive sector.

Four main findings emerge. First, Mexican auto sector value chains exhibit strong interconnectedness, with 30 percent of firms serving ten or more assemblers and contributing to a third of the transaction volume. Second, when the USMCA replaced NAFTA, car parts producers were the most affected group within the value chain. These firms experienced a threefold decrease in compliance rates compared to car assemblers. Third, however, the steep increase in regional content requirements (RCRs) was alleviated by a new "super-core roll-up" provision, which allowed some producers to round up their suppliers' domestic content to 100 percent. Finally, if the super-core roll-up provision had not been implemented, the fraction of Mexican parts producers qualifying for duty-free treatment within the bloc would have halved. Instead, the qualifying fraction dropped by only 14 percentage points.

1 Introduction

In recent decades, Free Trade Agreements (FTAs) have become increasingly popular.[1] These agreements facilitate trade between the member countries by granting preferential tariffs to goods produced within them. But as production chains have become increasingly globalized, implementing these FTAs has become increasingly complicated. Large chunks of the FTA documents are now

[1] See Maggi (2014)[22], for a comprehensive review of the economics of Free Trade Agreement (FTA)s, their motives, design, and evaluation.

devoted to codifying the conditions under which a good is considered originary, i.e., produced inside the FTA territory. These conditions, known as rules of origin (RoOs), play a crucial role in preventing trade circumvention and attracting economic activity to the FTA region.

The complexity of these rules, which vary significantly across trade deals and industries, has presented a challenge for governments, who often design them without sufficient guidance on their overall economic impact. As highlighted by Kniahi and de Melo (2022)[18], this complexity has made it difficult for researchers to study the effects of Rules of Origin (RoOs) and hindered governments' ability to regulate trade effectively. Accordingly, in this paper, I develop a methodology that allows governments to assess the incidence of their RoOs and explore the impact of alternative policy regimes. I implement this methodology using value-added tax records from Mexico, which provide transactions-level information on each firm's entire value chain. To my knowledge, I am the first to use this type of data to analyze RoOs.

A case study of Mexico

I focus my analysis on the Mexican auto sector for three reasons. First, automotive production in North America provides a compelling case study of global value chains (GVCs) and effectively demonstrates the impact of RoOs on value chains (VCs). Throughout NAFTA's 26 years, the automotive GVC became intricately integrated. Subsequently, with the replacement of NAFTA by USMCA in January 2020, there was a significant rise in the regional value content (RVC) requirements. These modifications have facilitated an insightful natural experiment, allowing us to evaluate compliance under both regulatory frameworks while isolating these effects from adjustments in firms' sourcing strategies. As a result, this approach allows for a deeper understanding of how RoOs impact origin compliance and RVC while also enabling the isolation of these effects from adjustments in firms' sourcing strategies.

Second, as evidenced by its prominence in both NAFTA and the recently negotiated USMCA, the automotive sector holds significant importance in Mexico's trade relationships. It accounts for 7 out of 10 articles within the RoOs chapter of the USMCA and 90 out of 270 pages in the RoOs chapter outline specific rules for the automotive industry, providing further proof of its significance.

Finally, as the seventh-largest automobile producer in the world and the largest in Latin America[2], Mexico's auto sector contributes significantly to the country's economy. It represents 18% of manufacturing GDP and 3.6% of national GDP. In addition, Mexico is a crucial player in the international auto market, being a prominent exporter of automotive products: approximately 32% of the country's manufacturing exports are of automobile products. Moreover, Mexico is the fourth largest auto-parts exporter globally and the top US supplier.

Contributions

My analysis yields three main contributions. The first is a comprehensive dataset on the Mexican production network, specifically focusing on the auto sector in 2017. A unique aspect of this dataset is the inclusion of Mexican firm-to-firm connections inferred from value-added tax (VAT) records. By combining them with customs data and other complementary sources, I recover the domestic connections of Mexican firms and their connections abroad. While previous studies have utilized VAT data to establish firm-to-firm connections in countries like Belgium, Japan, Chile, and Costa Rica,[3] this is the first paper to employ a similar approach for Mexico. Using these data, I characterize the value chain of 13 auto assemblers in Mexico, revealing the significant interconnectivity across their value chains for the first time. Remarkably, most firms serve at least one assembler. Additionally, such well-established suppliers also possess substantial shares of the trade volume. For instance, firms that serve at least five assemblers exchange more than half of the transaction volume.

My second contribution is the creation of an open-source origin calculator that evaluates a firm's RoO compliance based on the product it exports, its inputs' origin, and its production costs. This calculator constitutes the most detailed representation of RoOs for North America in the literature, a valuable tool for any researcher that studies RoOs in NAFTA or USMCA. I outline the methodology for developing this calculator in Section 4.

My third contribution regards the insights I elicit by combining the created dataset and calculator. I assess the potential differences in compliance if the USMCA's RoOs were applied during the sample year instead of the RoOs from NAFTA, which were in force at the time. I estimate a 9.65% decrease

[2]These rankings are in terms of units.

[3]See Dhyne et al. 2021 [9]; Kikkawa et al. 2020[17], Bernard et al. 2016[4]; Furusawa et al. 2017[13], Huneeus 2018 [15], Alfaro-Ureña et al. 2018 [1], to mention a few.

in assemblers' compliance rate under USMCA but, most notably, the estimated reduction for auto part producers is 18.33%.

My findings regarding a controversial interpretation of the USMCA's RoOs are of particular interest. In 2022, the United States unilaterally decided to implement a different method for calculating the RVC of *super-core* parts in the production of passenger vehicles or light trucks. However, the Dispute Settlement Panel rejected their method, which did not allow core parts producers to round up (”roll up”) the regional factor content of their inputs. I show that if the dispute settlement panel had ruled in favor of the US' interpretation, the compliance rate would have decreased by 50%, in contrast to the estimated 18% decrease when the super-core roll-up is allowed.[4]

In sum, this paper offers valuable insights into the intricate features of RoOs, uncovering the complexities and interplays of compliance rates and RCRs along the value chain, focusing on the context of the transition from NAFTA to USMCA regulations.

Relation to the literature

My work contributes to and builds upon the large empirical literature on FTAs. The most closely related papers study the same region and agreements. In this group, Conconi (2018) [6] and Head et al. (2022) [14] stand out, especially the latter, which also analyzes the effects of the USMCA on Mexican auto firms. Its methodology and objectives are somewhat different, however. In their project, inputs are viewed as a continuum, analyzing the impact of the new agreement on sourcing strategies. The approach implicitly assumes that inputs obtained within the region are exclusively made using regional resources.[5] In contrast, I treat firms as a discrete finite set and the value chain as a fixed graph, focusing on patterns of compliance along the entire upstream value chain. Given these differences, our results are not directly comparable. Nevertheless, in Section 6.2, I show how compliance is severely underestimated when non-RVC components of RoOs are omitted, when the upstream compliance is not accounted in RVC calculations, and when we assume a flat RCR across all product codes. Conconi et al. (2018)[6], on the other hand, explore the impact

[4]Notably, the implications of cumulation in RoOs have also been investigated by Bombarda and Gamberoni (2013)[5].

[5]While I relax this implicit assumption, it entails the introduction of other simplifying assumptions. I aim to transparently outline these differences and similarities between our approaches in the subsequent sections, recognizing the potential for learning from the complementarity of our perspectives.

of RoOs within FTAs on trade patterns of intermediate goods. Their study aims to uncover the implications of these rules on sourcing decisions and trade flows. Specifically, the authors concentrate on NAFTA's RoOs defined by changes in tariff classification, also known as *tariff shift*, rather than RCR requirements. By leveraging variations across countries and products, they demonstrate that NAFTA's RoOs incentivized a redirection of intermediate imports from third-party countries towards NAFTA partners.

Several other empirical studies merit mention. In particular, Kniahin & de Melo(2022)[18], provides a detailed characterization of RoOs, including provisions on regional value, changes in tariff classifications, cumulation, as well as product-specific allowances and exceptions. However, specific provisions related to specific processes are not studied due to a lack of detail in the available data. Freund (2019)[12] and Febelmayr et al. (2019)[11] highlight the need for improvements in the design of RoOs. Additionally, Yang (2022)[30] has shed light on the ambiguous effects of RoOs, showing that more stringent requirements often lead to lower regional content. If regional content requirements are too high, RoOs can have consequences opposite to those intended, effectively acting as barriers to trade. However, these papers do not consider another deterrent to compliance: the complexity of RoOs, which makes it difficult for businesses to comply and results in higher costs and time delays. This can particularly affect small and medium-sized firms, as they may not have the resources to navigate the complex rules and may choose to avoid utilizing FTAs altogether. Evidence from Colombia, as presented by Krishna et al. (2022)[20], supports this notion. They demonstrate that meeting RoO requirements increases production costs and imposes significant fixed costs in the form of documentation expenses. Additionally, their findings indicate that RoOs can negatively impact competition, favoring larger and more experienced firms more likely to utilize preferential benefits.

One feature of modern supply chains is that they exhibit high levels of specialization. Therefore, suppliers often customize their products to suit specific downstream uses. Thus, increasing trade barriers between two countries with integrated GVC imposes significant and heterogeneous costs on all firms in the FTA territory and in other countries. (See De Gortari 2019 [8], Antràs and de Gortari 2019[3]). I aim to further our understanding of the effects of RoO along the value chain, specifically focusing on the Mexican automobile industry and the transition from NAFTA to USMCA.

While my work is empirical, it is related to the theoretical literature analyzing the economic effects of RoOs. Notable papers include Rosellón (2000)[25], Falvey & Reed (2002)[10], Mukunoki (2017)[23], Krishna (2005)[19], Ju & Krishna (2005)[16], and Tsirekidze (2021)[28], who provide valuable insights into various aspects of RoOs.

The papers by Ju and Krishna[16] and Krishna[19] examine the impact of RoOs in FTAs. Ju and Krishna identify contrasting effects of RoO, with different impacts on imports of intermediate and final goods, affecting the welfare of producers inside and outside the FTA. Both studies contribute to understanding how RoO affect trade behavior and market access, shedding light on the complexities exporters face in navigating trade agreements.

Rosellón (2000)[25] demonstrates that a stricter rule of origin can boost the demand for domestic factors if the substitution effect outweighs the effects of reduced operational scale and output reallocation. It advocates for policy decisions on RoOs that aim to maximize welfare and foster domestic technological advancement by aligning the interests of stakeholders in the production chain.

Falvey & Reed (2002)[10] delve into the complexities of applying RoOs, emphasizing the challenges and variations in determining product origin. They highlight the potential discrepancies in origin determinations within the same country, influenced by the underlying objectives of the implemented laws. The paper underscores the supportive role of RoOs alongside other policy instruments, elucidating their impact on trade dynamics and the potential consequences for importing nations.

Mukunoki (2017)[23] explores how the formation of a FTA alters the patterns of Foreign Direct Investment (FDI) by non-FTA country firms, particularly in connection to the restrictiveness of RoOs. The study outlines potential effects such as deterring outside firms' FDIs, the substitution of efficient firms with less proficient ones, or the elimination of pre-existing FDIs before the FTA conclusion, complicating the welfare assessment of FTAs and potentially reducing consumer surplus.

Tsirekidze (2021)[28] provides a game theory perspective showing the essential role of RoOs in achieving global free trade. In the symmetric countries case, global free trade stability diminishes as countries engage more in GVCs, primarily due to free riding issues. In asymmetric countries settings, RoOs can stabilize global free trade by curbing the benefits countries derive from others' free trade agreements, underscoring the crucial role of RoOs in realizing global free trade.

One last strand of literature related to this project pertains to the study of *boolean networks*—a specific type of network modeling that proves highly useful when dealing with many components and complex interactions. Boolean networks are widely employed in Physics, Biology, and Computer Science (Saadatpour & Albert (2013) [26] and Schwab et al. (2020)[27] are examples of this literature) to model intricate systems, where the state of each node (in this case, firms) is determined by other variables in the network, such as the origin of inputs (i.e., upstream RoO compliance). Network modeling, with components represented as nodes (firms) and interactions denoted as edges (input purchases), represents a powerful method for structurally analyzing and modeling complex systems. Deciphering the structure and interactions within these networks lays the groundwork for understanding the system's overall behavior—in this instance, the Mexican auto VC.

In summary, treating the transition from NAFTA to USMCA as a natural experiment, this paper offers valuable insights into the intricacies of RoOs by uncovering the complexities and interplays of compliance rates and RCRs along the value chain.

Structure of the paper

The remaining sections of this paper are structured as follows: Section 2 provides an overview of the key concepts utilized in this paper to establish a solid foundation for the analysis. Section 3 outlines the methodology employed to identify and examine the Mexican auto value chain (VC), offering novel insights into its structure and dynamics. Section 4 presents the methodology adopted to develop the origin calculator, which is a crucial tool in evaluating the effects of RoOs (RoOs). Section 5 investigates the changes in RoOs from the North American Free Trade Agreement (NAFTA) to the United States-Mexico-Canada Agreement (USMCA), shedding light on the modifications and their potential implications. Section 6 carries out an empirical exercise, unveiling the main findings and outcomes derived from the analysis. Finally, in Section 7, I conclude the paper and present our closing remarks, summarizing the key takeaways and implications of this research.

2 Rules of Origin (RoOs)

In this section, we establish the key definitions needed to understand the methodology employed. We also introduce the terminology used to classify RoOs based on their structure. These definitions have been sourced from two primary references: the NAFTA and USMCA documents, and the Rules of Origin Facilitator (ROF) project. The latter is a collaborative initiative between the International Trade Centre (ITC), the World Customs Organization (WCO), and the World Trade Organization (WTO).[6]

Free Trade Agreements aim to promote international trade by eliminating barriers and extending preferential access to markets among member countries. These agreements typically cover trade in goods, services, and investment provisions. In addition, they may also include customs cooperation, trade facilitation, harmonization of standards, and regulatory cooperation measures. To ensure fair trade among member countries, preferential rules of origin are applied, preventing non-member countries from taking advantage of preferential tariffs without offering reciprocal benefits.

Harmonized System (HS) Classification, also known as the HS Nomenclature, is an international customs classification system created by the WCO. It assigns unique 6-digit codes to different groups of products. These codes help customs authorities identify products and determine the appropriate import duty, taxes, and trade measures. Understanding the HS classification is necessary to determine the applicable RoOs under any FTA, as different commodity codes carry different rules. The 6-digit codes of the classification scheme simultaneously represent chapters (the first 2 digits), headings (the first 4 digits), and subheadings (the full 6 digits). In the case of USMCA partners, these codes are further disaggregated into 8-digit items, also known as commodity codes or national tariff lines (NTLs).

Rules of origin (RoOs) To determine eligibility for preferential tariffs offered under a trade agreement, goods must comply with a set of criteria known as *rules of origin* (RoOs). These criteria are used to establish whether a good is considered to have originated in the region of the trade agreement. RoOs are specific to each product and are typically based on the HS classification scheme. This means that every HS code eligible for preferential tariff under a trade agreement has its own unique rule of origin. These rules can be set at different levels, ranging from an entire chapter to a

[6] To ensure conciseness and relevance, some details have been excluded if they are not directly relevant to NAFTA or USMCA. For a complete understanding of the concepts discussed in the following sections, please consult the official website of the ROF at findrulesoforigin.org.

very specific product within an HS or NTL. RoOs are negotiated and included as part of the main agreement between trading partners, usually in the form of a protocol or annex. Because RoOs are specific to each FTA, they can vary significantly across agreements.

In an FTA region, the origin(s) of a given good can be determined in two ways. The first way by which a good would be considered "originary" to (i.e., originating from) a region is if the good were obtained from entirely within that one single region. Examples in this category are livestock, agricultural products, or extracted minerals. Note that goods in this group are "originary" only if produced without the addition of any non-originary materials. The second way for determining that a good is "originary" to a given FTA region is if the good undergoes a substantial transformation within that region. In the auto sector, all RoOs fall into the latter category. This latter type of RoO is explained in the following subsection.

Substantial Transformation refers to a type of RoO that requires a good to go through a specific process in order to be considered originary to a particular country. There are three main avenues by which substantial transformation is considered to occur. The first is known as change in tariff classification (CTC), which requires that the final good be classified under a tariff classification group that differs from the classification group(s) of all non-originating materials used in the production process. The classification group can be a chapter, a heading, a subheading, or an item, which corresponds to the HS codes at two, four, six, and eight digits, respectively. Consider a situation where a manufacturer produces tractor spark plugs with the NTL code 85111002. The rule concerning these spark plugs requires a change in the classification subheading from any other subheading. Put plainly, for these tractor spark plugs to be recognized as originating products, their non-originating inputs should not be categorized under subheading 851110. This means the producer may source originary spark plugs from subheading 851110, but non-originary components in the manufacturing process cannot fall under this category for the tractor spark plugs to meet the requirements.

The second avenue is the RVC calculation, which requires that a percentage of the good's total value must have been added within the FTA region. When substantial transformation conditions are defined in this way, they are called regional content requirements (RCRs). Lastly, the specific processing (SP) rule stipulates that a particular process must be carried out at a certain stage of production in order for the good to be considered originary to where this processing took place.

For a given product, a RoO can be defined using a single type of substantial transformation or a combination of them (e.g., CTC and RVC) in determining its origin. Furthermore, there may be exceptions and allowances within each type, specifying certain conditions for particular products and permitting relaxations under special circumstances. Section 4 explains in detail how these three types are combined in NAFTA and the USMCA.

De minimis. This provision allows for the use of a small amount of non-originating materials in the production of a good without impacting its origin status. Essentially, this acts as a relaxation for strict rules of origin. The threshold for both NAFTA and the USMCA is set at 10%.

Roll-up. Under this provision, a part or an intermediate material that gains originating status under a FTA is considered 100% originating contingent upon further processing. This applies even if non-originating inputs were used to produce the part or the intermediate material. Essentially, this provision means that the value of non-originating materials used in the production of a good get disregarded and is another way of making RoOs more lenient. If roll-up is not allowed, firms are required to monitor the non-original content fraction for each input.

Net cost refers to the total cost of production minus any cost lost to sales promotion, marketing, after-sales service, royalties, shipping, packing, and non-allowable interest that may be included in the total cost.

Transaction value means the customs value, as determined in accordance with the Customs Valuation Agreement; that is, the price actually paid or payable for a good or material.

Regional value content. In the case of NAFTA and the USMCA's HS chapter designation for automobile products, the regional value content can be calculated following two methods:

- Net cost

$$RVC = \frac{NC - VNM}{NC} \times 100 \tag{1}$$

  where NC is the net cost of the good, and VNM is the value of non-originating materials.

- Transaction Value

$$RVC = \frac{TV - VNM}{TV} \times 100 \tag{2}$$

where TV is the transaction value of the good.

In the automotive industry, the majority of product-specific RoOs only permit the use of the net cost method. Therefore, in our origin calculator, we will exclude the transaction value method.

3 Identifying the Value Chain (VC)

The identification of the Mexican VC marks a significant and original contribution of this paper. To this end, we conceptualize the world economy as a production network, where a directed weighted graph is used to represent the relationships among firms. In this network, the nodes represent individual firms, the edges symbolize input purchases, and the weight of each edge indicates the trade volume between the buyer and the seller. Each firm specializes in producing a distinct product, allowing us to visualize the VCs as paths or sets of paths within this production network.

Although one may feel tempted to think of VCs linearly, VCs look more like a tree where the root node represents the final good's producer, and all edges point towards the root instead of away from it. [7] A VC can be classified as global when it extends across multiple countries, highlighting the interconnectedness of economies on a global scale. Lastly, we can view the production network as the union of all the VCs within the economy. These VCs overlap and intertwine, creating intricate patterns, such as cliques and cycles, and giving rise to complex interactions within the network.

3.1 Identifying auto assemblers

Our initial dataset captures a comprehensive network that illustrates interactions among all Mexican manufacturing firms, including their domestic exchanges and interactions with foreign firms. The foreign interactions are consolidated at the country-product level, ensuring that a thorough understanding of domestic manufacturing activity is maintained. It is important to note that this dataset represents a cross-section of the network and specifically covers the year 2017, a period during which

[7] Pol Antràs famously referred to these structures as snakes and spiders, respectively, in his 2018 Ohlin Lecture. [2]

NAFTA was in effect. Four different sources of information were combined to construct this dataset. The first source is VAT receipts that contain connections between Mexican firms. The second source is the firms' annual tax declarations, which provide details about their sales revenue, production costs, administrative costs, profits, and main activity. The third source is customs records that provide information about imports and exports at the product level. I have linked these three datasets using anonymized firm identifiers provided by the *Secretaría de Hacienda y Crédito Público* (SHCP, Secretariat of Finance and Public Credit). Lastly, the Mexican Economic Census of 2019, conducted by the *Instituto Nacional de Estadística y Geografía* (INEGI, National Statistics and Geography Institute), provides information about firms' production labor. For a more in-depth description of the data, please refer to appendix A in the current paper.

I begin by identifying the nodes of auto assemblers within the dataset. Initially, we focus on firms with North American Industry Classification System (NAICS) codes beginning with 3361, the number sequence that corresponds to "Motor Vehicle Manufacturing." From this category, we further analyze two subcategories: 336110, corresponding to "Automobiles and Pickup Trucks Manufacturing," and 336120, which corresponds to "Truck and Truck Tractors Manufacturing." A total of $61,028$ firms produce goods that fall into these activity codes. From within this set of auto assemblers, in order to conduct a comprehensive analysis of compliance under different sets of RoOs, we specifically concentrate on those assemblers that export at least a portion of their production. We exclude firms classified as retailers as opposed to producers. When exporting, companies are required to report the NTL code and provide a description of the goods being shipped, which assists us in validating these firms as assemblers. To avoid the inclusion of any firms misclassified as assemblers, we only consider those that exported more than 500 units in 2017. This criterion appears reasonable, as the company just above this threshold exports 732 vehicles, while the one just below exports only 93 vehicles. Applying this filtering process, we are left with a total of 13 auto assemblers, 10 of which are engaged in light-duty vehicle production, together accounting for 58.77% of the light vehicle exports reported in the official statistics for 2017. The remaining 3 assemblers produce heavy-duty vehicles and contribute to 45.91% of 2018's exports in the heavy truck segment.[8] It is important

[8]Source: INEGI's *Registro Administrativo de la Industria Automotriz de Vehículos Ligeros* (RAIAVL, Administrative Registry of the Automotive Industry for Light Vehicles) and *Registro Administrativo de la Industria Automotriz de Vehículos Pesados* (RAIAVP, Administrative Registry of the Automotive Industry for Heavy Vehicles).

to note that heavy vehicle statistics are only available for 2018 onward. However, when comparing the light vehicle production figures for 2018 with those of 2017, they are nearly identical, with the former representing 99.63% of the latter. table 10 shows the assemblers' exports by NTL code.

Table 1: Identified Assemblers

Assembler	**Vehicle Type**	**Exports**	**Avg. Price**	**Units**
Alpha	light	5,738.13	14,516.51	483,154
Beta	light	5,569.27	22,364.24	308,810
Gamma	light	4,533.09	24,659.12	232,011
Delta	light	3,371.91	15,931.40	194,483
Epsilon	light	2,199.79	14,635.18	174,174
Zeta	light	3,178.02	24,520.22	169,828
Theta	light	907.26	12,325.55	87,206
Iota	light	2,515.52	59,277.46	73,792
Kappa	light	1,274.90	30,175.20	65,328
Lambda	heavy	5,202.56	70,124.87	55,302
Mu	heavy	772.60	131,664.97	9,579
Nu	heavy	370.11	100,136.57	3,629
Xi	light	44.79	69,273.66	732

Note: Exports are reported in million dollars.

After pinning down the assemblers, the next step is to trace back their VC. This involves recording the assemblers' providers, their providers' providers, and so on. Throughout the remainder of this section, we will refer to an illustrative example of a production network depicted in Figure 1. Figure 2 provides a visual representation of the steps for identifying each VC, via the methods used in this analysis.

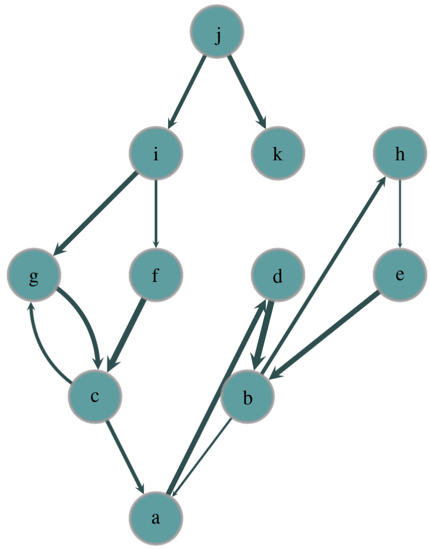


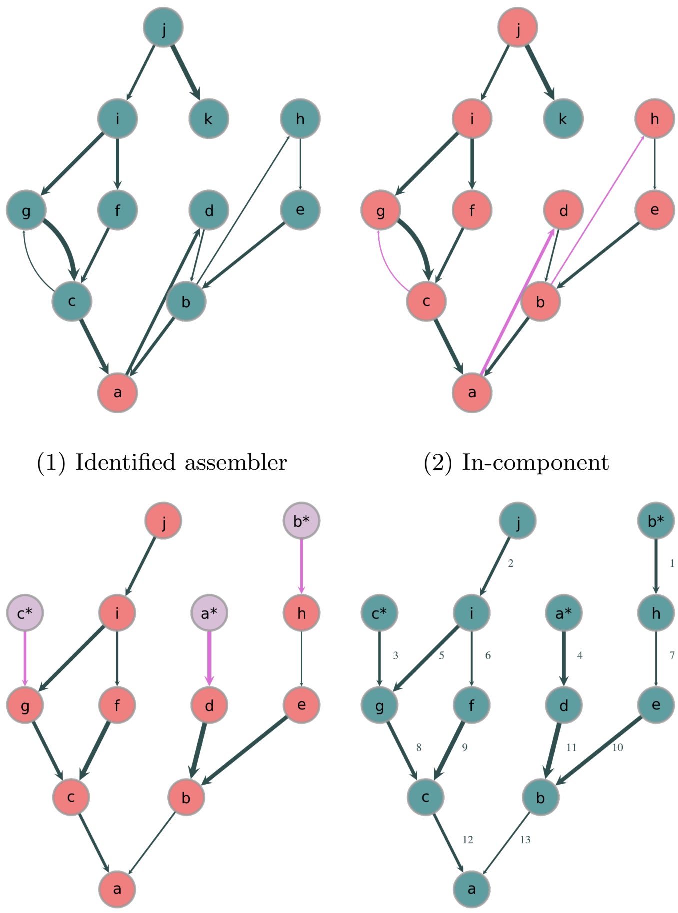
Figure 1: An example of a production network

While tracing an assembler's VC might seem straightforward in principle, two factors contribute to the task's complexity. Firstly, the sheer size of the data complicates the endeavor; even after filtering the dataset to include only manufacturing firms and their connections, there are still 174,261 nodes and 3,043,287 edges. Manually tracing each VC is not feasible due to scalability issues. To address this challenge, this study relies on the concept of an "in-component". An in-component in a directed graph refers to the set of vertices that can be reached by following directed edges in an inward direction from a given "root" vertex — in this case, an assembler. Thus, the in-component of an assembler represents the subset of firms that are part of the assembler's VC. In Panel 2 of Figure 2, the highlighted orange nodes indicate the firms within the in-component of vertex a. Note that firm k is excluded from this set, as it is part of firm j's downstream but is not part of the VC of assembler a. Component-finding algorithms are widely used in computer science and readily available in various programming languages. They are known for their efficiency, as they determine the components of a finite graph in linear time in terms of its number of nodes and edges, using either breadth-first search (BFS) or depth-first search (DFS) approaches. These algorithms start at a specified node (root) and examine its edges, initiating a new search whenever an unlabeled node is encountered. [9] Since these search algorithms were designed to recognize tree structures in graphs, and since trees are inherently directed and acyclic, labeling the in-component of a VC alone cannot fully trace the VC's entirety.[10] The search for edges will overlook cycles and thus cannot be considered exhaustive. I use Python's graph-tool library[24] for labeling each assembler's in-component as well as for the remaining steps in this section.

This study's approach is first to reduce the network by retaining only the nodes that belong to the in-component of at least one assembler.

[9] In BFS, the search covers all nodes within a given level of depth before progressing to the next level. In DFS, the search extends as far as possible along each branch before initiating a new search.

[10] See Figure 26 for examples of search algorithms and how they perform in our production network example.



(1) Identified assembler (2) In-component

(3) Sprouted cycles (4) Topological sort

Figure 2: Value Chain (VC) trace-back procedure

The presence of cycles in production networks poses our second challenge, for several reasons. Firstly, cycles can complicate our analysis and interpretation of the VC, in that they create interdependencies among firms that can be difficult to disentangle and understand. This can lead to feedback loops and self-reinforcing effects, which hinder our ability to identify the unique impacts of different RoO on compliance. Hence, addressing the presence of cycles is crucial for our analysis.

Previous work in the computer science literature has addressed this issue through various strategies and techniques. One commonly-used approach involves aggregating a network into a directed acyclic graph (DAG), transforming cyclic dependencies into sequential ones. This aggregation process includes identifying and eliminating cycles by collapsing interconnected nodes, thereby simplifying the network structure. For instance, Coscia (2018)[7] introduced a method that analyzes strongly connected components (SCCs) within a network, revealing the network's underlying hierarchical structure. While these strategies are useful in many applications, the interpretation of a collapsed cycle in the context of RoO remains unclear. For this study, I propose an alternative approach better suited to our analysis: instead of removing or collapsing cycles, we *unfold them* by identifying the edge within the cycle that is furthest from the root, duplicating the source node, and transferring the edge origin to the duplicated node. These are the pink edges in Figure 2's panels (2) and (3), and the duplicated nodes are labeled a^*, b^*, and c^* in panel (3). This method yields a tree representation of the value chain, where the node copies function as leaf nodes. Given this characteristic, I have termed this approach *sprouting*. appendix C describes the algorithm used to back-trace and sprout the VC simultaneously.

Since we cannot observe the sourcing decisions of foreign firms, back-tracing along a path stops whenever a foreign node is reached. Consequently, any nodes located upstream from this point are excluded from our analysis. The algorithm stops whenever all edges collected as part of the VC either are foreign or have no supplying nodes.

After successfully identifying the nodes and edges within a given VC, our final step involves arranging the nodes in sequential order, from the most upstream to the most downstream. This ordering is crucial, as it directly impacts suppliers' compliance, determining their origin and subsequently affecting their clients' RVC. Consequently, it has a direct bearing on the RoO compliance of the clients themselves. To accomplish this, we employ graph−tool's topological_sort function on a modified version of the VC, where the edges have been reversed. The topological sort algorithm establishes a linear ordering of the vertices in a DAG, ensuring that if an edge (u, v) is present in the graph, u precedes v in the ordering. As we aim to evaluate origin in an upstream–downstream direction, we need to reverse the direction of edges before sorting them, in order to ensure that assemblers' origin is assessed last. This step is depicted in Figure 2's panel (4).

3.2 Auto VC Features

The high degree of interconnectedness in the VC is immediately apparent. Here, a firm is considered to "serve" an assembler if that firm is part of the assembler's in-component; meaning, it is positioned upstream of the assembler. As shown in table 2, 93.38% of the VC firms serve more than one assembler, with 80% of the firms serving 5 or more assemblers. Remarkably, 10% of the firms serve nearly *all* assemblers. It is noteworthy that popular providers also hold significant trade volume shares. For example, firms that serve at least 11 assemblers collectively account for 21% of the trade volume in the VC.

Table 2: Firms present in multiple VCs

Assemblers Served	**Mean Sales Revenue**	**Firms in Value Chain**			**Trade Volume**	
		Count	**%**	**Cum. %**	**%**	**Cum. %**
13	1	0.03	0.03	17.02	0.01	0.01
12	315	10.42	10.45	32.41	5.87	5.88
11	998	33.01	43.46	37.34	21.42	27.30
10	244	8.07	51.53	31.90	4.47	31.77
9	77	2.55	54.08	43.76	1.94	33.71
8	86	2.84	56.92	44.08	2.18	35.89
7	89	2.94	59.86	40.49	2.07	37.96
6	148	4.90	64.76	76.73	6.53	44.49
5	448	14.82	79.58	60.70	15.63	60.12
4	100	3.31	82.89	65.15	3.74	63.86
3	291	9.63	92.52	91.39	15.29	79.15
2	26	0.86	93.38	114.47	1.71	80.86
1	200	6.62	100.00	166.56	19.15	100.00

Figure 3: VC Intersections

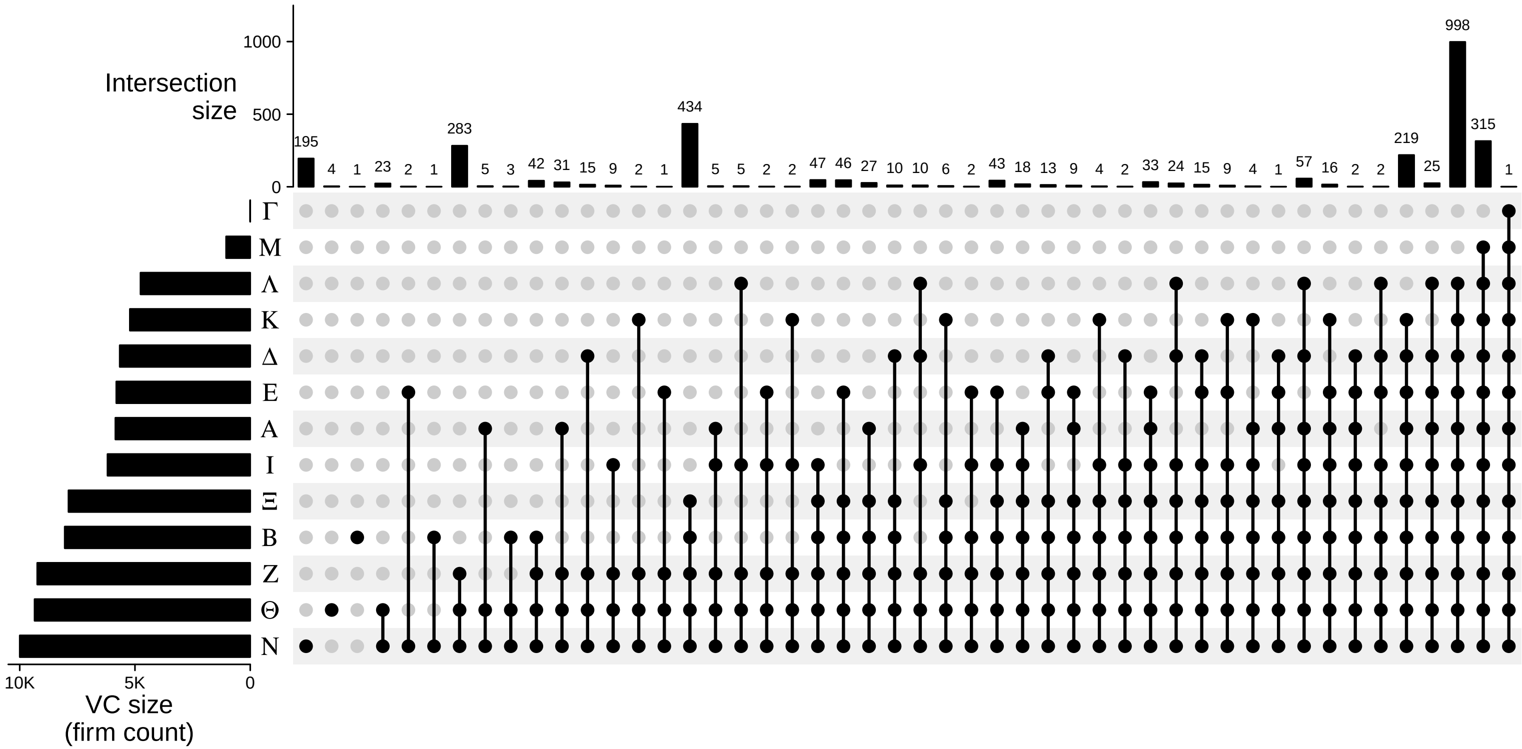
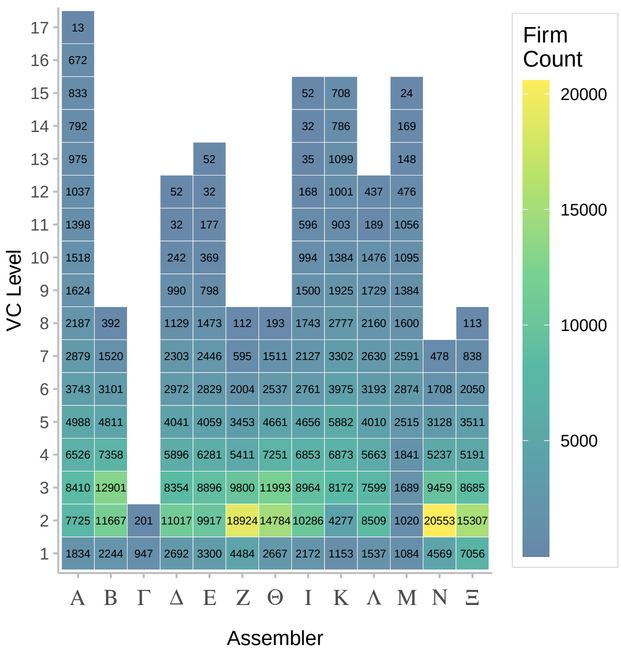


Figure 3 offers supporting evidence of interconnectedness in the VC. An intersection in this figure is defined by a subset of assemblers, and it is displayed if at least one firm serves all assemblers in the subset. Firms in an intersection are denoted by a black dot. If a firm is not part of an intersection, we see a gray shadow instead. The bars on the y-axis represent the number of firms upstream of each assembler, while the bars on the x-axis show the number of firms that are part of each intersection. We can see that, although the intersection including all assemblers contains a single firm, the second and third broadest intersections (in terms of the number of assemblers) are also among the most populated (in terms of number of upstream firms). Additionally, many intersections have a size larger than 10 firms.

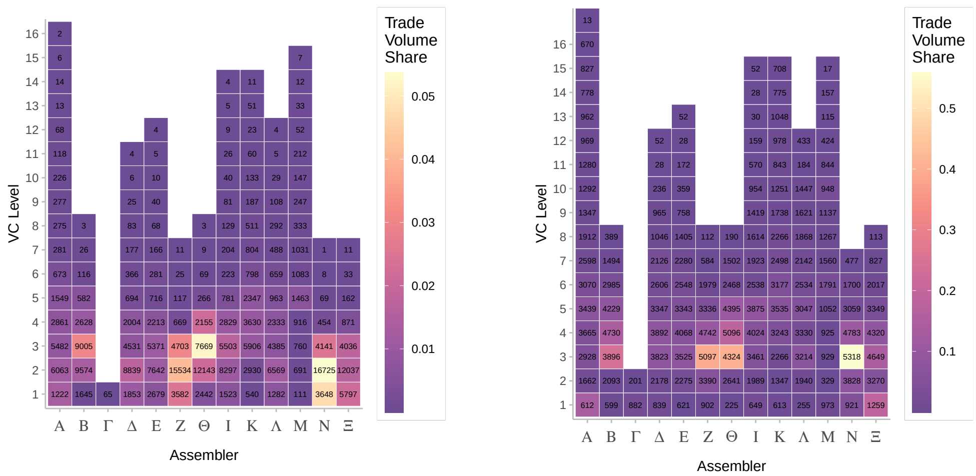
Figure 4 illustrates the distribution of firms at each level of assemblers upstream. The x axis displays the assemblers listed in table 1. The numbers in each cell indicate the firm count at a specific VC level of a given assembler. The VC level indicates number of links in the shortest path connecting an assembler to a given upstream firm. One notable observation is the emergence of a funnel pattern within the VC; broadly speaking, the number of firms directly serving assemblers is smaller, followed by a larger count at Levels 2 to 4, and then a decrease in the subsequent upstream layers.

Figure 4: Upstream Distribution by Source



We segregate the distribution based on domestic and foreign provenance to delve deeper into this characteristic. What becomes apparent is the the fact that this pattern persists. The funnel shape likely signifies that these firms are vertically integrated, and the densely populated zones in the VC possibly represent the juncture at which this integration begins. It is plausible that certain tax IDs are assigned to parts manufacturing, while others are designated for assembly within the same administration. Nonetheless, it is important to recognize that conclusive verification would require additional data analysis or corroborative evidence beyond the existing dataset.

Figure 5: Upstream Distribution by Source



(a) Domestic (b) Foreign

Now that we have reviewed some key features of the automotive VC in Mexico, our next step involves characterizing the products manufactured at different stages of the VC. This characterization will aid in narrowing down the set of RoOs analyzed and coded into the origin calculator.

To this purpose, I consider an HS if it there is a firm in the VC having such HS code or if the HS code is subject to an auto sector-specific RoO. table 3 provides an overview of the distribution of tariff item codes (products) considered in this project. Notably, Columns 3 and 7 showcase the share of trade volume in the VC, while Columns 4 and 8 highlight the share of Mexican exports to the US and Canada by product category.[11]

[11]It should be noted that the former pertains only to firms within the studied VC, whereas the latter encompasses all Mexican exports, including those from firms not contained within the studied subset.

Several insightful observations arise from this data. For instance, Column 8 indicates that 19% of Mexican exports to its North American partners consist of products in the auto sector, with the majority of these exports being parts. If we were to analyze the impact of RoO on Mexican firms and we only considered their effect on auto assemblers, we would be significantly underestimating their effects.

Furthermore, half of the auto parts exports are classified as super-core parts, which are crucial components within the VC. Notably, all vehicle and super-core parts are subject to RoOs under either NAFTA or the USMCA. This finding likely underscores the significance of the recent controversy surrounding within-firm super-core roll-up.

An additional insight from Columns 3 and 7 is that the majority of products in the VC are subject to RoOs, emphasizing the pervasive influence of RoOs across various stages of production. Moreover, despite the predominance of non-auto firms within the automotive VC, they contribute a modest 23% of the VC's trade volume, as indicated in Columns 6–7.

Table 3: Product Distribution by Type

	Not subject to RoOs				**Subject to RoOs**			
Product type	**Product Count**	**Product %**	**VC %**	**EX %**	**Product Count**	**Product %**	**VC %**	**EX %**
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Vehicles:	-	-	-	-	48	0.38	52.89	14.82
passenger vehicle	-	-	-	-	7	0.06	40.41	7.64
light truck	-	-	-	-	5	0.04	1.06	4.64
heavy truck	-	-	-	-	6	0.05	10.54	2.27
other vehicle	-	-	-	-	30	0.24	0.89	0.27
Parts:	1	0.01	0.00	0.01	436	3.48	23.58	18.89
super-core	-	-	-	-	159	1.27	15.20	9.48
other parts	1	0.01	0.00	0.01	280	2.24	8.37	9.41
Non-auto:	406	3.24	0.08	2.83	11632	92.89	23.44	25.84

4 Origin Calculator

This section describes the creation of an origin calculator that streamlines the process of assessing firms' RoO compliance. In what follows, we will use the terminology in table 4 to describe the structure of the auto sector RoOs found in NAFTA and the USMCA.

Table 4: The building blocks present in NAFTA and the USMCA

Rule	Definition
CC	The originating status is conferred to a good classified in a different HS chapter than the non-originating inputs.
CTH	The originating status is conferred to a good classified in a different HS heading than the non-originating inputs.
CTSH	The originating status is conferred to a good classified in a different HS subheading than the non-originating inputs.
CTI	The originating status is conferred to a good classified in a different HS tariff item than the non-originating inputs.
ALW	The originating status is allowed to be conferred from non-originating inputs of specific HS codes.
ECT	The originating status cannot be conferred to a good if the non-originating inputs are from HS codes listed under an exception.
RVC	A good obtains originating status if a defined RVC percentage has been reached.
SP	A good originates in the country where a defined technical requirement, i.e., a specified working or processing, has taken place.

The terms in table 4 are explained in detail in Kniahin & de Melo (2022)[18], along with other "building blocks" not present in the sector and agreements studied here.

The calculator has been created in two main steps and can assess compliance with NAFTA's and the USMCA's RoO. These steps transform the PDF documents defining the RoO into an R function that computes compliance.

First, I scrape each document and extract all product-specific RoO into a text file containing one RoO per line. Leveraging the uniform format in RoO statements, I transform them into a structured table. Specifically, I use phrases as markers and organize the statements into a spreadsheet. To better illustrate, consider USMCA's RoO for HS code 8701.10, which pertains to single-axle tractors:

"A change to a good of subheading 8701.10 from any other heading, provided there is a regional value content of not less than 60 percent under the net cost method."

The statement consists of two parts: the first states that non-originary inputs must be from a different HS heading; the second states that a regional value content of at least 60 percent is required.

Now consider USMCA's RoO for subheading 8701.20:

"A change to a good of subheading 8701.20 from any other heading, provided there is a regional value content of not less than 70 percent under the net cost method."

Where the highlighted parts in the statement are identical to those for the subheading 8701.10, there are 6 other RoO with this same pattern. Below, we can see the tokenized statements, where phrases used as markers are highlighted, and the delimiter "|" separates each token:

"A change to | a good of subheading 8701.10 | from any other heading, | provided there is a regional value content | of not less than 60 percent | under the net cost method."

"A change to | a good of subheading 8701.20 | from any other heading, | provided there is a regional value content | of not less than 70 percent | under the net cost method."

I use the markers as patterns that let me introduce the delimiters in the intended position using *regular expressions*. Regular expressions, or regex/regexp, are match patterns interpreted by string-searching algorithms, often used in "find and replace" operations. [12]

By tokenizing each statement and using regular expressions, we can summarize them as follows:

"CTC | 8701.10 | heading | VC | 60 | net cost"

"CTC | 8701.20 | heading | VC | 70 | net cost"

Then, using "|" as delimiters, I collect all RoO statements into a CSV file. Using R, we further process and rearrange the information on each RoO statement.

Through this process, I identified 13 different RoO types for NAFTA and twenty for the USMCA. Tables 5 and 6 summarize these findings.

[12] See https://regexr.com for learning, building, and testing regular expressions.

Table 5: NAFTA RoOs

	rule	RVC	RCR	comb	CTC	level	ECT	ALW	count	EX %	VC %
1	CC & RVC60	yes	60.00	AND	yes	chapter	no	no	1	0 %	0.08 %
2	CC + ALW50	yes	50.00	·	yes	chapter	no	yes	5	0.14 %	0.79 %
3	CTH	no	·	·	yes	heading	no	no	11	5.56e-05 %	2.8 %
4	CTH & RVC60	yes	60.00	AND	yes	heading	no	no	24	7.2 %	11 %
5	CTH & RVC62.5	yes	62.00	AND	yes	heading	no	no	27	43 %	43 %
6	CTH + ALW50	yes	50.00	·	yes	heading	no	yes	130	16 %	11 %
7	CTH + ALW60	yes	60.00	·	yes	heading	no	yes	9	2.1 %	0.65 %
8	CTH + ECT	no	·	·	yes	heading	yes	no	55	2.6 %	1.2 %
9	CTH + ECT50	yes	50.00	·	yes	heading	yes	no	60	8.4 %	2.1 %
10	CTH + ECT50	yes	50.00	·	yes	heading	no	no	11	2 %	2.1 %
11	CTH | RVC50	yes	50.00	OR	yes	heading	no	no	26	3.5 %	2.7 %
12	CTH | RVC60	yes	60.00	OR	yes	heading	no	no	38	8 %	7.6 %
13	CTSH + ALW50	yes	50.00	·	yes	heading	no	yes	2	6.6 %	1.4 %

Note: Column **EX %** shows the share of Mexican auto exports to the US and Canada for which a given RoO applies. Similarly, Column **VC %** shows the automotive VC trade volume share.

The names of these rule types follow a pattern: following the terminology in table 4, if an RoO requires a change in classification, the name start with CC, CTH, CTSH, or CTI, indicating whether the change is required at the chapter, heading, subheading or tariff item-level, respectively. Similarly, if it requires a value-added calculation, the name will start with “RVC” followed by 2 digits indicating the RCR. If the RoO contains both an RVC and a CTC component, these components are separated by “&” or “|” to indicate how these rules are combined.

Table 6: USMCA RoOs

	rule	RVC	RCR	comb	CTC	level	ECT	ALW	count	EX %	VC %
1	CC | RVC70	yes	70.00	OR	yes	chapter	no	no	1	0.085 %	·
2	CTH & RVC50	yes	50.00	AND	yes	heading	no	no	2	1.57e-04 %	0 %
3	CTH & RVC60	yes	60.00	AND	yes	heading	no	no	17	0.12 %	11 %
4	CTH & RVC62.5	yes	62.00	AND	yes	heading	no	no	6	0.069 %	43 %
5	CTH & RVC70	yes	70.00	AND	yes	heading	no	no	4	7.3 %	·
6	CTH & RVC75	yes	75.00	AND	yes	heading	no	no	19	40 %	·
7	CTH + ALW70	yes	70.00	-	yes	heading	no	yes	32	4.3 %	·
8	CTH + ECT	no	-	-	yes	heading	yes	no	44	1 %	1.2 %
9	CTH + ECT65	yes	65.00	-	yes	heading	yes	no	66	3.9 %	·
10	CTH + ECT70	yes	70.00	-	yes	heading	yes	no	8	3.8 %	·
11	CTH | RVC65	yes	65.00	OR	yes	heading	no	no	45	6.4 %	·
12	CTH | RVC70	yes	70.00	OR	yes	heading	no	no	45	4.7 %	·
13	CTH | RVC75	yes	75.00	OR	yes	heading	no	no	38	8.2 %	·
14	CTI	no	-	-	yes	heading	no	no	14	0.27 %	·
15	CTSH	no	-	-	yes	heading	no	no	27	1.9 %	0 %
16	CTSH + ECT	no	-	-	yes	heading	yes	no	5	1.5 %	·
17	CTSH + ECT65	yes	65.00	-	yes	heading	yes	no	2	6.8 %	·
18	CTSH + ECT70	yes	70.00	-	yes	heading	yes	no	11	0.25 %	·
19	CTSH | RVC75	yes	75.00	OR	yes	heading	yes	no	1	0.24 %	·
20	RVC75	yes	75.00	-	yes	-	no	no	64	9.2 %	·

Note: Column **EX %** shows the share of Mexican auto exports to the US and Canada for which a given RoO applies. Similarly, Column **VC %** shows the automotive VC trade volume share.

In addition, certain rule types include the "ECT" term to indicate exceptions to the CTC rule. However, these types also include a caveat; if a listed input falls under the exception, a good may still be considered originary if its RVC is above the RCR indicated by the 2 digits next to it. If the RoO just has "ECT" with no RCR, it means a good will not be considered originary if it falls under the exceptions, regardless of its RVC.

There are some instances wherein a rule includes details that cannot be observed in the data. For example, it may include different RCRs for two goods within the same NTL code.[13] See appendix E for a list of simplifying assumptions in programming the calculator.

The RoO types in Tables 5 and 6 can be further aggregated into groups to simplify the calculator algorithm. Such groups are shown in Tables 6a and 6b.

[13] In 2020, the Mexican government published the *Ley de los Impuestos Generales de Importación y de Exportación* (LIGIE, Import and Export General Tax Law), which adds two new digits to the NTL code called *Número de Identificación Comercial* (NICO, Commercial Identification Number). Such an addition will enable the removal of most simplifications in future calculator implementations.

Figure 6: RoO Groups

(a) NAFTA

	Group	Count	EX %	VC %
1	CTC	11	6e-05 %	2.8 %
2	CTC & RVCXX	52	51 %	53 %
3	CTC + ALWXX	146	25 %	14 %
4	CTC + ECT	55	2.6 %	1.2 %
5	CTC + ECTXX	71	10 %	2.1 %
6	CTC | RVCXX	64	11 %	10 %

(b) USMCA

	Group	Count	EX %	VC %
1	CTC	41	2.2 %	2.8 %
2	CTC & RVCXX	48	48 %	53 %
3	CTC + ALWXX	32	4.3 %	14 %
4	CTC + ECT	49	2.5 %	1.2 %
5	CTC + ECTXX	87	15 %	2.1 %
6	CTC | RVCXX	130	20 %	10 %
7	RVCXX	64	9.2 %	· %

After scraping the agreements' PDFs and organizing the statements into a table, I move on to the second step, which involves creating a mapping between product codes and their corresponding RoO group for each agreement. The resulting pseudo-code in appendix F illustrates how each RoO group is mapped into the origin calculator algorithm to assess firms' compliance.

Coding RoO statements at the group level offers a more efficient and accurate approach than converting each RoO into an if/then statement. While an alternative compliance calculator is publicly available on the Mexican Economy Secretariat's website,[14] it is not suitable for research purposes as it requires manual input and cannot be used on a large scale. However, this tool has helped test the accuracy of my algorithm.

5 Rules of Origin (RoOs): From NAFTA to the USMCA

The implementation of the USMCA has brought about significant changes in RoO for the automotive industry. Under NAFTA, automobiles and their parts were required to have at least 50% of their content made by member countries in order to qualify for zero tariffs. However, the new RoO under the USMCA have raised this requirement substantially, with an average of 62% now mandated. This is likely to have a strong impact on Mexican auto exports, with 95% of these now required to have a regional content of 70% or higher.

[14] For more information, visit: https://www.snice.gob.mx/cs/avi/snice/hce.calc.origen2020.html

Table 9: Changes to RCR

NAFTA \ USMCA	**50**	**60**	**62.5**	**65**	**70**	**75**	**No RoO**
50	·	·	·	2.89	3.26	2.85	2.89
60	0.00	0.04	0.02	·	10.54	8.33	·
62.5	·	·	0.00	·	·	41.99	0.53
No RoO	·	·	0.30	0.28	0.72	·	1.83

Note: values in each cell show the VC trade volume share for each RCR pair.

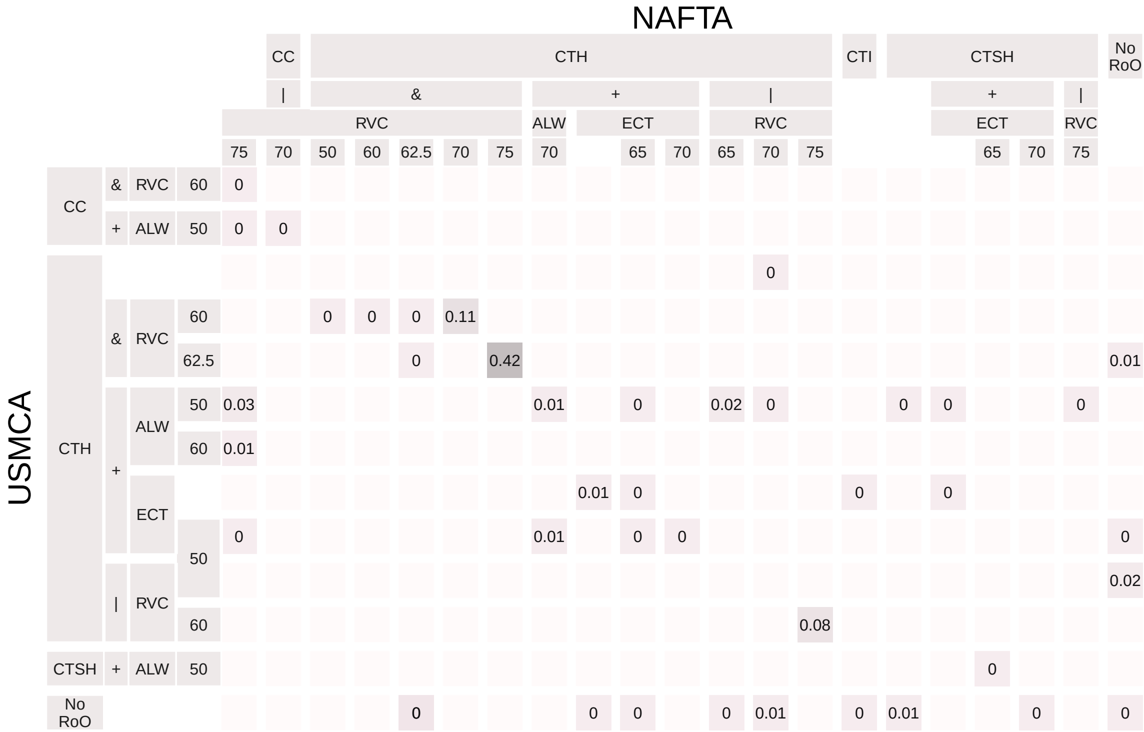
The structural changes in RoO between NAFTA and the USMCA are outlined in table 9. A closer look reveals that the majority of modifications involved an increase in RCR, from 50, 60, or 62.5 percent to either 60, 62.5, 65, 70, or 75 percent. Additionally, the USMCA introduced new RoO for HSclassifications that previously had none and also replaced Chapter-specific CTC rules with new RVC, set at a high RCR of 75 percent.

Another significant modification in RoO regards the roll-up of super-core parts and components. This provision gives producers the option to assess the RVC of super-core systems separately and roll-up their content. That is, if the system satisfies the RCR, then 100% of its value can be counted as originary for the value calculation of the vehicle. Although the provision allowing producers to roll up super-core parts was present under NAFTA, it underwent expansion under USMCA: whilst the RCR for super-core parts and their components rose from 62.5% to 75%, the scope of the systems to which these rules apply expanded. Previously, these rules only applied to engines and transmission systems; however, under the USMCA, they were extended to include axle, suspension, steering, body, and battery systems. Section 6, discusses this provision in detail.

As RoO become increasingly stringent, the issue of enforcement gains significant prominence. Specifically, the enforcement of RCRs poses a substantial challenge for governments, due to their reliance on self-reported documents. In order to certify their origin, firms present a certificate of origin, which is not bound by a prescribed format as long as it contains a minimum amount of information to identify the certifier's identity (which can be the producer, the importer, or the exporter), the product tariff item, the criteria it satisfies for origin, and supporting documentation.[15] By default, there is no additional check, but authorities in the importing country may request supplementary documentation and are required to "maintain criminal, civil, or administrative penalties for violations of its laws

[15] refer to appendix G for a detailed description of these requirements

Figure 7: Value Chain Trade Volume: Distribution by RoOs



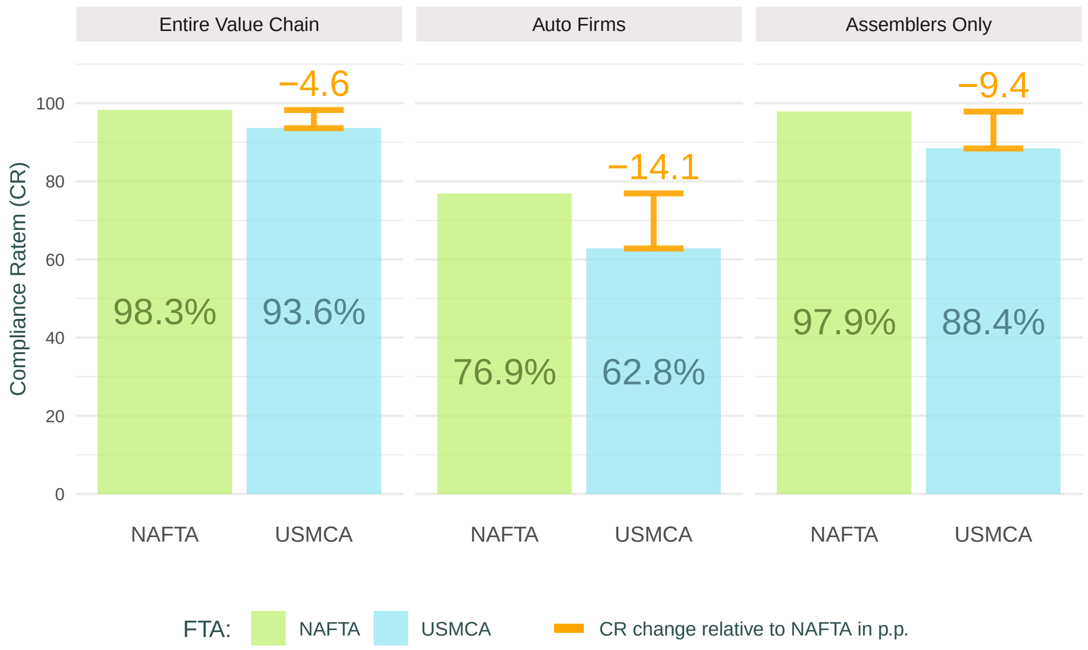
and regulations related to [the Origin procedures].” In essence, firms self-report their origin and may face audits by the importing country, yet there is no standardized approach to enforcement. This introduces an inherent risk of inaccuracies and misrepresentations, further complicating the regulatory oversight process. The significance of relying on self-reported origin certificates is especially apparent in the case of the US, since it does not collect VAT, unlike Canada and Mexico. VAT systems play a critical role in tax collection because they integrate into the production and distribution process, thereby bolstering transparency and compliance. If all member countries were to adopt a VAT system, the origin could be authenticated through VAT records. Consequently, alternative mechanisms for ensuring accurate reporting and compliance are imperative in this context.

6 Compliance Exercise

Equipped with the VC data and the origin calculator, I conducted the first exercise. The objective is to evaluate the origin of all products within the value chain under both sets of RoOs: those defined in NAFTA and those specified in the USMCA. The topological sort method, described in Section 3, is helpful in this stage. Employing this approach, we ensure that, firms in the upstream have previously been assessed for their origin at each production stage.

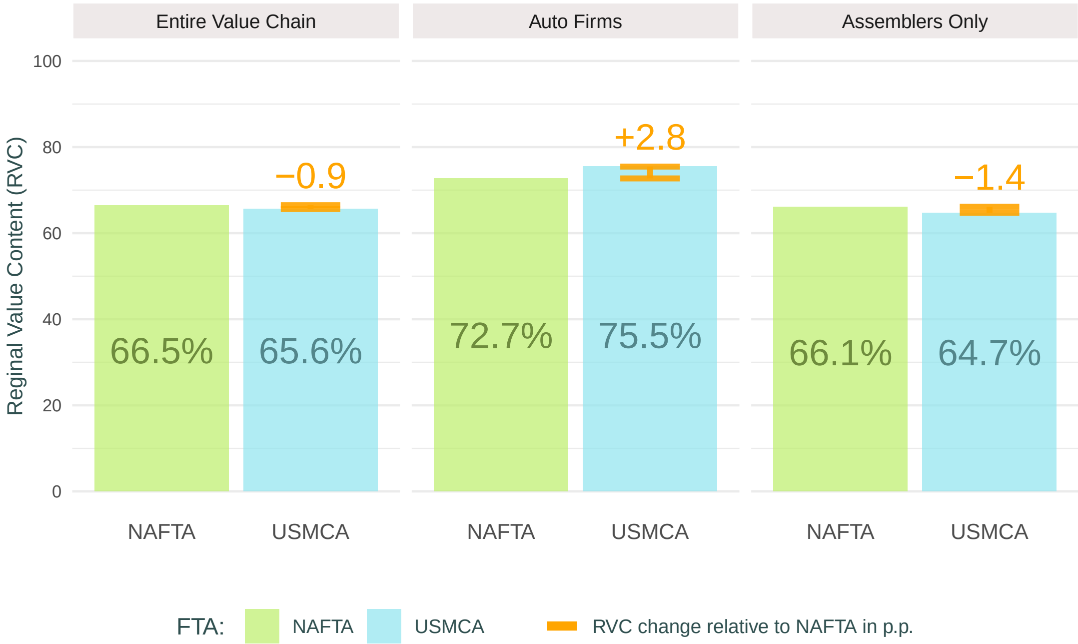
The baseline exercise involves evaluating compliance under both sets of rules for the value chain formed by our group of assemblers. It is important to note that we utilize data from 2017, a period during which NAFTA was in force. Therefore, the nature of this exercise can, at best, emulate the scenario that would have unfolded if accountants of each firm were required to assess the same production structure under two sets of rules. Despite our current omission of changes in the network, this exercise yields insightful outcomes. It contributes to our understanding of how RoO across products and along the VC interact within the production network, taking into account its topological characteristics. Figures 8 and 9 show how the compliance and RVC differ with NAFTA and USMCA RoOs. This implementation of the calculator closely aligns with both agreements, to the extent that the available data permit. Assumptions and simplifications are delineated in detail in appendix E. We then contrast these outcomes across three distinct sets: the complete VC, solely firms within the VC that are engaged in the production of either a car parts or a vehicle (i.e., the assemblers), and a subset comprising the 13 auto assemblers identified in Section 3.

Figure 8: Compliance Rate



As anticipated, compliance levels are lower under the USMCA RoOs, with a nearly ten percentage points decrease observed for assemblers. However, the impact on parts producers is notably more pronounced, as their compliance decreases almost twofold. It is worth noting that, as discussed in Section 3.2, nearly 20% of Mexican exports to its partners comprise vehicle parts. Notice also that, as a result of the super-core provision expansion, the RVC under the USMCA is higher than that under NAFTA, although not sufficient to drive compliance rates upward.

Figure 9: Regional Content Requirement



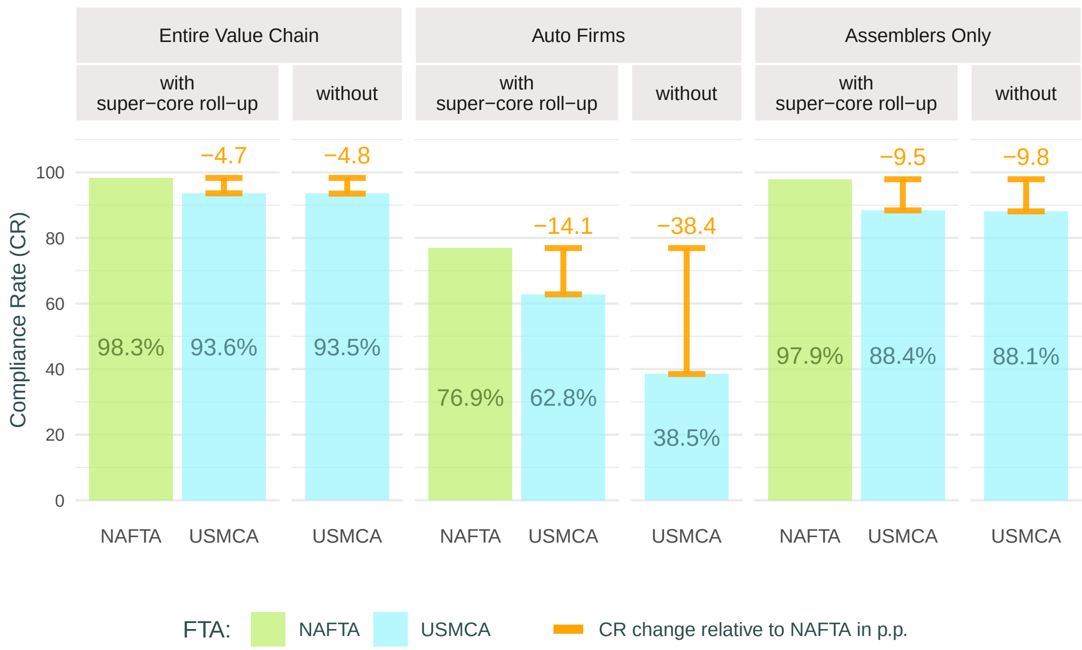
6.1 The Roll-up Dispute

In May 2021, the Mexican government requested formal discussions on the interpretation of the accumulation provision for super-core systems in the new rules of origin. This was due to the US unilaterally changing the way RVC is calculated, deducting any foreign content from the RVC calculation. After a controversy-resolution panel conducted its review in December 2022, it was concluded that automakers may continue to "roll up" the value of super-core parts and their car parts, allowing the whole of a system to count as originating in the region if the good contains the required percentage of regional content. While this increase in regional content requirements has made RoO stricter, the roll-up provision has also granted more flexibility. These conflicting impacts make the true overall effect of the new RoOs ambiguous ex-ante. In this section, we delve into the implications of the controversy.

According to USMCA regulations, these parts must originate within a given USMCA country for the vehicle or truck to be considered as having originated there. Moreover, Canada and Mexico have contended that the agreement permitted the inclusion of rolled-up content for originating super-core parts in the final vehicle RVC calculation. Conversely, the US has argued that the overall vehicle RVC calculation and the core parts origination requirement were distinct and separate calculations.

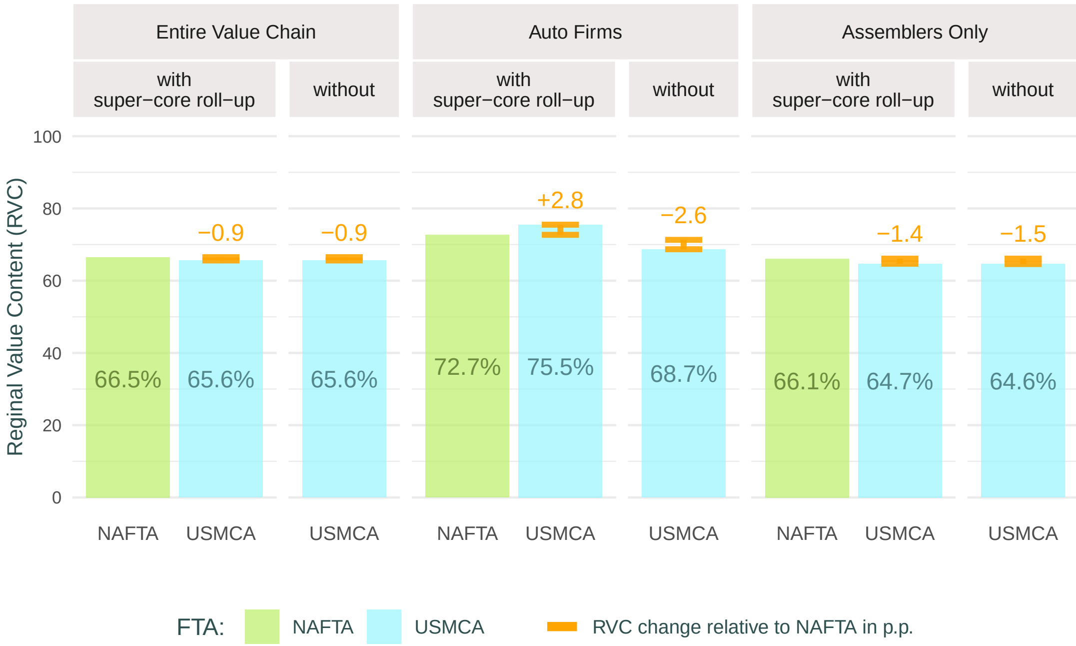
Mexico and Canada have argued that the USMCA negotiations indicated that, once an essential auto part is considered originary (by meeting a minimum of 75% of RVC), its regional value incorporated into the total RVC of the vehicle must be 100%, having already fulfilled the requirements. Contrastingly, the US interpretation suggested that even when an essential auto part qualifies as originary, its regional value when incorporated into the total RVC of the vehicle should not necessarily be 100%, but rather the percentage that has allowed it to meet the originating part requirements (which can be between 75% and 100%) — thus, making compliance with RoO more challenging for producers on the Mexican side of the border.[29] As Head et al. (2022)[14] show, stricter RoO affect Mexico and Canada more than the US, due to the fact that most of Mexico's and Canada's output is exported to the US, while the US auto output is mainly sold domestically.

Figure 10: Super-core Roll-up Effect on Compliance Rate



Tables 10 and 11 show the result from my estimated compliance rates, assuming opposite resolution panel rulings. Upon comparison of the compliance rates for both USMCA scenarios, it becomes evident that the super-core provision crucially dampened the effect of higher RCRs; while the compliance rate for auto assemblers would have experienced a twofold decrease, comparing compliance rates for auto firms under both scenarios leads to the conclusion that the parts producers are the party who benefited the most from the panel's resolution. Finally, we also note that when we consider all firms in the VC, the effect on auto-specific firms does not appear as pronounced.

Figure 11: Super-core Roll-up Effect on Regional Value Content



The findings in Figure 11 serve to reinforce the notion that the super-core roll-up provision significantly influences compliance rates through firms' RVC. This observation leads us to consider the possibility that policymakers dedicate a considerable amount of resources to formulating intricate regulations, which, in practice, appear to have far less impact on practical outcomes compared to a single paragraph discreetly situated in an appendix within each agreement.

6.2 Alternative RoO specifications

We examine four hypothetical scenarios to understand further how each component of RoO interacts and translates into firms' outcomes. In the baseline scenario, we hold the RoO unchanged, but we remove the roll-up option. The second scenario involves assessing the compliance of all firms in the VC, under the assumption that a producer located in the region automatically satisfies the origin criteria; this approach is referred to as the "no upstream compliance" assumption while focusing exclusively on the RVC portion of the RoO and assuming a uniform RCR, equal to the mean requirement specified in the agreements. Finally, the fourth scenario entails evaluating the compliance of upstream firms while retaining RVC-only RoO with a flat RCR.

Figure 12: Compliance Rate Under Alternative Specifications — Entire Value Chain

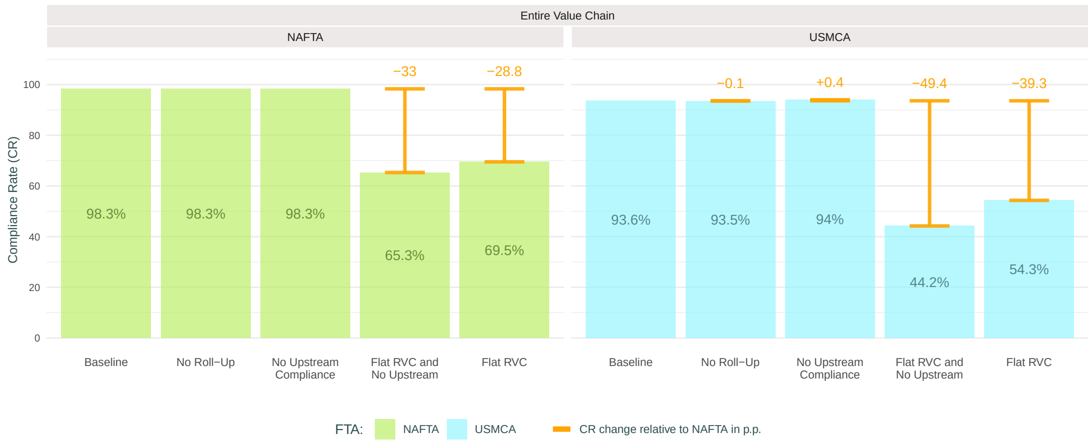


Figure 13: Compliance Rate Under Alternative Specifications — Auto Firms

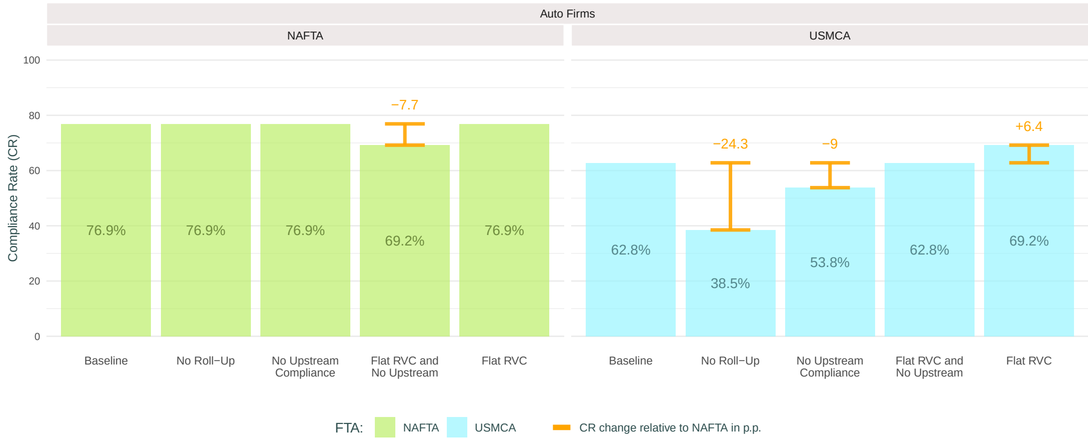
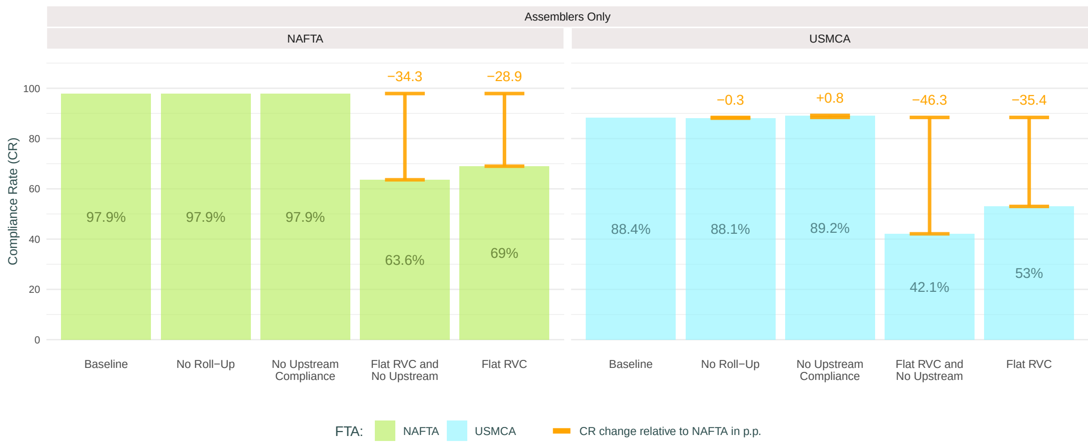


Figure 14: Compliance Rate Under Alternative Specifications — Only Assemblers



Figures 12–14 display the compliance rate results for the entire VC, for auto firms, and for assemblers, respectively. Similarly, Figures 15–17 illustrate the variations in RVC for the three sets of firms. Notably, and surprisingly, the absence of roll-up has no significant impact on the outcome for any group, except for a modest 1.4 percentage points (6.8 p.p) decrease in the regional content of auto firms under NAFTA (USMCA) rules (See Figure 16). This unanticipated observation may be inferred from the similarity of outcomes under the no-upstream compliance scenario. This suggests that upstream compliance had limited influence on downstream firms under NAFTA, possibly due to

lower RCRs and fewer systems being eligible for a super-core roll-up.

Figure 15: RVC Under Alternative Specifications — Entire Value Chain

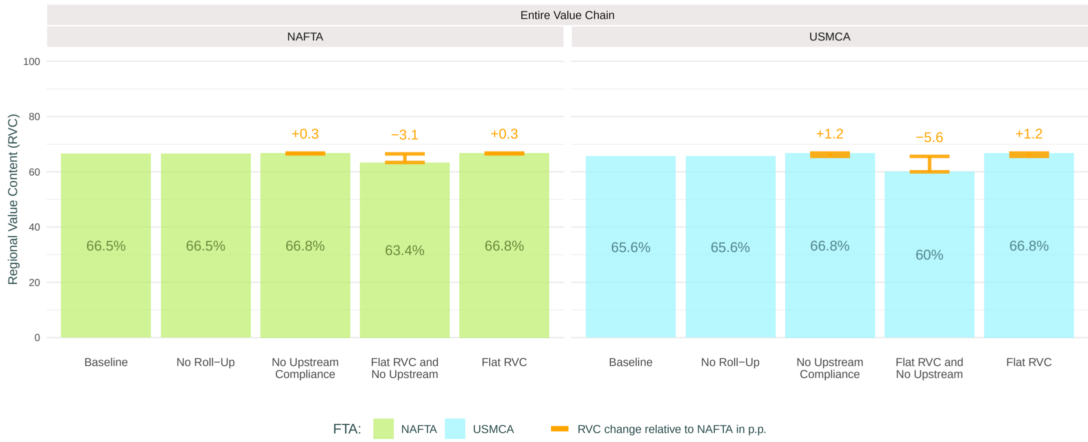


Figure 16: RVC Under Alternative Specifications — Auto Firms

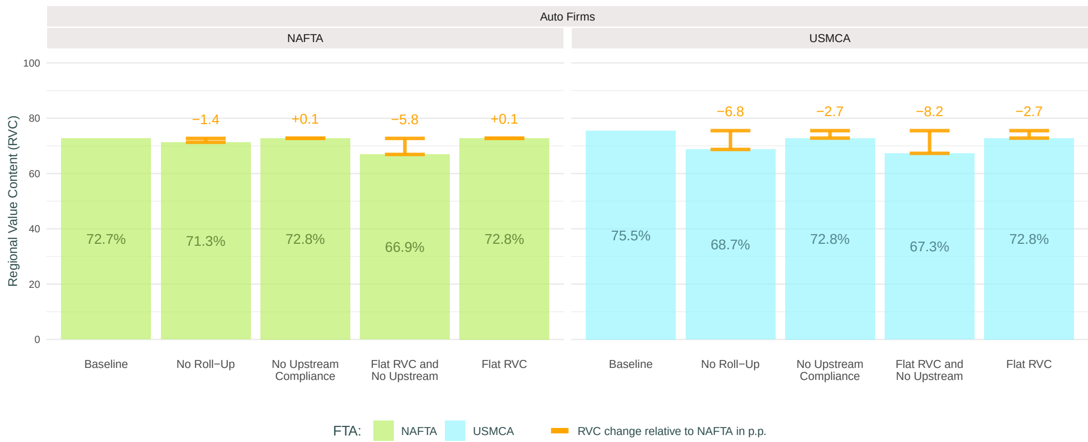
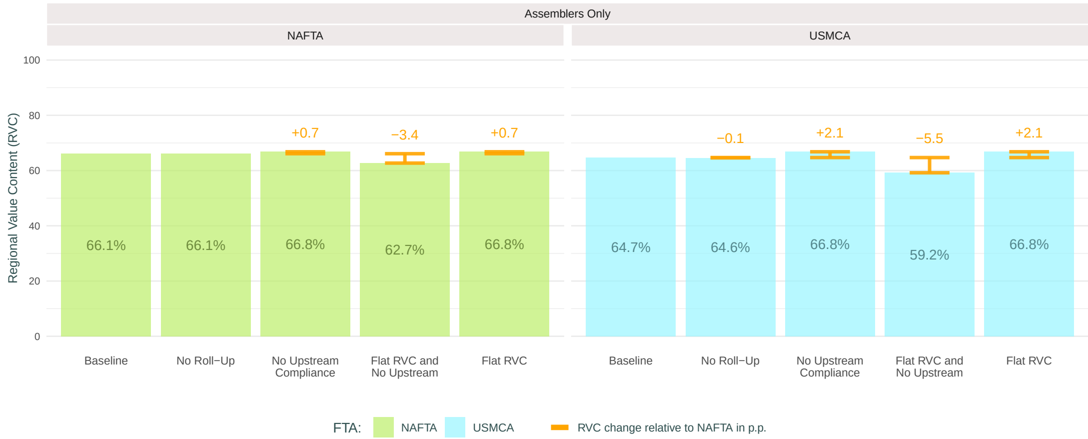


Figure 17: RVC Under Alternative Specifications — Only Assemblers



Interestingly, the elimination of the roll-up provision affects the auto-firms almost exclusively. When comparing this group with the assemblers' group, we find that the impact is mainly influenced by parts producers. It is worth noting that the reduction in the average RVC from NAFTA to USMCA for auto firms is just under 10%, yet this adjustment holds significant implications for the origin of the firms, as it positions the average auto firm content below the 75% baseline, which coincides with the super-core RCR under USMCA.

7 Concluding Remarks

This paper introduces innovative tools for analyzing RoOs, made feasible by the recent availability of new firm-to-firm trade datasets. Leveraging this data, I investigate the patterns within the automotive industry value chain, which is a central sector for the Mexican economy. The study reveals three primary findings: Firstly, the auto value chain demonstrates extensive interconnectedness, with the majority of firms serving multiple assemblers, and approximately half of these firms servicing ten or more assemblers. This inter-connectivity is not only reflected in the firm count but also in trade volume, with a third of the VC's trade volume concentrated among firms serving ten or more assemblers. Secondly, the most significant changes to RoOs, in terms of their trade shares, were increases of RCR while preserving the underlying RoO type. Parts producers, rather than car assemblers, are the firms most affected by these changes. Furthermore, as RCRs become more stringent, the significance of upstream compliance escalates. Thirdly, the recent dispute between USMCA partners centered on one of the most pivotal provisions in the agreement: the super-core systems roll-up. The compliance rate of auto firms without this provision is nearly three times lower than the rate estimated when the super-core roll-up is permitted. In conclusion, this work aims at advancing our knowledge of global value chains and their relationship to trade policy. In combination with the origin calculator, it offers potential avenues to improve policy design and evaluation efforts. It also prompts further exploration of numerous research questions using the methodologies presented here.

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Appendices

A Data Sources

In this section, I describe the construction of the dataset used in our analysis. I combine four sources to reconstruct the Mexican auto VC for 2017. I defer a discussion of the imputation of firms' production labor to appendix B.

(i) Domestic Firm-to-firm Linkages.– We retrieve connections among Mexican firms from Online Tax Receipts provided by the SHCP, called commercial CFDI for their acronym in Spanish, CFDIs. We use the *commercial* prepend to distinguish these receipts from payroll CFDIs. The unit of observation in commercial CFDIs is a month and a pair of firms, the buyer and the seller. For each entry in the dataset, we observe the monthly value of transactions, the number of receipts issued in that month, and the taxes retained, one of them being the VAT. Firms source different inputs at different periodicities based on the nature of the inputs, supplier availability, market conditions, business needs, and external factors. This and the fact that firms declare taxes annually impose a

natural yearly restriction on what constitutes one realization of the production network. Therefore we aggregate all monthly data at the yearly level. Thus, an observation in this dataset is characterized by a buyer, a seller, and a (yearly) transaction value.

(ii) State and Main Activity.– This dataset specifies the state where the firms' tax ID is registered and the product 6-digit NAICS code for the firm's main activity, obtained from the firms' annual tax declarations. The main activity of a firm is defined by the product accounting for the largest share of the firm's sales revenue.

(iii) Imports and Exports.– We retrieve firms' foreign linkages from custom records, which include all imports and exports at the product level (NTL code). The unit of observation is given by each transaction at the product level and the corresponding importer-seller or exporter-buyer firm pairs; however, to ensure consistency and mitigate the impact of noisy recording of foreign firm identities, I consolidate all foreign transactions into annual country-product pairs.

The datasets in (i)-(iii) can be linked using anonymized firm identifiers. I use (i)-(ii) to measure firms' sales revenue and materials purchases.

Production Labor.– The last data source is the Mexican Economic Census of 2019, which I use to infer firms' production labor. I compute the mean ratio of input purchases to production labor for firms within each 6-digit NAICS code. Then, I utilize these ratios to estimate the production labor for each firm by multiplying it with their materials purchases.[16]

Constructing an appropriate dataset to characterize the Mexican production network poses one of the key challenges. This is primarily due to the vast size of the datasets involved, such as the commercial CFDI data and the customs records. In 2017 alone, the commercial CFDI data consisted of a staggering $1,719,086,142$ observations, with each observation containing 21 fields of information. Similarly, the customs records comprised over $110,235,291$ transactions at the product level, spread across 14 different tables, and encompassing more than 150 fields of data.

Furthermore, before being able to generate descriptive statistics of the network, a significant amount of cleaning and validation of these datasets was necessary. The intricate details of this process are outlined comprehensively in LopezEspino (2022)[21]. Due to the sheer volume of data, handling, and processing, it necessitated the use of an high-performance computing (HPC) cluster,

[16]An objective for future projects is to merge the Economic Census with the other firm-level datasets, which will allow the investigation of a broader set of economic questions.

along with an Apache Spark engine. R served as the main programming interface for this stage of the analysis.

To minimize the impact of purchases that are not directly utilized in production, I adopt a reasonable assumption and focus solely on manufacturing firms and their transactions. By doing so, I create a refined network dataset that comprises 174261 nodes and 3043287 edges, representing a subset of firms and their inter-dependencies within the production network.

Table 10: Assemblers' exports by product code

NTLC	**Vehicle Type**	**Duty**	**Exports**
87012001	heavy truck	heavy	5,276,988
87012002	heavy truck	heavy	3,000
87032101	passenger vehicle	light	300,163
87032102	passenger vehicle	light	58
87032199	passenger vehicle	light	352,685
87032201	passenger vehicle	light	5,412,845
87032202	passenger vehicle	light	125
87032301	passenger vehicle	light	23,378,731
87032302	passenger vehicle	light	1,597
87032401	passenger vehicle	light	1,097,565
87032402	passenger vehicle	light	1,064
87042104	light truck	light	65
87042199	light truck	light	4,944
87042299	heavy truck	heavy	169,450
87042399	heavy truck	heavy	778,797
87043199	light truck	light	767,499
87043299	heavy truck	heavy	117,031

Note: exports are reported in thousand dollars.

Table 11: Manufacturing sectors in the Auto Value Chain

NAICS Subsector	Description	Value Chain Trade Volume			Firms in Value Chain		
		USD	Share	Cum. Share	Count	Share	Cum. Share
336	Transportation equipment manufacturing	1.72e+10	30 %	30%	515	9.94 %	9.94%
468	Retail trade of motor vehicles, parts, fuels and lubricants	3.2e+09	5.6 %	36%	259	5 %	14.94%
435	Wholesale trade of agricultural, industrial, commercial and services machinery, equipment and furniture, and other general purpose machinery and equipment	2.92e+09	5.1 %	41%	670	12.93 %	27.87%
326	Plastic and rubber industry	2.59e+09	4.5 %	45%	180	3.47 %	31.34%
335	Electric appliances, accessories and electric power generation equipment manufacturing	2.11e+09	3.7 %	49%	134	2.59 %	33.93%
332	Metal products manufacturing	2.08e+09	3.6 %	53%	363	7 %	40.93%
434	Wholesale trade of agricultural, forestry and industrial raw materials, and waste materials	1.36e+09	2.4 %	55%	444	8.57 %	49.50%
327	Nonmetallic mineral products manufacturing	1.32e+09	2.3 %	57%	41	0.79 %	50.29%
333	Machinery and equipment manufacturing	1.03e+09	1.8 %	59%	289	5.58 %	55.87%
331	Basic metal industry	9.55e+08	1.7 %	61%	100	1.93 %	57.80%
339	Other manufacturing industries	9.25e+08	1.6 %	62%	157	3.03 %	60.83%
334	Manufacturing of computer, communications, and measuring equipment, and other electronic equipment, components and appliances manufacturing	1.9e+08	0.33 %	63%	54	1.04 %	61.87%
325	Chemical industry	1.67e+08	0.29 %	63%	30	0.58 %	62.45%
436	Wholesale trade of trucks and new parts for automobiles, pickup trucks and trucks	1.13e+08	0.2 %	63%	13	0.25 %	62.70%
467	Retail trade of hardware and glass	4.45e+07	0.077 %	63%	40	0.77 %	63.47%
314	Textile products manufacturing, except apparel	2.85e+07	0.049 %	63%	3	0.06 %	63.53%
211	Oil and gas extraction	2.55e+07	0.044 %	63%	5	0.1 %	63.63%
337	Furniture, mattresses and blinds manufacturing	2.09e+07	0.036 %	63%	32	0.62 %	64.25%
324	Petroleum and coal products manufacturing	2.04e+07	0.035 %	63%	1	0.02 %	64.27%
313	Textile inputs manufacturing, and textiles finishing	7,774,067	0.014 %	63%	2	0.04 %	64.31%
321	Wood industry	6,782,282	0.012 %	63%	7	0.14 %	64.45%

B Imputation of Production Labor and Robustness Checks

The potential source of measurement error in this analysis is limited to the net costs. As the labor costs associated with production are not directly observable in the dataset, I employ summary statistics from the 2019 Mexican Economic Census to estimate the net cost.

From the economic census, I derive the input purchase-to-net cost ratio for all firms at the activity code level (six-digit NAICS). Subsequently, I utilize these ratios to infer the approximate net costs for individual firms.

To validate the accuracy of this approximation method, I cross-verify it using an alternative data source. Some firms in the value chain are required to present annual tax declarations, allowing me to estimate net costs by leveraging the accounting structure of these declarations.

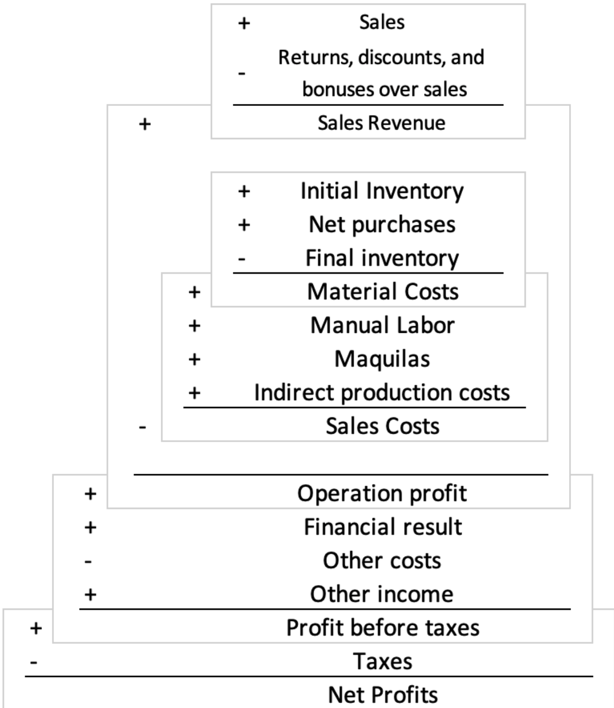
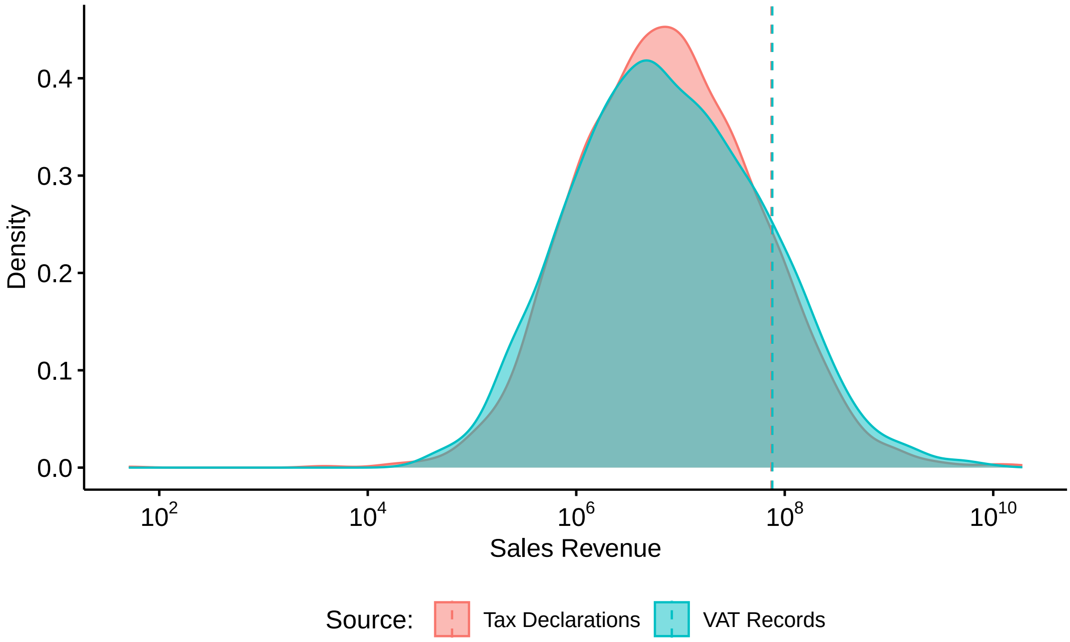


Figure 18: Accounting Items in Annual Tax Declarations

I calculate the net cost as the difference between sales and the sum of indirect production costs. In Figure 25, I present the distribution of net costs derived from both sources, as well as a third approach. In this third method, I obtain the input purchase-to-net cost ratio from firms' declarations and then utilize it to estimate net costs based on their manufacturing input purchases. Upon examining the subset of firms for which data is available from both sources, the distributions closely resemble each

Figure 19: Sales Revenue by Data Source



other. Nevertheless, it is conceivable that the distribution of net costs from annual tax declarations is marginally skewed to the right, given that only larger firms are mandated by law to submit an annual tax declaration.

By comparing figures 24 and 25, we see that the source of discrepancy for net costs stems from input purchases. This is due to the fact that I only consider manufacturing purchases, to reduce the likelihood of accounting for non-production related purchases inside the net costs. See table 11 for a list of sectors considered.

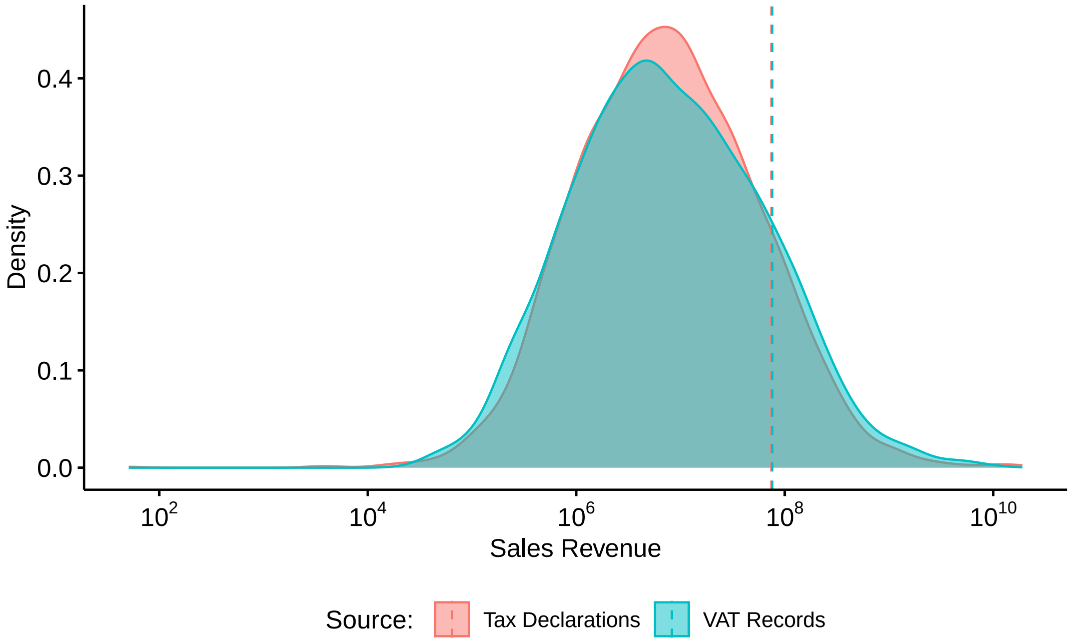


Figure 20: Sales Revenue by Data Source, intersecting firms

Figure 21: Production Labor by Data Source

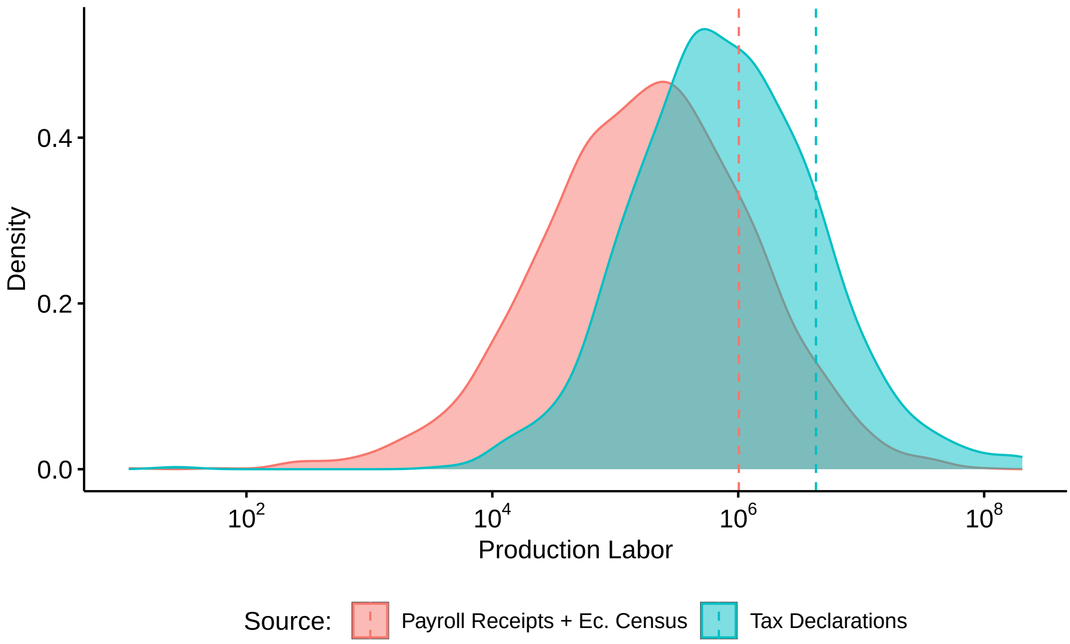


Figure 22: Production Labor by Data Source, intersecting firms

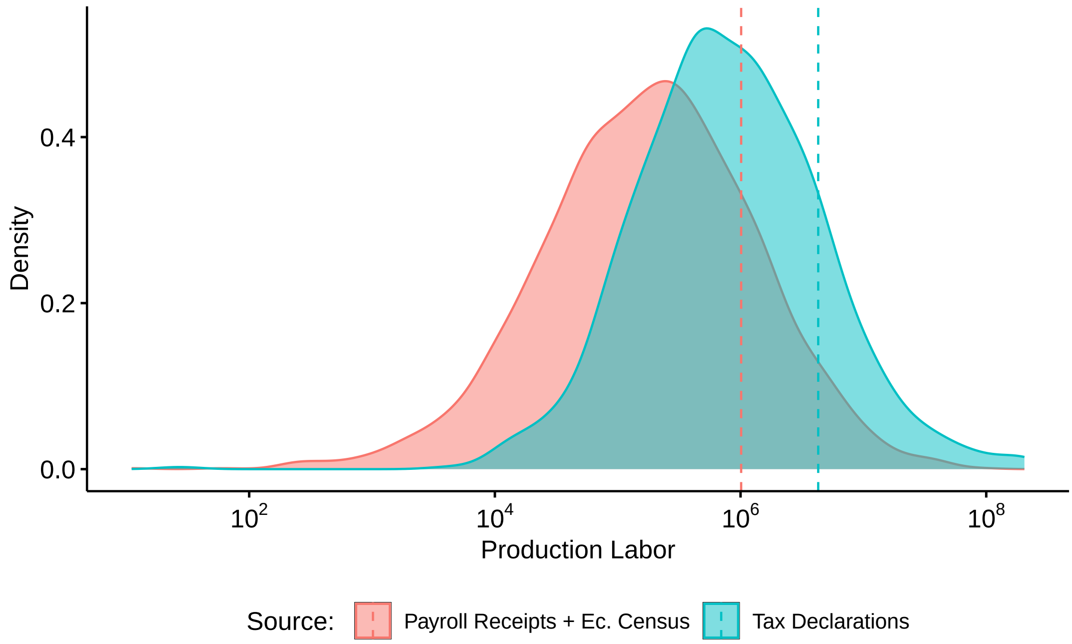


Figure 23: Input Purchases by Data Source

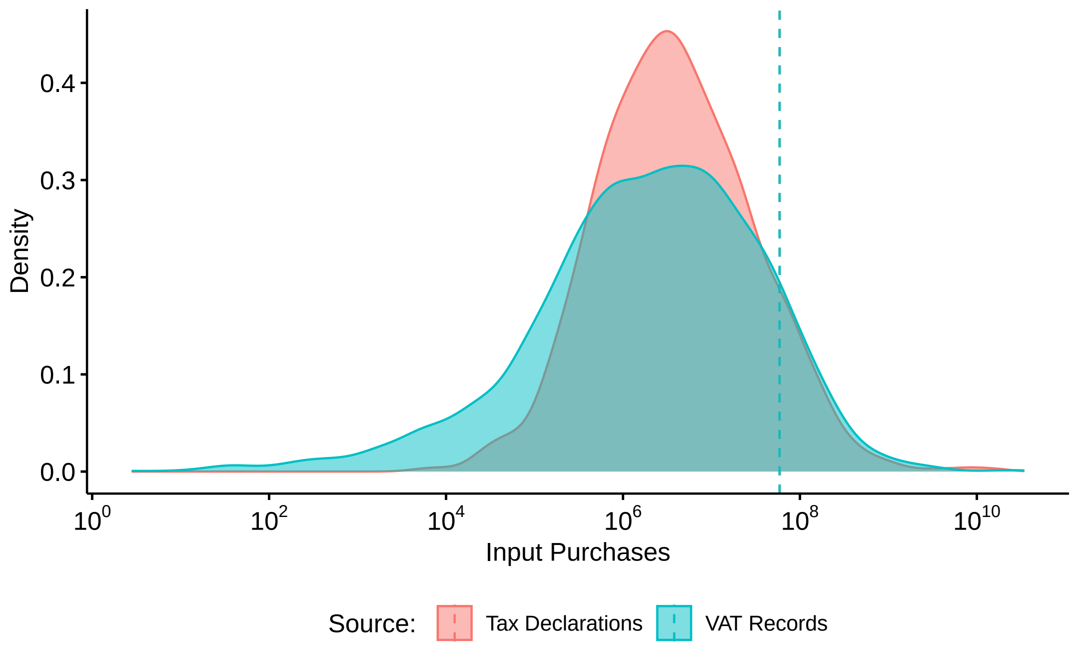


Figure 24: Input Purchases by Data Source, intersecting firms

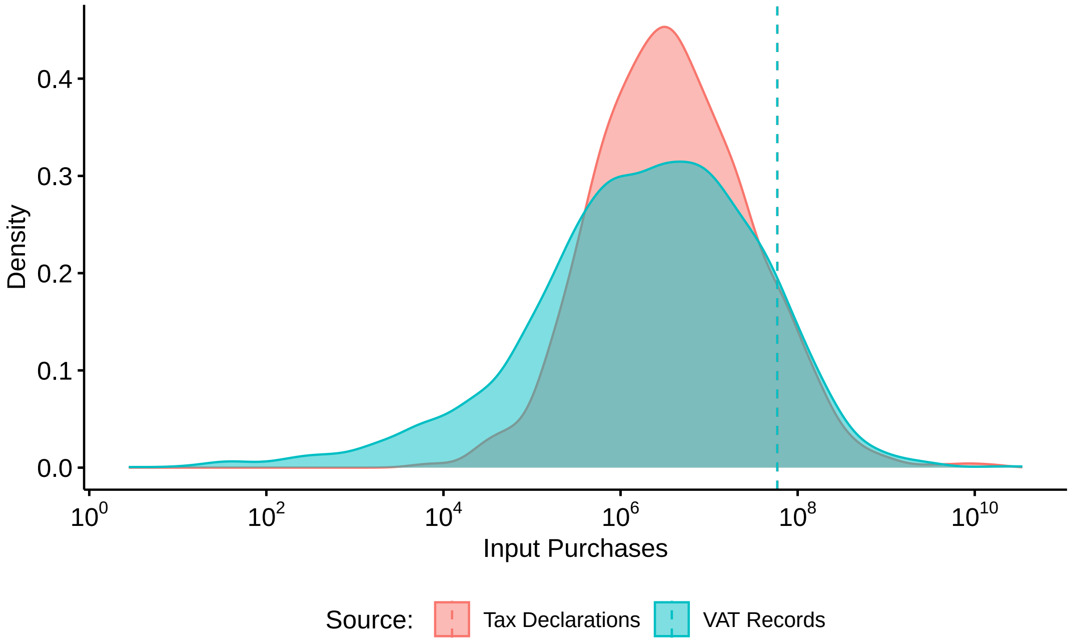
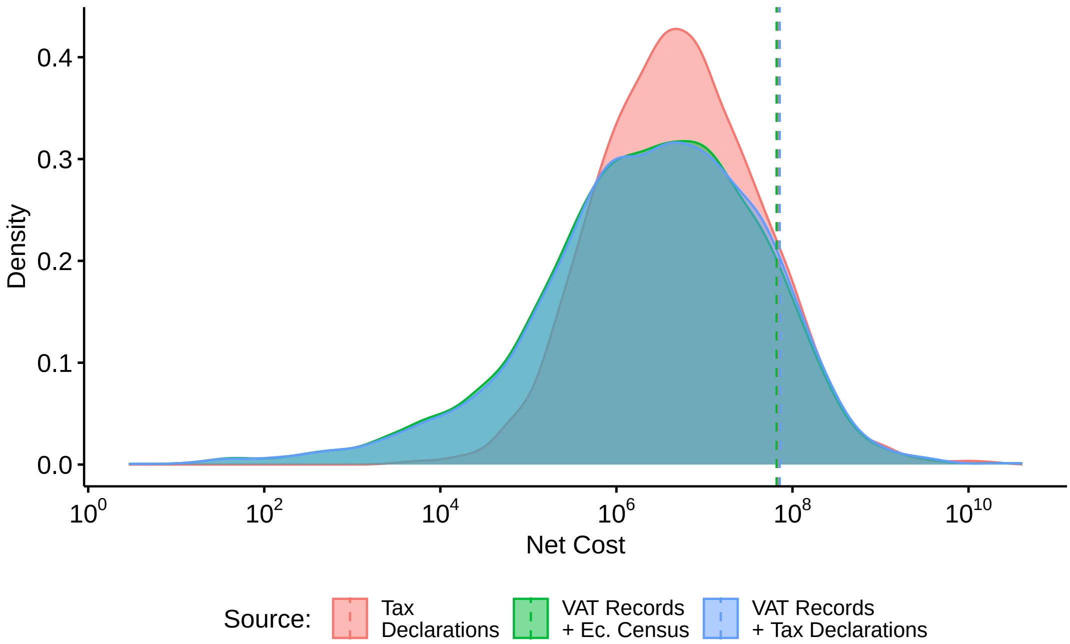


Figure 25: Net Cost Comparison



C Trace-back and Sprout Algorithm

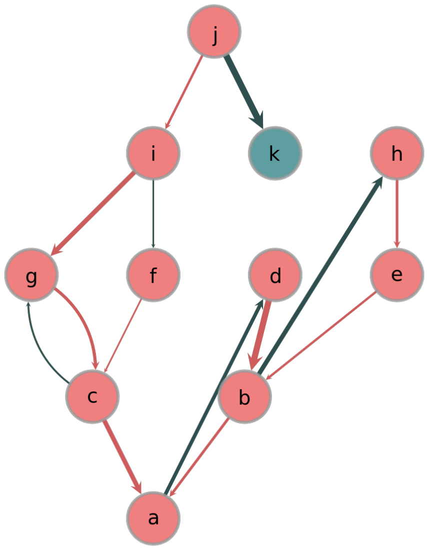
Algorithm 1 Sprouting function

function SPROUT($G, branch$) ▷ *G:graph, branch:edge*
  $s \leftarrow$ source of edge $branch$
  $t \leftarrow$ target of edge $branch$
  $t^* \leftarrow$ copy node t of graph G
  target of $branch \leftarrow t^*$
  $G \leftarrow$ remove node t form graph G
  return G
end function

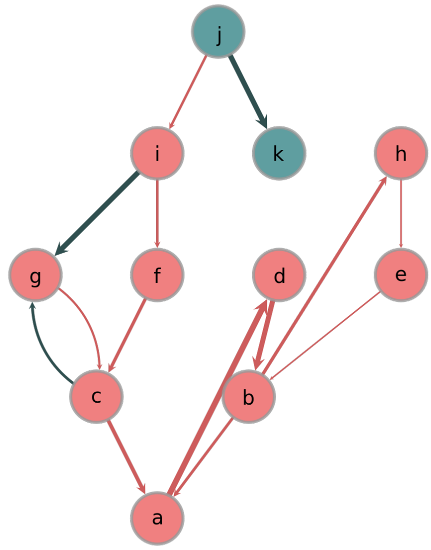
Algorithm 2 Traceback function

function TRACEBACK($G, root$) ▷ *G:graph, root:node (assembler)*
  $ic \leftarrow root$'s in-component in graph G
  $g \leftarrow$ filter G to keep only nodes in ic
  while g **is not** DAG **do**
    $c \leftarrow$ get a cycle in graph g
    $branch \leftarrow$ find the edge furthest away from $root$
    $g \leftarrow$ SPROUT($g, branch$)
  end while
  return g
end function

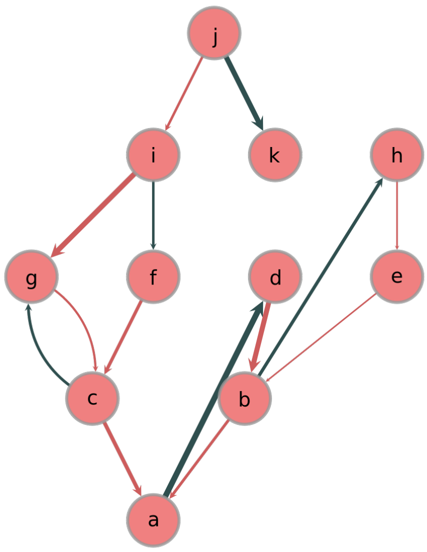
Figure 26 shows how this is the case, with BFS, as well as other popular search and tree finding algorithms.



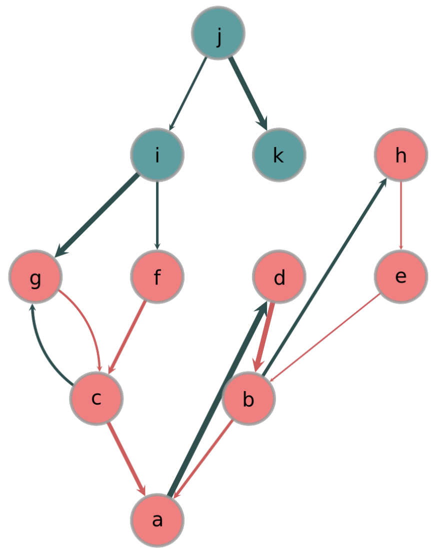
(a) BFS



(b) A^* algorithm



(c) Predecessor tree



(d) Dominator tree

Figure 26: Back tracing with alternative algorithms

Figure 27: Domestic Firm Level Distribution: Auto Parts

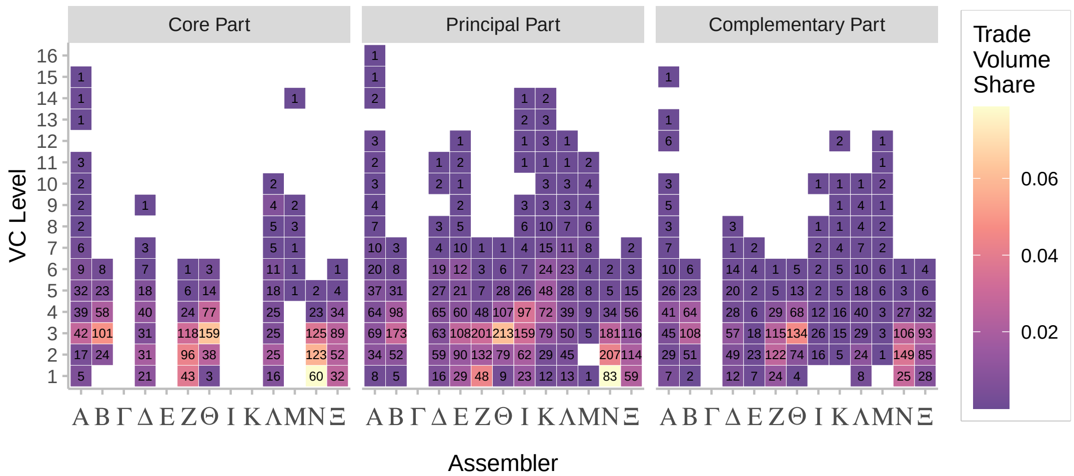


Figure 28: Foreign Firm Level Distribution: Auto Parts

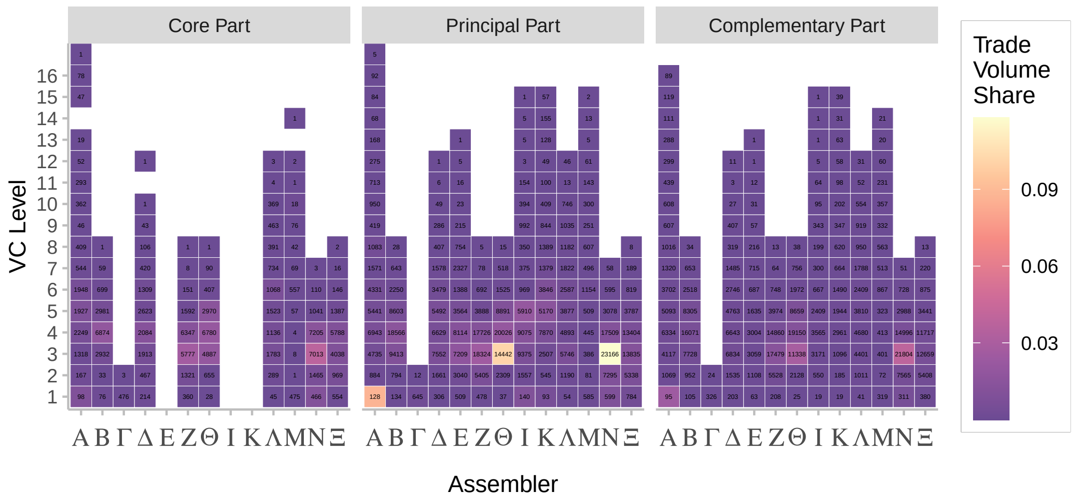
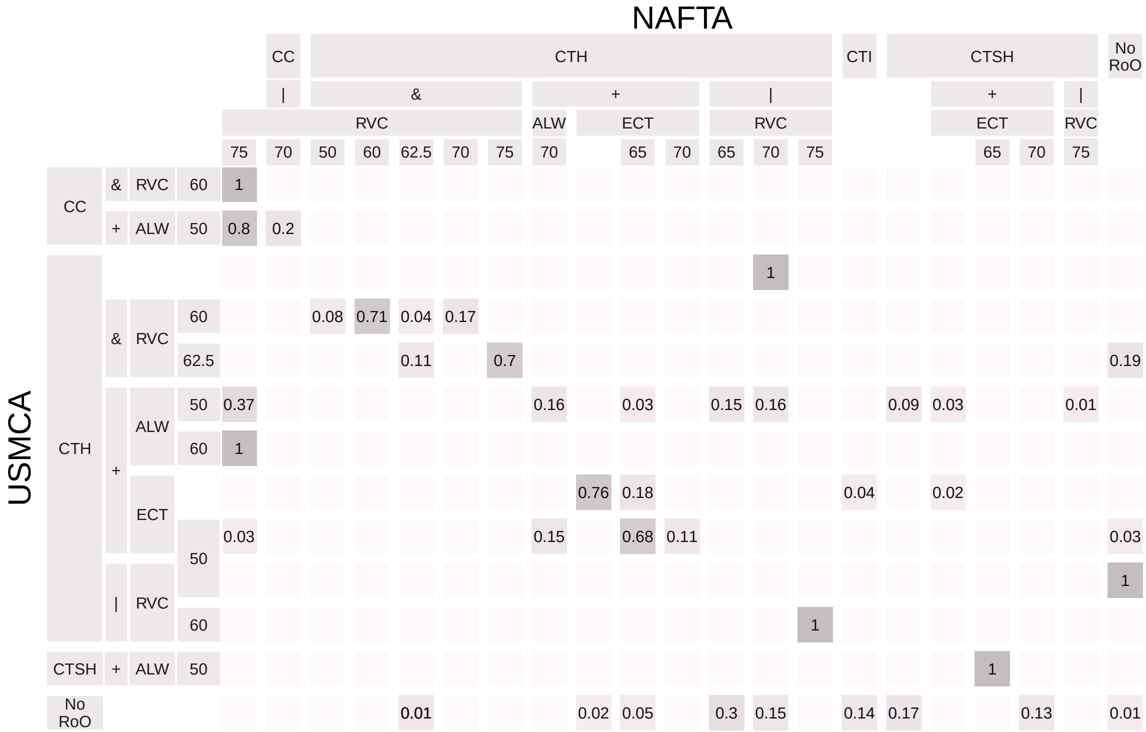
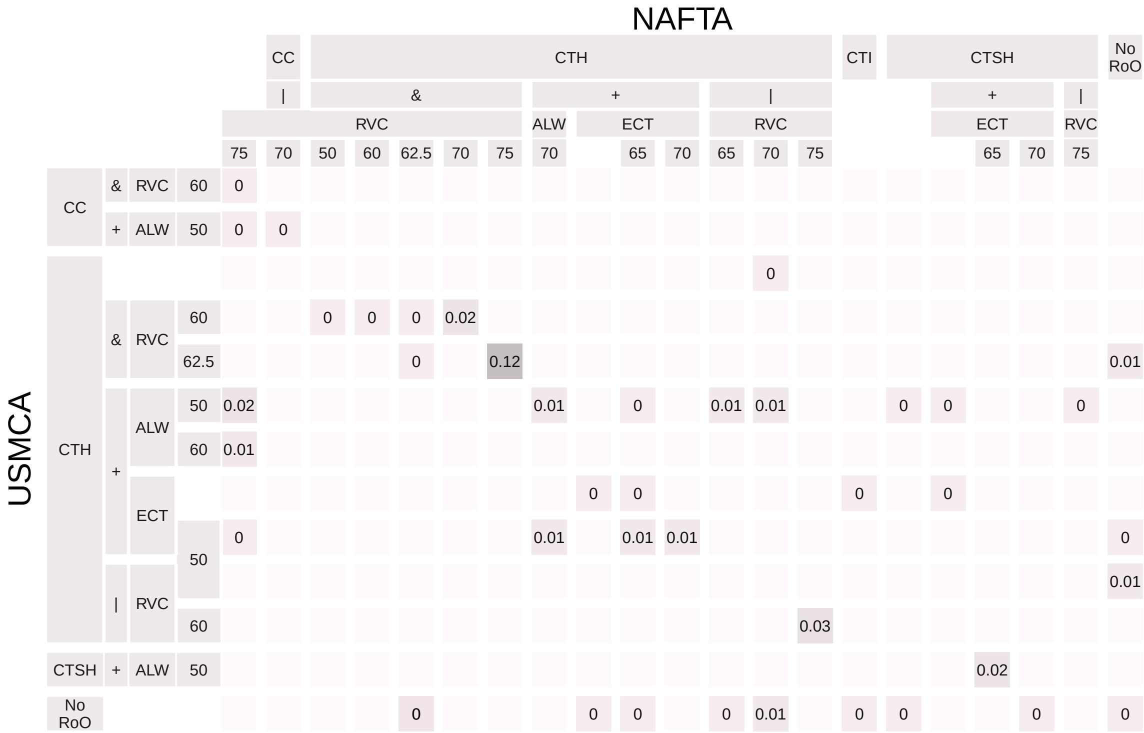


Figure 29: RoO Transition Matrix



D Additional Statistics

Figure 30: Mexican Exports to FTA partners: Distribution by RoOs



E RoO simplifying assumptions

Table 12: Origin calculator's simplifying assumptions

TC	Assumption
8702.10, 8702.90	A change to a motor vehicle for the transport of 16 or more persons
8703.21-8703.90	A change to a passenger vehicle
8704.21, 8704.31	A change to a light truck
8704.22, 8704.23	A change to a heavy truck
8704.32, 8704.90	A change to a vehicle that is solely or principally for off-road
87.06, 87.07	A good for use in a passenger vehicle or light truck
8708.10, 8708.21, 8708.70, 8708.93, 8708.95	A good for use in a passenger vehicle, light truck, or heavy truck
8708.29	A good, different from body stamping, for use in a passenger vehicle, light truck, or heavy truck
8708.30	A good for use in a passenger vehicle, light truck or heavy truck
8708.40, 8708.50, 8708.80, 8708.94	A good for use in a passenger vehicle or light truck
8708.91	A good for use in a passenger vehicle, light truck or heavy truck
8708.92	A change to silencers (mufflers) or exhaust pipes for use in a passenger vehicle, light truck, or heavy truck
8708.99	Chassis frames are for use in a passenger vehicle or light truck

F Origin Calculator Algorithm

Algorithm 3 Regional Value Content Function

function CONTENT(vnm, nc)
  $rvc \leftarrow (nc - sum(vnm\$value))/nc$
  return rvc
end function

Algorithm 4 de Minimis Function

```
Require: ect, alw ∈ {true, false}
function MINIMIS(ntlc, vmn, tv, roo, ect, alw)
    ctclist ← substring(HS$code, 1, roo$level) == substring(ntcl, 1, roo$level)
    if ect == alw then
        exlist ← ctlist
    else if alw then
        from ← roo$from                              ▷ from is a list of allowed NTL codes
        alwlist ← filter HS$code where
                HS$code == substring(ntcl, 1, level)
        exlist ← ntlc ∈ ctclist \ alwlist
    else
        except ← roo$except                          ▷ list of NTL code exceptions
        exlist ← ntlc ∈ except ∪ ctclist
    end if
    vmn_exc ← filter vmn where
            substring(vmn$pcode, 1, roo$level) ∈ exlist
    m ← 1 − (tv − sum(vmn_exc$value))/tv
    return m
end function
```

Algorithm 5 origin calculator

```
function CALCULATOR(ntlc, fta, inputs, nc, tv, flat)
Require: flat ∈ {true, false}
    IMPORT(roos_nafta, roos_usmca)
    region ←“CAN”,“MEX”,“USA”
    if fta ==“NAFTA” then
        rooi ← roos_nafta where ntlc == roos_nafta$product
    else
        rooi ← roos_usmca where ntlc == roos_usmca$product
    end if
    vmn ← inputs where inputs$country ∉ region
    rvc ←RVC(vmn, nc)
    if flat or rooi$type ==“RVCXX” then
        if rvc > rooi$rcr_flat then
            roo ← 1
        else
            roo ← 0
        end if
    else if rooi$type ∈ {“CTC”,“CTC + ECT”} then
        min ← MINIMIS(ntlc, vmn, vc, roo, ect, alw)
        if min < 0.1 then
            roo ← 1
        else
            roo ← 0
        end if
    else if rooi$type ∈ {“CTC + ECTXX”} then
        min1 ←MINIMIS(ntlc, vmn, vc, rooi, rooi$ect,false)
        State min2 ←MINIMIS(ntlc, vmn, vc, rooi,false, rooi$alw)
        if min1 < 0.1 then
            roo ← 1
        else if min2 < 0.1 and rvc > rooi$rcr then
            roo ← 1
        else
            roo ← 0
        end if
    else                                  ▷ rooi$type ∈ { “CTC & RVCXX”,“CTC | RVCXX”}
        min ←MINIMIS(ntlc, vmn, vc, roo, ect, alw)
        if rooi$comb ==“OR” then
            if min < 0.1 or rvc > rooi$rcr then
                roo ← 1
            else
                roo ← 0
            end if
        else
            if min < 0.1 and rvc > rooi$rcr then
                roo ← 1
            else
                roo ← 0
            end if
        end if
    end if
    return roo
end function
```

G Certificate of Origin

Under NAFTA, there were official documents that producers had to fill out to certify their product's origin.[17] In an attempt to reduce red tape and modernize compliance, member countries have included three main modifications to USMCA. First, in addition to producers, exporters, and importers can now present the CO. Second, these formats are no longer required as long as a minimum amount of information is included. These are:

1. whether the certifier is the exporter, producer, or importer.
2. certifier's name, title, address (including country), telephone number, and email address
3. exporter's name, address (including country), e-mail address, and telephone number if different from the certifier
4. producer's name, address (including country), e-mail address, and telephone number, if different from the certifier or exporter or, if there are multiple producers
5. importer's name, address, e-mail address, and telephone number. The address of the importer shall be in a Party's territory
6. description and HS Tariff Classification
7. origin criteria under which the good qualifies.
8. blanket period: the period of the certification covers multiple shipments of identical goods for a specified period of up to 12 months
9. the certification must be signed and dated by the certifier and accompanied by the following statement:

   I certify that the goods described in this document qualify as originating and that the information contained in this document is true and accurate. I assume responsibility for proving such representations and agree to maintain and present, upon request or to make available during a verification visit, documentation necessary to support this certification.

[17] Such formats are available for all partners in the US Customs and Border Protection (CBP) website: https://www.cbp.gov/trade/nafta/nafta-certificate-origin

H List of Abbreviations

BFS breadth-first search

CBP Customs and Border Protection

CFDI *Comprobante Fiscal Digital por Internet* (Online Digital Tax Receipt)

CTC change in tariff classification

DAG directed acyclic graph

DFS depth-first search

FDI Foreign Direct Investment

FTA Free Trade Agreement

FTA Free Trade Agreement

GDP gross domestic product

GVC global value chain

HPC high-performance computing

HS Harmonized System

INEGI *Instituto Nacional de Estadística y Geografía* (National Statistics and Geography Institute)

ITC International Trade Centre

LIGIE *Ley de los Impuestos Generales de Importación y de Exportación* (Import and Export General Tax Law)

NAFTA North American Free Trade Agreement

NAICS North American Industry Classification System

NICO *Número de Identificación Comercial* (Commercial Identification Number)

NTL national tariff line

RAIAVL *Registro Administrativo de la Industria Automotriz de Vehículos Ligeros* (Administrative Registry of the Automotive Industry for Light Vehicles)

RAIAVP *Registro Administrativo de la Industria Automotriz de Vehículos Pesados* (Administrative Registry of the Automotive Industry for Heavy Vehicles)

RCR regional content requirement

ROF Rules of Origin Facilitator

RoO rule of origin

RoO rule of origin

RVC regional value content

SCC strongly connected component

SHCP *Secretaría de Hacienda y Crédito Público* (Secretariat of Finance and Public Credit)

SP specific processing

USMCA United States-Mexico-Canada Agreement

VAT value-added tax

VC value chain

WCO World Customs Organization

WTO World Trade Organization