

Task Complementarity and Spatial Organization of Firms*

Edwin Jiang[†]
The University of Sydney

Vladimir Tyazhelnikov[‡]
The University of Sydney

September 2023

Abstract

We introduce a quantifiable model of international production of a complex good that consists of multiple parts. Production of any pair of parts in the same country exhibits pair-specific cost complementarity, and consequently, decisions on production locations are interrelated, which generates rich patterns of clustering. We use the World Input-Output Database to estimate the model for the case of US production and find that these complementarity costs are highly heterogeneous across industries and, on average, account for 1.86% of total production costs. Gains from trade associated with the decrease in these costs, which we interpret as non-tariff trade liberalization, are 50% larger than in the case of a decrease in tariffs. Finally, using our model, we construct an index of international integration, that, unlike standard measures, accounts not only for the total costs of parts produced abroad but also what parts are produced and how similar these parts are to one another. We find that this index is a better predictor of the welfare consequences of trade liberalization than conventional measures of offshoring.

JEL Classification: F12, F23, D24, L14

Keywords: Offshoring, Complementarity, Unbundling, Deep Trade Integration, Combinatorial Discrete Choice

*We thank Kirill Borusyak, Jackie Chan, Robert Feenstra, Ekaterina Kazakova, Luca Macedoni, James Markusen, Andreas Moxnes, Veronica Rappoport, John Romalis, Thomas Sampson, Rowan Shi, Catherine Thomas, Felix Tintelnot, Conor Walsh, Ray Zhang for helpful suggestions and Martin Richardson for his comments discussing the paper at the Ph.D. conference. We also thank seminar participants at Higher School of Economics, New Economic School, European Trade Study Group 2019, 2nd Ph.D. Conference in Economics and Business, Sydney Trade Workshop, Organisational Economics Workshop, 12th Bari Conference Economics of Global Interactions, Rimini Workshop on International Trade and Intellectual Property Rights, Aarhus University, and CEP LSE seminar. This paper has been previously circulated under a name of "Shadow Offshoring and Complementarity in Inputs"

[†]ljia6698@uni.sydney.edu.au

[‡]vladimir.tyazhelnikov@sydney.edu.au

1 Introduction

Dramatic technological advancements in the telecommunications and computing have revolutionised how multinational corporations (MNCs) organise their production. [Baldwin \(2006\)](#) calls this process “the second unbundling” and argues that these technological changes have been the major driver of globalisation in the last three decades.¹

Yet, the implication of these changes and their impact on global production have received little attention from trade economists relative to the analysis of the consequences of conventional trade liberalisation—such as decrease in trade costs and tariffs. One reason behind this gap is that non-tariff, non-transportation trade costs, which we call unbundling costs, are not strictly linked to the physical border crossing, complicating their systematic measurement. Unlike conventional trade costs, which are also present in our model, unbundling costs are defined not for individual inputs but for each pair of inputs. Such costs arise when a firm chooses to produce every given pair of inputs in different countries. These unbundling costs, however, can be tracked through distortions in firms’ international sourcing decisions.

In this paper, we argue that the presence of tariffs and transportation costs is not the only reason that MNCs choose to co-locate the production of various inputs. Other reasons relate to technological similarity; costly managerial expertise acquired for the production of one input can be partially transferred to the production of another input.² Similarly, when laws, standards, and regulations are not harmonised across countries, the co-location of similar inputs is beneficial.³ Lastly, co-location is beneficial if a company wants to avoid compatibility issues at the final assembly stage.

These various considerations introduce a large extent of interdependence in input sourcing decisions. Currently, the dominant way to model this interdependence is by assuming that the production structure exhibits some degree of sequentiality, which links the decisions at the adjacent stages of production through the costs of crossing the border.

Take the production of the Boeing 787 Dreamliner as an example. A large fraction of the aircraft’s value is produced in Japan and includes wings and parts of the fuselage, which are further shipped to Everett, WA for final assembly. The wings, which are made of composite plastic, were also designed in Japan. These production and development decisions

¹[Fort \(2017\)](#) finds that firms’ adoption of communication technology leads to higher fragmentation of the production process.

²[Antràs et al. \(2008\)](#) study this channel and introduce a model, that links managerial activity and communication technologies.

³[Dhingra et al. \(2023\)](#) document the rapid rise of deep trade agreements, which would affect unbundling costs directly. In our paper we argue that to properly assess the consequences of deep trade integration on international firm organisation, one has to directly account for the presence of unbundling costs defined at industry-pair level.

are unlikely to be independent even though Boeing does not have to perform these tasks in sequential order. Moreover, sequential production models allow modelling the interdependence in production decisions of adjacent parts only, which accounts for a small share of potential complementarity links for complex goods.⁴

Our paper introduces a different perspective: a model of international production of a complex good, that requires multiple inputs, and the production of any two inputs exhibits some degree of complementarity: when a firm chooses to produce any given pair of inputs in different countries to take advantage of cheaper input costs, it faces complementarity costs that we call unbundling costs.⁵ We allow these costs to be different for every pair of inputs, thereby modelling different degree of the complementarity of various inputs. Inputs from different countries differ in costs and are perfect substitutes with firms having different input demand depending on their industry.

We find that in this case, individual firm’s decisions on the production locations of inputs are interdependent: the production costs of each input depend on all other inputs’ production locations. The presence of these unbundling costs prevents firms from substantially fragmenting their production process across countries; instead, they choose to organise their production in clusters of technologically similar inputs. When unbundling costs decrease, firms’ incentives to cluster their production also decrease because the individual costs of production of each input become relatively more important, which allows firms to reallocate their production to lower-cost locations.⁶ The share of unbundling costs in total costs of production and production location in a given country are then non-monotonic in unbundling costs, and reshoring (a situation when a previously offshored input is once again produced domestically) is possible in the event of a monotone change in these costs.

To quantify the impact that unbundling costs have on production decisions, we construct an index that we call the allocation efficiency measure (*AEM*). This index measures how similar a given allocation of inputs across the countries is to the cases of free trade and

⁴For a good that consists of N parts, the maximum possible number of links that a sequential model can account for is $N - 1$. Thus for an aircraft, which consists of 2 million parts, it will account for a negligible fraction of all pairs of parts. Even for less complex production processes, this share is fairly small, so for a good that consists of 10 parts, the sequential production model accounts for only 20% of all links.

⁵Production complementarity is a well-studied phenomenon in the industrial organisation literature both theoretically (Milgrom et al. (1990)) and empirically (Biesebroeck (2007), Friedlaender et al. (1983)). Thompson (1985), Markusen (1989), Lopez-de Silanes et al. (1994), Costinot (2009a), Costinot (2009b), and Ding et al. (2019) introduce theoretical models international trade that feature cost complementarity.

⁶One example of unbundling costs playing an important role in shaping global production is outsourcing of call centers to India. While services cost considerations play an important role in these decisions, outsourcing of call centers is possible because they can be relatively painlessly detached from the rest of the production and services tasks. Other tasks (such as janitorial services) are also often cheaper to perform abroad, still they are too expensive or even impossible to perform in countries different from the headquarters location because of technological limitations (high unbundling costs).

autarky. If the allocation is identical to that in free trade, the *AEM* is equal to 1 and indicates the highest degree of integration – trade liberalisation will not result in the reallocation of production tasks across the border. Conversely, a zero value of the *AEM* corresponds to the allocation identical to autarky and indicates that there is considerable potential for the reallocation of resources across borders in the event of trade liberalisation.

An important difference between our measure of integration and all other measures is that the *AEM* accounts not only for how much is produced internationally but also which inputs are offshored and how similar they are. Additionally, the *AEM* uses the free trade equilibrium as a baseline while conventional measures of integration doesn't keep track of the outcome under free trade. Consider the following example: two firms produce the same share of inputs abroad, but the first firm organises its production in clusters and produces inputs similar to one another in the foreign country, while the other firm chooses to produce abroad inputs with a low degree of complementarity. Conventional measures of integration suggest that these two firms are equally integrated into the world economy, while in fact, the second firm exhibits a higher degree of integration and is less sensitive to changes in unbundling costs.

In order to derive aggregate industry- and economy-level outcomes in terms of *AEMs*, complementarity cost shares, and prices based on individual firm decisions and examine how they respond to exogenous changes to trade barriers, we combine our complementarity mechanism with the standard trade literature assumptions. We follow [Antras et al. \(2017\)](#) and use the standard [Melitz \(2003\)](#) heterogeneous firms' framework with monopolistic competition and CES preferences in the final goods market and the Ricardian [Eaton and Kortum \(2002\)](#) framework in the input market.

We then argue that the cost complementarity between any pair of inputs is related to their technological and labour demand similarity: and we can use relevant data to estimate complementarity costs. For each pair of industries, we compute pairwise labour demand similarities based on industry-level labour and occupation data in the US, as well as technological distances based on flows of R&D expenditures and patent citation patterns. We then combine the labour and technology components based on their relative importance in determining coagglomeration as estimated by [Ellison et al. \(2010\)](#) to produce a combined complementarity cost matrix.

The estimation challenge that we face is the complex nature of production interdependency, which makes closed-form characterisation of the solution impossible. The brute force approach will also not work—for N inputs, the number of possible permutations is equal to 2^N , which becomes unfeasible even for moderate values of N . We instead rely on an algorithm that allows solving this kind of discrete choice problems first introduced by [Jia](#)

(2008) and further extended by Arkolakis et al. (2022). This algorithm uses a simple recursive process to quickly narrow down the number of potential solutions from 2^N , which allows us to correctly solve each firm’s allocation problem for a reasonable value of N in a feasible amount of time.⁷

We then use the US input-output use tables and consider 22 final good industries, each of which uses the output of all 22 industries as inputs. We use the simulated method of moments to match simulated and observed domestic input shares for each input used in the production of each product.

Our estimation suggests that unbundling costs, on average, account for a sizeable 1.86% of total production costs and are highly heterogeneous across manufacturing industries, ranging between 0.91% for Petroleum and Coal Products Manufacturing and 2.85% for Miscellaneous Manufacturing. The economy-wide value of the *AEM* 0.782 indicates that unbundling costs prevent firms from exploiting almost a quarter of the potential benefits from international integration. *AEM* values are also highly heterogeneous across different manufacturing industries; the index takes the lowest value of 0.356 for the Motion Picture and Sound Recording Industries and the highest value of 0.936 for Electrical Equipment, Appliance, and Components Manufacturing.

While *AEM* captures the firm-level degree of international integration based on the observed firm behaviour, one major disadvantage of this measure is that it relies on the numerical solution of a structural model. We overcome this obstacle by offering a simplified index *SAEM*, which can be immediately calculated for each firm using the data on its import shares and industry complementarity. We find that *AEM* and *SAEM* are highly correlated with the latter being agnostic to the market structure and technological parameters assumptions, making it easy to calculate and use in a broad context.

To understand what welfare implications the presence of complementarity has, we perform counterfactual exercises. To make our results tractable, we use our estimates of trade and unbundling costs for 2003-2020 and compute standard deviation for each of these costs. We then evaluate what effect a one-standard-deviation change in each of these costs has on welfare. Our first finding is that the effect of changes in unbundling costs is highly asymmetric – a 1 standard deviation increase in the value of the unbundling costs can lead to a 0.93% decrease in welfare.⁸ In contrast, the effect in a 1 standard deviation decrease in the unbundling costs is much larger and leads to a 1.39% increase in welfare. This asymmetry

⁷This algorithm can be extended to a multi-country case by properly re-writing the cost function and coding decisions to produce input in a given countries as a combination of multiple binary decisions. In this paper, however, we focus on a two-country case to make the quantitative analysis tractable.

⁸We examine a change to the magnitude of labour demand complementarity, as it makes up most of the overall unbundling costs.

arises from the high degree of misallocation caused by unbundling costs: a reduction in unbundling costs not only directly decreases the final good price, it also enables firms to access cheaper inputs that further reduce their costs.

We also find that a 1 standard deviation change in iceberg trade costs generally has a symmetric effect on welfare, which is 40% smaller than the effect of decrease in unbundling costs. Moreover, the presence of unbundling costs dampens the effect of conventional trade liberalisation by approximately 10%. It follows then that comprehensive trade liberalisation such as ratification of deep free trade agreement would be more effective than a simple reduction in tariffs.

Our paper fits into the large strand of literature on organisational structure and global value chains including [Feenstra and Hanson \(1996\)](#), [Grossman and Rossi-Hansberg \(2008\)](#), [Grossman and Rossi-Hansberg \(2012\)](#), [Fally and Hillberry \(2015\)](#), [Johnson and Moxnes \(2019\)](#), and [Harms et al. \(2012\)](#) (for an excellent review of this literature see [Chor \(2019\)](#)).

Our paper contributes to an actively developing area of the global value chains literature on the complex interdependence of allocation decisions that includes [Antràs and De Gortari \(2020\)](#), [Tintelnot \(2017\)](#), [Antras et al. \(2017\)](#), [Oberfield et al. \(2020\)](#), and [Tyazhelnikov \(2022\)](#). In particular, our framework nests [Tyazhelnikov \(2022\)](#) for the two-country case and allows for richer patterns of proximity-concentration trade-off. Moreover, our model moves beyond the dichotomy of simultaneous and sequential production structures raised by [Baldwin and Venables \(2013\)](#) and offers a unifying framework that nests both structures.

The complementarity mechanism in our paper is symmetric to the trade-offs in [Tintelnot \(2017\)](#), and [Antras et al. \(2017\)](#) and relies on the same discrete choice algorithm of [Arkolakis et al. \(2022\)](#) to quantify the model. In [Tintelnot \(2017\)](#), a firm makes a binary decision of whether to open a plant in a given country to reach consumer markets, when the profit from opening this plant depends on the locations of all other plants. In [Antras et al. \(2017\)](#) a firm makes a choice of whether to import an input from a given country under the assumption that the returns from which this input depend on the set of countries this firm chose to source other inputs. In contrast to [Tintelnot \(2017\)](#) and [Antras et al. \(2017\)](#), we work in a two-country setting and consider the binary choice of whether produce domestically or to offshore each input but under a more complex complementarity structure.

Similar to [Head and Mayer \(2019\)](#), we consider two types of trade costs. In [Head and Mayer \(2019\)](#), however, a firm incurs additional costs only when headquarters and production activities are performed in different countries; it can be regarded as a particular case of our assumption that any pair of tasks produced in different countries generates a cost penalty.

Finally, our paper contributes to the literature on measuring the intensity of offshoring (for another excellent review of the literature, see [Antràs \(2020\)](#)). While the main focus

of this literature is to address the problem of double counting (for example, [Johnson and Noguera \(2012\)](#)), in our approach, we abstract from this issue and focus on accounting for the similarity/dissimilarity of offshoring activities and its implications for trade outcomes. To properly account for potential complementarities, as in [De Gortari \(2019\)](#), we have to rely on a more structural approach than most literature in this area.

The remainder of the paper is organised as follows: Section 2 introduces a theoretical framework, Section 3 estimates the model, Section 4 discusses the results of the estimation, provides comparative statics, and introduces a new measure of offshoring, and Section 5 concludes the paper.

2 Theoretical Framework

We construct a two-country, many-sector framework in which an individual firm's production decisions are affected by complementarity among inputs. Countries are denoted by i and j in the superscripts, while industries are denoted by the subscripts m , n , and k . There are $N + 1$ sectors in each country, with one of the sectors being perfectly competitive and the rest characterised by monopolistic competition. We make assumptions on demand and market structure to make our results comparable with the rest of the literature, while the main driver of our results is the individual firms' allocation problem.

2.1 Preferences

Consider a world with a representative consumer, whose preferences are quasilinear with respect to an external homogeneous sector 0 and a Cobb-Douglas aggregator over the consumption of heterogeneous goods from N sectors.

$$U = \frac{1}{\zeta} \left(\prod_{n=1}^N U_n^{\alpha_n} \right)^{\zeta} + q_0, 0 < \zeta < \frac{\sigma - 1}{\sigma},$$

where ζ is the elasticity of substitution between the aggregator of heterogeneous varieties and a homogeneous good, α_n is the weight of consumption of goods from sector n and U_n is the CES-aggregator:

$$U_n = \left(\int_{\omega \in \Omega} q_n(\omega)^{\frac{\sigma-1}{\sigma}} d\omega \right)^{\frac{\sigma}{\sigma-1}}, 1 < \sigma,$$

where σ is the elasticity of substitution between varieties from the same industry. The demand function for good ω from industry n is then

$$q_n(\omega) = \alpha_n P_n^{\frac{\xi - \sigma}{1 - \xi}} p_n(\omega)^{-\sigma},$$

where P_n is a CES price index for industry n : $P_n = \left[\int_{\omega \in \Omega} p_n(\omega)^{1 - \sigma} d\omega \right]^{\frac{1}{\sigma - 1}}$

2.2 Production Technology

Every firm produces a final good, which requires combining intermediate inputs; inputs from different sectors are perfect complements and have to be used in a fixed proportion. Firm z in sector n solves a problem of allocating each of its input plants in one of two countries $i = 1$ and $i = 2$: the same inputs sourced from different countries are perfect substitutes.⁹ In this paper, we abstract from a discussion of property rights and assume that a firm takes its organisational structure as given, regardless of whether an input is produced by the firm itself or sourced from a subsidiary.

Production of the final good in each sector n in country i is characterised by a unique input requirement vector of length N , $\Theta_n^i = (\theta_{1n}^i, \dots, \theta_{Nn}^i)$, where $\theta_{mn}^i \in (0, 1)$ is sector n 's requirement (in terms of quantity) for sector m input, and $\sum_{m=1}^N \theta_{mn}^i = 1$ for any n .

For firm z in sector n , the production cost of one unit of intermediate input from sector m and country i is given as $a_{mn,z}^i$, and the firm's cost of using this input after accounting for the firm's input requirements is $c_{mn,z}^i \equiv \theta_{mn}^i a_{mn,z}^i$. The firm's production decisions are collected in a decision vector of length N , $S_{n,z} = (s_{1n,z}, \dots, s_{Nn,z})$, where $s_{mn,z}$ is an indicator that equals 1 if an intermediate input from sector m is sourced from country 1, and 0 if the input is instead sourced from country 2. If at least one of the inputs is sourced from a different location from the rest, unbundling costs arise and are added to the total costs of the final good. The marginal costs that firm z in sector n incurs for the production of its final good are then,

$$MC_{n,z} = \sum_{m=1}^N [s_{mn,z} c_{mn,z}^1 + (1 - s_{mn,z}) c_{mn,z}^2 + T(s_{mn,z}, c_{mn,z}^1, c_{mn,z}^2)] + \varphi \sum_{m=1}^N \sum_{k=1}^N |s_{mn,z} - s_{kn,z}| \mathbf{C}_{mk}, \quad (1)$$

where T are conventional trade costs, that arise when input m crosses the border, \mathbf{C}_{mk} is the (m, k) element of the complementarity matrix and reflects the costs associated with the

⁹While we generally abstract from considering vertically differentiated inputs with quality differences, we can consider quality difference to be reflected through price of said input: in other words, a quality-adjusted input price.

production of inputs m and k in different countries;^{10,11} φ is a cost multiplier that regulates the scale of complementarity effects. If we assume that assembly takes place domestically ($i = 1$),¹² and further assume iceberg trade costs, τ , applied to imported intermediate inputs, the marginal cost can then be expressed as,

$$MC_{n,z} = \sum_{m=1}^N [s_{mn,z} c_{mn,z}^1 + (1 - s_{mn,z}) \tau c_{mn,z}^2] + \varphi \sum_{m=1}^N \sum_{k=1}^N |s_{mn,z} - s_{kn,z}| \mathbf{C}_{mk}. \quad (2)$$

The complementarity cost matrix, \mathbf{C} , summarises multiple factors that could affect firm's optimal production allocation. It can be thought of as unbundling costs that result from breaking up the production chain. These costs can represent additional coordination efforts or an increased likelihood of incompatible inputs from using outsourced components. The matrix is of size N by N ,

$$\mathbf{C} = \begin{pmatrix} 0 & \mathbf{C}_{12} & \cdots & \mathbf{C}_{1m} \\ \mathbf{C}_{21} & 0 & \cdots & \mathbf{C}_{2m} \\ \vdots & \vdots & \ddots & \vdots \\ \mathbf{C}_{m1} & \mathbf{C}_{m2} & \cdots & 0 \end{pmatrix},$$

where element \mathbf{C}_{mk} represents the complementarity cost on component k that arises from outsourcing component m . All diagonal elements are equal to 0, meaning that any given input does not exhibit cost complementarity with itself. The firm's decision vector determines which elements of this matrix are active in the firm's cost function.

Consider the following simple example: a firm z from country 1 in sector n uses inputs from 6 sectors. Its decision vector $S_{n,z}$ is then a vector of 6 indicators; for instance parts 1, 3, 4, and 6 are produced in country 1 and parts 2 and 5 in country 2: $S_{n,z} = (1, 0, 1, 1, 0, 1)$. In this case, the active elements of matrix \mathbf{C} will correspond to the input pairs produced in different countries. The firm's complementarity costs incurred through the production

¹⁰Note that we focus on the case of two countries for tractability and because of data limitations. Our framework can be easily extended to the case of $K > 2$ countries; in this case, the location of each task can be coded by $\tilde{K} = \lceil \log_2 K \rceil$ dummy variables. For example, for the case of $K = 4$ countries, marginal costs can be written down as: $MC = \sum_{m=1}^N [s_m^1 s_m^2 c_m^1 + (1 - s_m^1) s_m^2 c_m^2 + s_m^1 (1 - s_m^2) c_m^3 + (1 - s_m^1) (1 - s_m^2) c_m^4 + T(s_m^1, s_m^2, c_m^1, c_m^2, c_m^3, c_m^4)] + \varphi \sum_{m=1}^N \sum_{k=1}^N (1 - |s_m^1 - s_k^1|) (1 - |s_m^2 - s_k^2|) \mathbf{C}(m, k)$. All of the propositions from Section 2.3.2 are valid and the solution algorithm from Section 3.2 applies.

¹¹Alternatively we could have represented complementarity in the cost function through a reduction in costs if inputs m and k are produced in the same country. Both notations correspond to the same values of costs and hence identical optimal allocations.

¹²It makes the problem computationally simpler but we will relax this assumption later.

process are then equal to the sum of the active elements of the complementarity matrix.

$$\varphi \begin{pmatrix} 0 & 1 & 0 & 0 & 1 & 0 \\ 1 & 0 & 1 & 1 & 0 & 1 \\ 0 & 1 & 0 & 0 & 1 & 0 \\ 0 & 1 & 0 & 0 & 1 & 0 \\ 1 & 0 & 1 & 1 & 0 & 1 \\ 0 & 1 & 0 & 0 & 1 & 0 \end{pmatrix} \mathbf{C} = \varphi \begin{pmatrix} 0 & \mathbf{C}_{12} & 0 & 0 & \mathbf{C}_{15} & 0 \\ \mathbf{C}_{21} & 0 & \mathbf{C}_{23} & \mathbf{C}_{24} & 0 & \mathbf{C}_{26} \\ 0 & \mathbf{C}_{32} & 0 & 0 & \mathbf{C}_{35} & 0 \\ 0 & \mathbf{C}_{42} & 0 & 0 & \mathbf{C}_{45} & 0 \\ \mathbf{C}_{51} & 0 & \mathbf{C}_{53} & \mathbf{C}_{54} & 0 & \mathbf{C}_{56} \\ 0 & \mathbf{C}_{62} & 0 & 0 & \mathbf{C}_{65} & 0 \end{pmatrix}$$

Interestingly, in both cases, when a firm chooses to produce all inputs domestically or internationally, all elements of \mathbf{C} will be inactive because all inputs are produced in the same country, and the firm will not incur any unbundling costs.

In this formulation, we have two types of trade costs, iceberg trade costs T , which we interpret as tariff barriers and the costs of shipping intermediate inputs, and unbundling costs \mathbf{C} , which we interpret as non-tariff barriers. For clarity, we ignore the shipment costs of the final good, as including them will create a channel of horizontal FDI, which is well studied in the trade literature (see for example, [Tintelnot \(2017\)](#) and [Ramondo and Rodríguez-Clare \(2013\)](#)). This simplification allows us to not distinguish between domestic and foreign firms and consumers.

Note that both iceberg trade costs and unbundling costs are included in the marginal cost determination above. In this model, we nominally disregard fixed costs for clarity: however, our model can be easily extended to account for fixed costs of operation. So long as individual firm size remains constant, the optimisation problem of a firm remains identical except that a firm is minimizing its average, not marginal costs. This extended model can then be solved by an algorithm from [Arkolakis et al. \(2022\)](#) but rather than considering heterogeneous productivity, we would solve the model for each possible value of firm's sales.

2.3 Firm Behaviour

The firm's objective is to choose a production decision, $S_{n,z}$, that minimises its costs as outlined by Equation 1. The second term of Equation 1 connects unbundling costs to firm's cost minimisation decisions and enables us to identify sourcing behaviour. One can see that the term associated with \mathbf{C} makes a firm's decision on production location interdependent—a firm does not simply choose the cheapest location for each input but instead has to take into account production locations of all other parts. The complex nature of the problem leads to the absence of the closed form solution. In Section 3.2, we propose a discrete choice algorithm that, for given production cost vectors, trade costs, and complementarity matrix, finds an optimal allocation in a feasible time. In this section, we outline the properties of

the firm's behaviour that hold for any parameter values.

2.3.1 Limiting Cases

One of the two important limiting cases is when every element of the complementarity matrix equals 0 ($\mathbf{C}_{mk} = 0$ for $\forall m, k \in \{1, \dots, N\}$). In this case, the complementarity channel is shut down, the firm's decisions become independent, and the model exhibits the behaviour of simultaneous production models such as in [Feenstra and Hanson \(1996\)](#).

The more interesting case is when elements on the second diagonals of \mathbf{C} are non-zero, and all other elements are equal to zero. In this case, decisions of firms are also interrelated but only through production locations of adjacent parts.¹³ In other words, after dropping the iceberg trade costs component, Equation 1 can be rewritten as

$$MC_{n,z} = \sum_{m=1}^N [s_{mn,z} c_{mn,z}^1 + (1 - s_{mn,z}) c_{mn,z}^2] + \sum_{m=2}^N \varphi |s_{mn,z} - s_{(m-1)n,z}| \mathbf{C}_{m,m-1},$$

which is a cost function of a sequential production model as in [Tyazhelnikov \(2022\)](#).¹⁴ [Tyazhelnikov \(2022\)](#) shows that the sequential production model generates a proximity-concentration trade-off that he calls clustering. The unbundling costs formulation then nests both simultaneous and sequential production models for the two-country case and thus generates more general patterns of clustering and can be considered as a more general way to model firms' organisational structure.

2.3.2 Properties

We consider the effects of non-tariff trade liberalization for the case of a uniform decrease in the unbundling costs, or equivalently, a decrease in the complementarity cost multiplier φ . The proofs of Propositions 1-5 and 8 from [Tyazhelnikov \(2022\)](#) rely on the revealed preferences argument and do not depend on the sequentiality of the production process, so they also hold for this model. In particular, the following propositions hold:

Proposition 1. *The firm's marginal costs are non-decreasing in φ and increasing if a firm is engaged in international production.*

¹³As the order of parts in \mathbf{C} is arbitrary, any matrix that has non-zero elements on second diagonals after changing the order of parts also satisfies this property.

¹⁴A constant φ represents the case of specific trade costs; when φ_m is proportional to the value of the intermediate good at stage m , the cost function embeds iceberg trade costs.

This proposition is relatively straightforward: a firm cannot be worse off when facing lower unbundling costs. If the firm does not change its previous allocation and is not engaged in international production, its marginal costs will not change. In the case in which a firm produces internationally, its marginal costs will decrease.

Proposition 2. *The firm's quantity of complementarity activities $\sum_{m=1}^N \sum_{k=1}^N |s_{mn,z} - s_{kn,z}| \mathbf{C}_{mk}$ is non-decreasing in φ .*

This is another proposition based on a revealed preferences argument: if a firm chose to engage in international production, it would not choose to integrate less when the costs of integration are lower.

Proposition 3. *The value of firm's complementarity activities is non-monotonic in φ : in the case of lower φ , it directly reduces unbundling costs, but also encourages increased degree of fragmentation that can increase unbundling costs.*

This proposition indicates that firms' expenditure on supporting international activity can depend non-monotonically on the costs of such activity. For example, a decrease in the cost of telecommunication services will lead to an increase in the usage of these services, while the effect on the telecommunication expenditure will be ambiguous. Furthermore, the expenditure on telecommunication services will be equal to zero in both cases when the services are free and prohibitively expensive.

With the decrease of costs of complementarity φ , the quantity of complementarity activities $\sum_{m=1}^N \sum_{k=1}^N |s_{mn,z} - s_{kn,z}| \mathbf{C}_{mk}$ does not change or increases, so their product $\varphi \sum_{m=1}^N \sum_{k=1}^N |s_{mn,z} - s_{kn,z}| \mathbf{C}_{mk}$ can either decrease or increase depending on which effect is stronger. Note that both for the cases of autarky $\varphi = \infty$ and free trade $\varphi = 0$, $\varphi \sum_{m=1}^N \sum_{k=1}^N |s_{mn,z} - s_{kn,z}| \mathbf{C}_{mk} = 0$ and $\varphi \sum_{m=1}^N \sum_{k=1}^N |s_{mn,z} - s_{kn,z}| \mathbf{C}_{mk} > 0$ for some $0 < \varphi < \infty$ if a firm chooses to engage in international production for any value of φ .

Proposition 4. *If the firm changes its unique optimal allocation due to decreases in φ , this firm's per-unit non-unbundling costs will decrease as saving in production cost is prioritised.*

This proposition follows from the previous propositions and states that the reason why a firm may choose to reallocate its production is driven by production efficiency considerations, not potential cost savings on the costs of complementarity activities, which is $\sum_{m=1}^N [s_{mn,z} c_{mn,z}^1 + (1 - s_{mn,z}) c_{mn,z}^2 + T(s_{mn,z}, c_{mn,z}^1, c_{mn,z}^2)]$ for each unit. Trade liberalization always leads to the more efficiently allocation of resources across countries, so unbundling costs can be interpreted as frictions preventing firms from allocating their resources.

The reason behind this reallocation is a fall in unbundling costs decreases the relative importance of complementarity considerations and, thus, increases the importance of production costs in the cost function. For instance, when unbundling costs are equal to zero, a firm would make a decision based exclusively on the difference in production costs between the two countries.

Proposition 5. *The production of a single part in a given country can depend non-monotonically on φ . Reshoring is possible.*

Due to the presence of unbundling costs, firms choose to organise their production in clusters of technologically similar inputs. Lower unbundling costs mean that the incentives to cluster production are also lower. As a result, a situation called reshoring is possible: an input that a firm chose to produce internationally as a part of a cluster can be again produced domestically for a lower value of φ when the firm de-clusters its production.

All of these results hold on a firm, industry, and economy level.

2.3.3 Input Requirements

Firms from different industries face the same complementarity cost matrix \mathbf{C} and ex ante identical costs of production $a_{mn,z}^i$. Their allocation problems, however, are different because of the industry-specific vector of input requirements Θ_n^i , which affects effective costs of production of a given input $c_{mn,z}^i \equiv \theta_{mn}^i a_{mn,z}^i$. It follows that possible benefits from international production of input m depend on both its production costs and input requirements and are equal to $|\theta_{mn}^i (a_{mn,z}^1 - a_{mn,z}^2)|$.

The production location choice for each individual input, conditional on the location of all other inputs, is subject to a trade-off between potential production cost benefits from international production and losses associated with the unbundling costs. The weight of unbundling costs in Equation 1 will then be higher for inputs with a lower corresponding input share. As a result, clustering forces will be greater for “less important” inputs, and these inputs tend to be produced in the same location as complementary “more important” inputs.

2.4 Market Structure

There are $N + 1$ sectors in each of the two countries. The N sectors, indexed as $n, m \in \{1, \dots, N\}$, are characterised by monopolistic competition on the final goods market for each, while the other sector is perfectly competitive with country-specific productivity γ_i .

There is free entry in each monopolistically competitive sector, and there are industry-specific sunk costs η_n . We assume that there are no fixed costs of production or exporting,

thus shutting down the firm selection mechanism from [Melitz \(2003\)](#). Due to the free entry assumption, in equilibrium, the expected profits in each industry are equal to the sunk costs in this industry, which pins down the number of firms in each sector in each country to Z_n .

Inputs are produced from labour in a perfectly competitive environment and then are costlessly assembled in the final good (costly assembly can be easily introduced as one of the inputs). Workers are perfectly mobile across all sectors, and thus, the wage in each sector in country i is equalised to γ_i ¹⁵. We normalise the wage at home to 1, so $\gamma_1 = 1$ and $\gamma \equiv \gamma_2$ that can be interpreted as a relative wage. Imported inputs are subject to symmetric iceberg trade costs of τ , and in Section 4.1, we use changes in τ to estimate the effect of trade liberalisation in the form of tariff changes. Additionally, we assume that there are country-specific productivity shifters in each industry μ_n^i ; these productivity shifters can also be interpreted as sector-specific wages.

2.5 Equilibrium

The model takes the set of parameters $(\sigma, \zeta, \boldsymbol{\alpha}, \varphi, \mathbf{C}, T, \mathbf{c}, \boldsymbol{\eta}, \gamma, \boldsymbol{\mu})$, as exogenous, where \mathbf{c} is the set of intermediate input costs that each firm faces.

First, each firm in industry n , given $(\varphi, \mathbf{C}, T, \mathbf{c}, \gamma_i)$, chooses its optimal production allocation $S_{n,z}^* = \arg \min_S MC(S, \mathbf{c})$ with associated marginal costs $MC_{n,z}^* \equiv MC(S_{n,z}^*, \mathbf{c})$.

Given consumer demand and its marginal costs, firm z sets the price of its output to $p_{n,z} = \frac{\sigma}{\sigma-1} MC_{n,z}^*$, so that the price index for sector n is $P_n = (\int_{z \in Z} p_{n,z}^{1-\sigma} dz)^{\frac{1}{1-\sigma}}$. The sales of firm z are then $q_{n,z} = \frac{\alpha_n E}{P_n} (\frac{p_{n,z}}{P_n})^{-\sigma}$, where E is the total amount of expenditure on the consumption of heterogeneous goods. The market share of each firm in market n is then $\frac{q_{n,z}}{\sum_z q_{n,z}} = \frac{q_{n,z}}{Q_n}$.

In equilibrium, firm z 's demand for input from sector m is $q_{mn,z} = \frac{\theta_{mn}^i p_{n,z} q_{n,z}}{s_{mn,z} c_{mn,z}^1 + (1 - s_{mn,z}) c_{mn,z}^2}$. The industry-wide demand for inputs is then $q_{mn} = \sum_z \frac{q_{n,z}}{Q_n} q_{mn,z}$, and in country 1, the domestic share of each input used in sector n is

$$\pi_{mn}^1 = \frac{\sum_z \frac{q_{n,z}}{Q_n} s_{mn,z} c_{mn,z}^1}{\sum_z \frac{q_{n,z}}{Q_n} [s_{mn,z} c_{mn,z}^1 + (1 - s_{mn,z}) c_{mn,z}^2]}, \forall z \in Z^1.$$

¹⁵[Tyazhelnikov \(2022\)](#) shows that in a setting without a homogeneous good sector, for given labour endowments in both countries, there exists a unique equilibrium with endogenous wages that clears the labour market. This analysis can be applied in this paper for the cases of an industry-specific or perfectly mobile labour force.

3 Estimation

In this section we present the data used, how we construct the complementarity cost matrix, and the calibration process to fit the model to data.

3.1 Data

We use the input-output account data from the Bureau of Economic Analysis (BEA) between 2003 and 2020. The annual release of input supply and use tables covers 71 3-digit 2012 North American Industry Classification (NAICS) industry categories in the United States. We limit our analysis to 22 of the 71 industries based on the availability of data on industry complementarities, with most of them in the manufacturing sector. The BEA also provides import matrices of inputs at the same level, which allow us to calculate the home share of intermediate inputs for each industry, i.e. the proportion of each required input that is sourced from the home country.

We also use the Occupational Employment and Wage Statistics (OEWS) data from the Bureau of Labor Statistics (BLS) over the same period to establish labour complementarity across industries. The OEWS data is derived from survey responses from nonfarm establishments in the US. The survey responses are compiled to produce semiannual employment and wage estimates for around 800 occupations at various levels of industry classifications. We use the relationship between occupations and 3-digit NAICS industries to construct part of the complementarity relations.

Furthermore, we use the technology flows matrix by [Scherer \(1982\)](#) and the National Bureau of Economic Research (NBER) Patent Database to estimate technological complementarity using the methodology proposed by [Ellison et al. \(2010\)](#). Scherer’s technology matrix is calculated based on how much research and development (R&D) expenditure flows from one industry to another. And the NBER Patent Database records the patent citation patterns between 1975 and 1999, namely how many patents generated in one industry is cited by another. Since both sets of data are classified in 1987 Standard Industrial Classification (SIC), we use the concordance files in the NBER and U.S. Census Bureau’s Center for Economic Studies (NBER-CES) Manufacturing Industry Database to bring these datasets to 3-digit 2012 NAICS level.¹⁶

¹⁶We would like to acknowledge Richard Hornbeck who kindly provided relevant data.

3.1.1 The Matrix of Complementarity

We consider the three Marshallian factors behind geographical industrial agglomeration to construct an empirical counterpart of the matrix of complementarity \mathbf{C} : input-output linkages, shared labour market pooling, and technological spillovers. Of these three factors, input-output linkage is captured in the input-output relations that we calibrate in the estimation process, and is thus excluded from this section. For the remaining two factors, we can separately construct and linearly combine their respective complementarity cost matrix. We refer to the labour complementarity matrix as \mathbf{C}^L , and the technology complementarity matrix as \mathbf{C}^T .

To estimate the effect of labour market pooling, we construct a measure of labour force similarity for each pair of industries. Let $Lshare_{on}$ be the share of occupation o employment among industry n 's total employment, element \mathbf{C}_{nm}^L in the labour complementarity cost matrix is then

$$\mathbf{C}_{nm}^L = \sum_{o \in O} \min\{Lshare_{on}, Lshare_{om}\} \in [0, 1],$$

where O is the collection of all occupations in the dataset. For this study we use occupations at the 5-digit level. For any pair of industries nm and each occupation o , we can calculate $\min\{Lshare_{on}, Lshare_{om}\}$ which shows how much of the occupation o employment in one industry can be readily utilised by the other. For instance, if $Lshare_{on} < Lshare_{om}$, the extent of labour force similarity in terms of occupation o is determined by the smaller proportion $Lshare_{on}$. Two industries with similar occupation composition will end up with higher complementarity. With 18 annual releases of the OEWS data, we calculate the labour complementarity cost matrix for each year and take the mean as the benchmark matrix in order to filter out any idiosyncratic noise.¹⁷

For technological spillovers, we construct a technology complementarity matrix following the methodology proposed by Ellison et al. (2010). The similarity of industries can be reflected by how much of one industry's R&D expenditures and patent citation originates from or is directed at another industry. For each pair of industries nm , we calculate

$$Tech_{nm} = \max\{TechIn_{n \rightarrow m}, TechIn_{n \leftarrow m}, TechOut_{n \rightarrow m}, TechOut_{n \leftarrow m}\},$$

where $TechIn_{n \rightarrow m}$ is the share of R&D expenditure by industry n among all R&D expenditure spent on m , and $TechOut_{n \rightarrow m}$ is the share of R&D expenditure on m among all R&D expenditure spent by n . These four terms in the maximisation operator represent the tech-

¹⁷The estimated labour complementarity cost matrix is robust to different levels of occupation aggregation: a matrix constructed based on 3-digit occupations has a correlation coefficient of 0.970 with the estimated matrix based on 5-digit level occupations.

nology flow between the two industries, and the largest among them reflects their degree of similarity. Similarly, we calculate

$$Cit_{nm} = \max\{CitIn_{n \rightarrow m}, CitIn_{n \leftarrow m}, CitOut_{n \rightarrow m}, CitOut_{n \leftarrow m}\},$$

where $CitIn_{n \rightarrow m}$ and $CitOut_{n \rightarrow m}$ are citation counterparts defined in the same way as $TechIn_{n \rightarrow m}$ and $TechOut_{n \rightarrow m}$ above. Using regression estimates from Ellison et al. (2010) where Marshallian factors are fitted to explain pairwise industry coagglomeration, we assign weights to the technology and citation factors, and derive the technology complementarity cost matrix where each element is

$$\mathbf{C}_{nm}^T = \frac{0.180}{0.180 + 0.081} Tech_{nm} + \frac{0.081}{0.180 + 0.081} Cit_{nm}.$$

Combining labour and technology complementarity, the total complementarity cost matrix is

$$\varphi \mathbf{C} = \varphi^L \mathbf{C}^L + \varphi^T \mathbf{C}^T,$$

where φ^L and φ^T are the complementarity cost multipliers for labour and technology complementarity cost matrices, respectively.

To simplify notation, we consider the complementarity cost multiplier introduced in Section 2.2 as the collection of these two parameters, $\varphi \equiv (\varphi^L, \varphi^T)$. While both labour and technology complementarity cost matrices are time-invariant based on the available data and the methodology we adopt, φ can differ across years as the relative strength of labour and technology complementarity evolves.

In Tables 1 and 2 we present the two complementarity cost matrices. Among manufacturing industries (NAICS 31-33), the largest labor complementarity is 0.7493 between 332 (Fabricated Metal Product Manufacturing) and 333 (Machinery Manufacturing), while the largest technology complementarity is 0.3874 between 313-314 (Textile Mills and Textile Product Mills) and 315-316 (Apparel Manufacturing and Leather and Allied Product Manufacturing). The lowest labour complementarity is 0.2554 between 311-312 (Food Manufacturing and Beverage and Tobacco Product Manufacturing) and 334 (Computer and Electronic Product Manufacturing), while the lowest technology complementarity is 0.0001 between 315-316 and 324 (Petroleum and Coal Products Manufacturing). The correlation between two complementarity cost matrices is 0.2777, reflecting the fact that they are somewhat related but ultimately capturing different relations between industry pairs.

Table 1: Labour Complementarity Matrix

Sectors	113	311-312	313-314	315-316	321	322	323	324	325	326	327	331	332	333	334	335	336	337	339	511	512	811
113	1	0.1398	0.1130	0.1031	0.1813	0.1095	0.1275	0.1479	0.1217	0.1034	0.2904	0.1013	0.1263	0.1104	0.0861	0.0991	0.0946	0.1400	0.1323	0.1282	0.0945	0.1635
311-312	0.1398	1	0.4030	0.3315	0.4782	0.5064	0.3575	0.3909	0.4743	0.4919	0.4905	0.4064	0.3578	0.3256	0.2554	0.3420	0.3105	0.3533	0.3652	0.2004	0.1672	0.2910
313-314	0.1130	0.4030	1	0.6193	0.4168	0.4756	0.4028	0.3706	0.4448	0.4952	0.4584	0.4278	0.4264	0.3912	0.3084	0.4039	0.3577	0.4868	0.4514	0.2312	0.1554	0.2684
315-316	0.1031	0.3315	0.6193	1	0.3308	0.3777	0.4128	0.2821	0.3682	0.3933	0.3725	0.3225	0.3612	0.3465	0.2969	0.3581	0.2904	0.4248	0.4226	0.2535	0.1768	0.2304
321	0.1813	0.4782	0.4168	0.3308	1	0.4997	0.3693	0.3765	0.3931	0.5385	0.5348	0.4135	0.4577	0.4522	0.3014	0.4704	0.4251	0.6222	0.4978	0.2066	0.1452	0.3060
322	0.1095	0.5064	0.4756	0.3777	0.4997	1	0.4669	0.4390	0.5084	0.6126	0.5688	0.5051	0.4522	0.4177	0.3302	0.4349	0.3887	0.4333	0.4692	0.2613	0.1470	0.2849
323	0.1275	0.3575	0.4028	0.4128	0.3693	0.4669	1	0.2993	0.3789	0.4198	0.4048	0.3341	0.3856	0.3546	0.2917	0.3495	0.2808	0.4046	0.4622	0.3929	0.2092	0.2640
324	0.1479	0.3909	0.3706	0.2821	0.3765	0.4390	0.2993	1	0.5933	0.4258	0.4731	0.4550	0.3996	0.4069	0.3586	0.4013	0.4020	0.3396	0.4015	0.2361	0.1608	0.2479
325	0.1217	0.4743	0.4448	0.3682	0.3931	0.5084	0.3789	0.5933	1	0.5185	0.5043	0.4747	0.4610	0.4791	0.4346	0.4872	0.4315	0.4020	0.5198	0.3005	0.1967	0.2612
326	0.1034	0.4919	0.4952	0.3933	0.5385	0.6126	0.4198	0.4258	0.5185	1	0.6034	0.6955	0.6028	0.5603	0.3902	0.5957	0.5357	0.5179	0.6146	0.2186	0.1437	0.2800
327	0.2904	0.4905	0.4584	0.3725	0.5348	0.5688	0.4048	0.4731	0.5043	0.6034	1	0.4621	0.4800	0.4341	0.3414	0.4381	0.3987	0.4654	0.4850	0.2334	0.1566	0.3118
331	0.1013	0.4064	0.4278	0.3225	0.4135	0.5051	0.3341	0.4550	0.4747	0.6955	0.4621	1	0.6276	0.5381	0.3565	0.5410	0.5364	0.4070	0.5115	0.1826	0.1333	0.2435
332	0.1263	0.3578	0.4264	0.3612	0.4577	0.4522	0.3856	0.3996	0.4610	0.6028	0.4800	0.6276	1	0.7493	0.4146	0.6093	0.6107	0.5180	0.6071	0.2376	0.1713	0.2870
333	0.1104	0.3256	0.3912	0.3465	0.4522	0.4177	0.3546	0.4069	0.4791	0.5603	0.4341	0.5381	0.7493	1	0.5346	0.7325	0.7357	0.5031	0.6726	0.2644	0.1883	0.2589
334	0.0861	0.2554	0.3084	0.2969	0.3014	0.3302	0.2917	0.3586	0.4346	0.3902	0.3414	0.3565	0.4146	0.5346	1	0.6405	0.5070	0.3488	0.4924	0.3997	0.1914	0.1982
335	0.0991	0.3420	0.4039	0.3581	0.4704	0.4349	0.3495	0.4013	0.4872	0.5957	0.4381	0.5410	0.6093	0.7325	0.6405	1	0.6937	0.5109	0.6901	0.2542	0.1721	0.2379
336	0.0946	0.3105	0.3577	0.2904	0.4251	0.3887	0.2808	0.4020	0.4315	0.5357	0.3987	0.5364	0.6107	0.7357	0.5070	0.6937	1	0.4535	0.6064	0.2055	0.1509	0.2330
337	0.1400	0.3533	0.4868	0.4248	0.6222	0.4333	0.4046	0.3396	0.4020	0.5179	0.4654	0.4070	0.5180	0.5031	0.3488	0.5109	0.4535	1	0.5802	0.2353	0.1612	0.2795
339	0.1323	0.3652	0.4514	0.4226	0.4978	0.4692	0.4622	0.4015	0.5198	0.6146	0.4850	0.5115	0.6071	0.6726	0.4924	0.6901	0.6064	0.5802	1	0.3405	0.2219	0.2786
511	0.1282	0.2004	0.2312	0.2535	0.2066	0.2613	0.3929	0.2361	0.3005	0.2186	0.2334	0.1826	0.2376	0.2644	0.3997	0.2542	0.2055	0.2353	0.3405	1	0.2873	0.2202
512	0.0945	0.1672	0.1554	0.1768	0.1452	0.1470	0.2092	0.1608	0.1967	0.1437	0.1566	0.1333	0.1713	0.1883	0.1914	0.1721	0.1509	0.1612	0.2219	0.2873	1	0.1730
811	0.1635	0.2910	0.2684	0.2304	0.3060	0.2849	0.2640	0.2479	0.2612	0.2800	0.3118	0.2435	0.2870	0.2589	0.1982	0.2379	0.2330	0.2795	0.2786	0.2202	0.1730	1

Table 2: Technology Complementarity Matrix

Sectors	113	311-312	313-314	315-316	321	322	323	324	325	326	327	331	332	333	334	335	336	337	339	511	512	811
113	1	0.0017	0.0043	0.0010	0.4224	0.0129	0.0001	0.0004	0.0155	0.0201	0.0086	0.0019	0.0421	0.1395	0.0102	0.0064	0.0109	0.0235	0.0283	0.0005	0.0000	0.0000
311-312	0.0017	1	0.0011	0.0007	0.0014	0.0790	0.0010	0.0005	0.0395	0.0136	0.0009	0.0008	0.0352	0.1763	0.0259	0.0080	0.0305	0.0010	0.0119	0.0019	0.0016	0.0003
313-314	0.0043	0.0011	1	0.3874	0.0048	0.0156	0.0055	0.0007	0.0665	0.1044	0.0057	0.0022	0.0302	0.0777	0.0596	0.0080	0.0141	0.0053	0.0462	0.0062	0.0060	0.0014
315-316	0.0010	0.0007	0.3874	1	0.0019	0.0137	0.0012	0.0001	0.0147	0.0856	0.0017	0.0008	0.0190	0.0262	0.0261	0.0059	0.0102	0.0033	0.0326	0.0027	0.0023	0.0007
321	0.4224	0.0014	0.0048	0.0019	1	0.0224	0.0075	0.0006	0.0126	0.0282	0.0086	0.0020	0.0440	0.0601	0.0206	0.0075	0.0356	0.0663	0.0267	0.0047	0.0054	0.0015
322	0.0129	0.0790	0.0156	0.0137	0.0224	1	0.0310	0.0012	0.0479	0.0625	0.0098	0.0069	0.0408	0.0920	0.0447	0.0069	0.0142	0.0109	0.0302	0.0182	0.0214	0.0025
323	0.0001	0.0010	0.0055	0.0012	0.0075	0.0310	1	0.0002	0.0197	0.0282	0.0039	0.0021	0.0313	0.0948	0.0508	0.0080	0.0162	0.0189	0.0427	0.1829	0.2118	0.0000
324	0.0004	0.0005	0.0007	0.0001	0.0006	0.0012	0.0002	1	0.1233	0.0082	0.0023	0.0057	0.0349	0.1515	0.0300	0.0017	0.0210	0.0014	0.0130	0.0004	0.0003	0.0001
325	0.0155	0.0395	0.0665	0.0147	0.0126	0.0479	0.0197	0.1233	1	0.1779	0.0551	0.0346	0.0376	0.0860	0.0518	0.0138	0.0331	0.0098	0.0524	0.0185	0.0136	0.0037
326	0.0201	0.0136	0.1044	0.0856	0.0282	0.0625	0.0282	0.0082	0.0551	1	0.0219	0.0204	0.0318	0.0646	0.0316	0.0119	0.0265	0.0213	0.0724	0.0254	0.0263	0.0116
327	0.0086	0.0009	0.0057	0.0017	0.0086	0.0098	0.0039	0.0023	0.0346	0.0204	1	0.0369	0.0403	0.1051	0.0321	0.0122	0.0243	0.0034	0.0184	0.0042	0.0041	0.0018
331	0.0019	0.0008	0.0022	0.0008	0.0020	0.0069	0.0021	0.0057	0.0346	0.0204	0.0369	1	0.0962	0.1991	0.0787	0.0983	0.0128	0.0023	0.0230	0.0016	0.0018	0.0015
332	0.0421	0.0352	0.0302	0.0190	0.0440	0.0408	0.0313	0.0349	0.0376	0.0318	0.0403	0.0962	1	0.1751	0.0649	0.0550	0.1306	0.0307	0.0385	0.0360	0.0285	0.0239
333	0.1395	0.1763	0.0777	0.0262	0.0601	0.0920	0.0948	0.1515	0.0860	0.0646	0.1051	0.1991	0.1751	1	0.0827	0.0920	0.1795	0.0421	0.0547	0.0853	0.0513	0.0674
334	0.0102	0.0259	0.0596	0.0261	0.0206	0.0447	0.0508	0.0300	0.0518	0.0316	0.0321	0.0787	0.0649	0.0827	1	0.1181	0.1103	0.0421	0.1192	0.0475	0.0435	0.0087
335	0.0064	0.0080	0.0080	0.0059	0.0075	0.0069	0.0080	0.0017	0.0138	0.0119	0.0122	0.0983	0.0550	0.0920	0.1181	1	0.0696	0.0088	0.0282	0.0128	0.0116	0.0064
336	0.0109	0.0305	0.0141	0.0102	0.0356	0.0142	0.0162	0.0210	0.0331	0.0265	0.0243	0.0128	0.1306	0.1795	0.1103	0.0696	1	0.0234	0.0333	0.0176	0.0122	0.1471
337	0.0235	0.0010	0.0053	0.0033	0.0663	0.0109	0.0189	0.0014	0.0098	0.0213	0.0034	0.0023	0.0307	0.0421	0.0421	0.0088	0.0234	1	0.0367	0.0110	0.0126	0.0010
339	0.0283	0.0119	0.0462	0.0326	0.0267	0.0302	0.0427	0.0130	0.0524	0.0724	0.0184	0.0230	0.0385	0.0547	0.1192	0.0282	0.0333	0.0367	1	0.0536	0.0466	0.0165
511	0.0005	0.0019	0.0062	0.0027	0.0047	0.0182	0.1829	0.0004	0.0185	0.0254	0.0042	0.0016	0.0360	0.0853	0.0475	0.0128	0.0176	0.0110	0.0536	1	0.1051	0.0001
512	0.0000	0.0016	0.0060	0.0023	0.0054	0.0214	0.2118	0.0003	0.0136	0.0263	0.0041	0.0018	0.0285	0.0513	0.0435	0.0116	0.0122	0.0126	0.0466	0.1051	1	0.0000
811	0.0000	0.0003	0.0014	0.0007	0.0015	0.0025	0.0000	0.0001	0.0037	0.0116	0.0018	0.0015	0.0239	0.0674	0.0087	0.0064	0.1471	0.0010	0.0165	0.0001	0.0000	1

3.2 Firm's Problem

We find each firm's optimal production allocation decision to estimate the extent of international integration. The presence of input complementarity rules out a brute force solution of the firm's problem. For the allocation of N inputs between 2 possible locations, each firm's optimal decision lies among 2^N combinations: finding the optimal allocation is hardly feasible for large N . Even for the moderate $N = 22$ that we use in this paper, the number of possible permutations exceeds 4 million for each firm.

This problem belongs to the class of discrete combinatorial problems. We recursively apply the mapping procedure from [Arkolakis et al. \(2022\)](#) to explicitly solve each firm's problem.¹⁸ With N components and two locations to choose from, a firm's optimal allocation, S^* , is a vector of N indicators, where element $s_m = 1$ if input m is produced in country 1, and $s_m = 0$ otherwise. Vector S^* is then bounded above by an upper bound vector where the indicators all equal to 1, and below by a lower bound where the indicators all equal 0.

Let \bar{S}^h denote the upper bound of the set containing S^* before the h th iteration of the algorithm, $h = 1, 2, 3, \dots$, and \underline{S}^h denote the lower bound of this set. Both \bar{S}^h and \underline{S}^h are updated through each iteration of the algorithm and converge to identify the unique $S^* = \bar{S}^h = \underline{S}^h$ for some h . Initially, \bar{S}^1 is a vector of 1s, and \underline{S}^1 a vector of 0s.

Furthermore, let $D_m MC(S) = MC(S(s_m = 1)) - MC(S(s_m = 0))$ be the derivative with respect to the m th component of the marginal cost function under decision vector S , i.e., $D_m MC(S)$ reflects the change in the objective function as the m th indicator in vector S changes from 0 to 1, while holding every other indicator constant. With cost minimisation as its objective, a firm would prefer indicator $s_m = 0$ if the derivative $D_m MC(S)$ is positive.

Outer loop $\bar{s}_m^{(h+1)} = 0$ for all m such that $D_m MC(\bar{S}^h) > 0$, where $\bar{S}_m^h \neq \underline{S}_m^h$.

$\underline{s}_n^{(h+1)} = 1$ for all n such that $D_n MC(\underline{S}^h) < 0$, where $\bar{S}_n^h \neq \underline{S}_n^h$.

If $\bar{S}^h \neq \underline{S}^h$, the first step is to identify any change to the decision vector that would result in a lower marginal cost. Starting with decision vector \bar{S}^h , for any element m where the upper bound and lower bound do not coincide, i.e., $\bar{S}_m^h \neq \underline{S}_m^h$, the derivative $D_m MC(\bar{S}^h)$ is calculated: it compares the marginal cost under \bar{S}^h where the m th indicator $s_m = 1$ and a perturbed version of \bar{S}^h where $s_m = 0$.

If the derivative of $MC(\bar{S}^h)$ with respect to the m th component is positive, it means that the firm can achieve a lower marginal cost than $MC(\bar{S}^h)$ by, holding all other indicators in \bar{S}^h constant, producing input m instead in the foreign country, i.e. if element s_m changes from 1 to 0. The next iteration $\bar{S}^{(h+1)}$ will then have indicator s_m set to 0.

¹⁸Our objective function exhibits the single crossing differences property required by the [Arkolakis et al. \(2022\)](#) algorithm for any complementarity matrix \mathbf{C} without negative elements.

In the context of the firm's allocation problem, the process here is that, given the production pattern implied by \bar{S}^h , the firm considers whether it is preferable to outsource some inputs, i.e. changing their production indicator from 1 to 0, on a case-by-case basis.

Analogously, from \underline{S}^h , if the derivative of $MC(\underline{S}^h)$ with respect to the n th component is negative, the firm can achieve a lower marginal cost by producing input n from the home country, i.e. if the n th indicator changes from 0 to 1. The next iteration $\underline{S}^{(h+1)}$ will then have indicator $s_n = 1$.

If $\bar{S}^h \neq \underline{S}^h$ and the two bounds no longer change after new iterations of the outer loop, in other words, when there are no immediate cost saving perturbations available for either bound, the algorithm applies the inner loop to break the deadlock.

Inner loop If $MC(\bar{S}^h) > MC(\underline{S}^h)$,

$$\bar{s}_m^{(h+1)} = 0 \text{ for } m \text{ where } D_m MC(\bar{S}^h) = \inf\{D_l MC(\bar{S}^h) \mid \forall l \text{ where } \bar{s}_l^h \neq \underline{s}_l^h\}.$$

If $MC(\bar{S}^h) < MC(\underline{S}^h)$,

$$\underline{s}_n^{(h+1)} = 1 \text{ for } n \text{ where } D_n MC(\underline{S}^h) = \inf\{D_l MC(\underline{S}^h) \mid \forall l \text{ where } \bar{s}_l^h \neq \underline{s}_l^h\}.$$

Given that the optimal decision vector S^* belongs to the set with upper bound \bar{S}^h and lower bound \underline{S}^h , it is possible that the bound associated with the lower marginal cost is itself the optimal S^* . Hence during this step, the algorithm focuses on improving the bound associated with the higher marginal cost.

If there is no immediate improvement or decrease in marginal cost available, the next best option is to change the indicator that is associated with the least amount of increase in the marginal costs. While this does not immediately result in a lower marginal costs, it breaks the deadlock across the iterations and enables the algorithm to determine the next step: it will again apply the outer loop to the new candidates in the $(h + 1)$ th iteration to identify any cost saving potential now available.

This algorithm always reaches a solution. With reasonably high complementarity among inputs, the algorithm can find the optimal decisions with 100% accuracy, which can be verified for small N where the brute force approach can be employed to find the optimal solution.

3.3 Calibration and Estimation

In our estimation process, we consider the US to be country 1, and the rest of the world to be country 2. We focus on calibrating the parameters from the perspective of the US.¹⁹

¹⁹The program can be expanded to calibrate with respect to both countries at the same time.

We use the following values for the demand parameters: $\sigma = 4$ and $\zeta = 0.5$ and take final good demand shares α_n from the input-output use data. To quantify the model, we employ a standard stochastic formulation as in [Eaton and Kortum \(2002\)](#) and assume that input costs $a_{mn,z}^i$, $i = 1, 2$, are generated through independent draws from the Fréchet distribution with a common shape parameter $\kappa = 4.12$ ([Simonovska and Waugh \(2014\)](#)).²⁰ The observed cost of intermediate input from sector m for firm z operating in sector n in country i is $c_{mn,z}^i = \theta_{mn}^i \mu_m^i a_{mn,z}^i$, where μ_m^i is a country- and sector-specific shifter.

We shut down the entry and variety channels for the heterogeneous sectors: for any parameter values, we set the sunk cost η_i such that $Z_m^1 = Z_m^2 = 200$. Henceforth, we ignore sunk cost parameters and the number of firms.

The calibration objective is to match observed and simulated domestic input shares in each industry. We calculate the domestic input shares for the US, π^1 , from the import matrices of the corresponding input-output account. The domestic input share is thus an N by N matrix, π .

Note that we assume that the sector-level input requirements Θ_n^i are in terms of quantities because inputs are perfect complements, while the empirical counterpart from the input-output tables, $\tilde{\Theta}_n^i$, is expressed in terms of expenditure shares. To overcome this problem, for a given value of model parameter values, we construct a synthetic input-output table in terms of quantities, $\hat{\Theta}_n^i$, such that industries' expenditure shares generated in the model match $\tilde{\Theta}_n^i$ from the data.

The key variables we calibrate are the collection of complementarity cost multipliers φ , the iceberg trade cost τ , and the sector-specific relative cost of intermediate inputs μ^2/μ^1 .²¹ We normalise μ^1 to a vector of 1s, so that we only require μ^2 to find the relative cost of intermediate inputs.

The recursive calibration procedure is as follows: given $(\sigma, \zeta, \alpha, \kappa, \mathbf{C})$, we first calibrate φ by minimising the distance between the observed π from data and simulated $\hat{\pi}$ from the model to find $\hat{\varphi} = \arg \min_{\varphi} (\pi(\hat{\varphi}) - \pi)^2$. $\hat{\pi}$ can be derived by applying the algorithm discussed in Section 3 to solve each firm's cost minimisation problem and find the home share of intermediate inputs at the sector level, for all sectors. The home share of input m in sector n is defined as the weighted average of the proportion of factor payments from all Z firms operating in sector n to the firm's domestic suppliers of sector m intermediate inputs.

Given $\hat{\varphi}$, we then estimate iceberg trade costs parameter, τ , and the sector-specific relative cost for foreign producers $\hat{\mu}^2 = \arg \min_{\mu^2} (\pi(\widehat{\mu^2}, \hat{\varphi}, \tau) - \pi)^2$. After this, we re-

²⁰As we do not have a closed form solution, we are not restricted by parametric assumptions; we choose a commonly used Fréchet distribution to make our results comparable with the rest of the literature.

²¹We do not normalize μ^2/μ^1 to 1, so productivity shifter estimation will also estimate γ . For brevity, we omit γ from the estimation procedure, but it can be recovered after the estimation is complete.

weight the synthetic input-output table, $\theta_m^i(\hat{n})$, which describes the cost contribution of each intermediate input, so that the simulated intermediate input use in each sector converges towards the data. Using the adjusted input requirements, we again estimate $\hat{\mu}^2 = \arg \min_{\mu^2} (\pi(\widehat{\mu^2}, \hat{\varphi}, \hat{\Theta}, \tau) - \pi)^2$. Finally, we estimate $\hat{\varphi} = \arg \min_{\varphi} (\pi(\hat{\mu}^2, \hat{\varphi}, \hat{\Theta}, \tau) - \pi)^2$. This procedure is repeated until the estimated complementarity cost multiplier remains stable across iterations, i.e. when $\hat{\hat{\varphi}}$ is sufficiently close to $\hat{\varphi}$.

This estimation procedure can be summarised as the following program:

Step 0 For an initial guess of productivity shifters $\mu^2 = 1$, input requirements $\hat{\Theta}_n^1 = \hat{\Theta}_n^2 = (\frac{1}{N}, \dots, \frac{1}{N})$, and $\varphi = 0$, each firm chooses its optimal allocation S (see Section 3.2 for details), industry input usage shares are computed.

Step 1 for a given value of φ , μ^2 , τ , S , find $\hat{\Theta}_n^1$ that matches industry input usage shares in the US to $\tilde{\Theta}_n^i$, for all $n \in N$.

Step 2 for given φ , μ^2 , τ , and $\hat{\Theta}_n^1$, firms choose their optimal allocations S .

Step 3 Repeat Steps 1-2 until $\hat{\Theta}_n^1$ stops changing, for all $n \in N$.

Step 4 For given values of φ , μ^2 , τ , and $\hat{\Theta}_n^1$, find the optimal allocation S for all country 1 firms.

Step 5 For given values of $\hat{\Theta}_n^1$ and S , find iceberg trade cost τ and relative productivity shifters μ^2 and φ that minimise $(\hat{\pi}(\varphi, \mu^2, \tau) - \pi)^2$.

Step 6 repeat Steps 4-5 until φ , μ^2 , and τ stop changing.

Step 7 Repeat Steps [1-6] until φ , μ^2 , τ , and $\hat{\Theta}_n^1$ stop changing.

Our estimation procedure consists of two nested loops. The inner loop is Steps 1-3 to ensure that the input requirements $\hat{\Theta}_n^1$ are consistent with the observed home input usage shares from the BEA input-output data. The outer loop consisting of Steps 4-7 finds the relative wage, productivity shifters, iceberg trade cost, and complementarity cost multiplier that minimise the objective function to match the observed outsourcing pattern.

4 Results

Under the benchmark specification in 2019, unbundling costs account for 1.86% of total production costs across the economy. Table 3 shows a breakdown of the complementarity cost

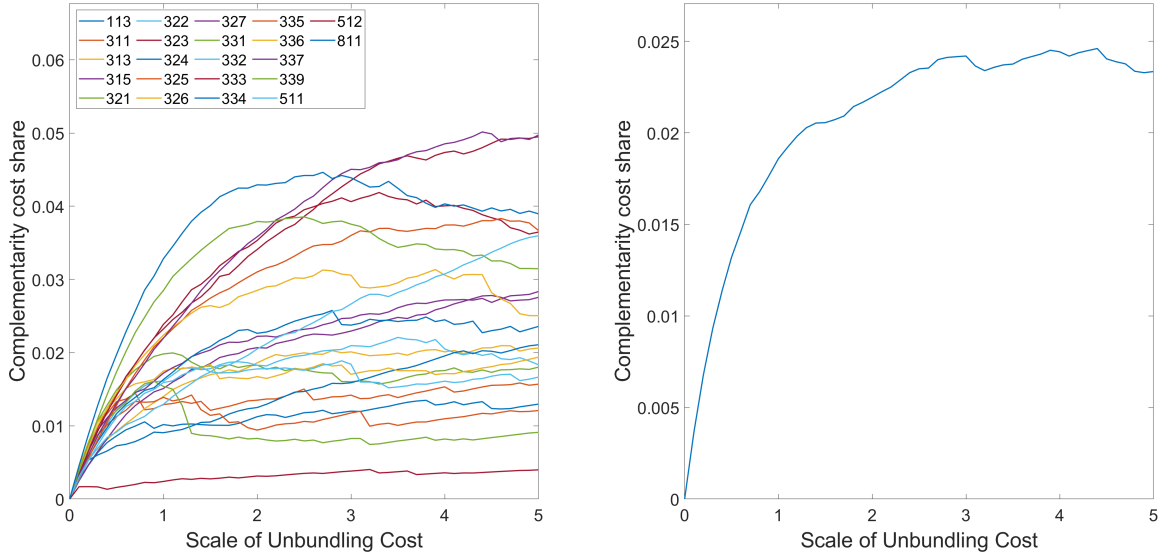


Figure 1: Paths of the economy- and sector-level complementarity cost share as φ changes

share for each sector with the largest share of 3.28% being observed in the Repair and Maintenance sector, and the smallest share of 0.24% being observed in Motion Picture and Sound Recording Industries. Among NAICS manufacturing industries (31-33), the highest share is 2.849% for Miscellaneous Manufacturing (339), and the smallest is 0.906% for Petroleum and Coal Products Manufacturing (324).

Focusing on NAICS manufacturing industries, it makes sense for resource reliant industry like Petroleum and Coal Products Manufacturing (324) to incur the smallest complementarity cost share: the location of these resources likely dictates the where the relevant tasks are performed. On the other hand, most industries that manufacture composite products with a variety of inputs, such as Machinery Manufacturing (333), Electrical Equipment, Appliance, and Component Manufacturing (335), and Transportation Equipment Manufacturing (336), have a higher share of complementarity cost. A notable exception is Computer and Electronic Product Manufacturing (334), where production tends to be concentrated in Asia: it is considered as one single region in this setup and thus not allocating tasks in different Asian countries does not increase the estimated complementarity cost.

The complementarity cost share is dependent on the scale of unbundling cost, i.e. the size of the complementarity cost multiplier φ . The top panel of Figure 1 shows that an industry's complementarity cost share could either increase or decrease, as predicted in Section 2.3.2. Aggregated across the economy, the complementarity cost share follows the direction of change in the scale of complementarity cost, which can be observed in the bottom panel of Figure 1.

Table 3: Complementarity Cost Share by Sector

113	Forestry and Logging	1.017%
311	Food Manufacturing and Beverage and Tobacco Product Manufacturing (inc. 312)	1.290%
313	Textile Mills and Textile Product Mills (inc.314)	1.400%
315	Apparel Manufacturing and Leather and Allied Product Manufacturing (inc. 316)	1.510%
321	Wood Product Manufacturing	1.982%
322	Paper Manufacturing	1.609%
323	Printing and Related Support Activities	2.386%
324	Petroleum and Coal Products Manufacturing	0.906%
325	Chemical Manufacturing	1.390%
326	Plastics and Rubber Products Manufacturing	1.748%
327	Non-metallic Mineral Product Manufacturing	1.719%
331	Primary Metal Manufacturing	1.539%
332	Fabricated Metal Product Manufacturing	1.590%
333	Machinery Manufacturing	2.324%
334	Computer and Electronic Product Manufacturing	1.633%
335	Electrical Equipment, Appliance, and Component Manufacturing	2.199%
336	Transportation Equipment Manufacturing	2.238%
337	Furniture and Related Product Manufacturing	2.196%
339	Miscellaneous Manufacturing	2.849%
511	Publishing Industries (except Internet)	1.294%
512	Motion Picture and Sound Recording Industries	0.240%
811	Repair and Maintenance	3.283%
	Aggregate	1.859%

Notes: column 2 indicates the complementarity cost as a share of total costs, derived from baseline simulation with calibrated parameters $\varphi^L = 0.0008$, $\varphi^T = 0.0002$, and $\tau = 1.025$.

We also examine the sensitivity of international production to changes in the scale of unbundling costs φ . Holding relative input costs and iceberg trade costs constant at the calibrated values, we perform the counterfactual analysis for the case of a decrease in φ , which is uniform and proportional for both the labour complementarity effect φ^L and technology complementarity effect φ^T . To compare the extent of offshoring across different specifications of the model, we construct a new measure to characterise the extent of offshoring.

4.1 Measuring the Extent of Offshoring

4.1.1 Allocation Efficiency Measure

Our benchmark measure accounts for the amount of misallocation associated with unbundling costs. This measure, which we call the allocation efficiency measure (*AEM*), compares the actual total input costs incurred against the total input costs under limiting cases of unbundling costs, $\bar{\varphi}$: no unbundling costs $\bar{\varphi} = 0$ and infinitely large unbundling costs $\bar{\varphi} = \infty$.

Let $MC_{n,z}^1(\varphi, S(\varphi))$ be the marginal costs of a firm z from industry n in country 1 that faces unbundling costs φ and uses allocation S , which is optimal for the given φ . The country index in the superscript of the MC term is suppressed since we focus on firms in country 1. Under zero unbundling costs, a firm's problem only involves finding the allocation decision where the cost of each input is minimised, after considering iceberg trade cost τ : its cost function is then

$$MC_{n,z}(0, S(0)) = \sum_{m=1}^N \min_{s_{mn,z}} [s_{mn,z} c_{mn,z}^1 + (1 - s_{mn,z}) \tau c_{mn,z}^2].$$

As φ becomes non-zero, complementarity costs arise, the firm adapts its outsourcing decision and ends up with a different production allocation that is associated with a higher cost than $MC_{n,z}(0, S(0))$. In other words, for any $\varphi > 0$, $MC_{n,z}(0, S(\varphi)) \geq MC_{n,z}(0, S(0))$. When $\varphi = \infty$, unbundling becomes prohibitively expensive, and the firm's marginal costs are

$$MC_{n,z}(\infty, S(\infty)) = \min_{s_{mn,z}} \sum_{m=1}^N [s_{mn,z} c_{mn,z}^1 + (1 - s_{mn,z}) \tau c_{mn,z}^2] = MC_{n,z}(0, S(\infty)),$$

where the last equality follows because allocation $S(\infty)$ is such that the value of φ does not affect the cost function. Hence the maximum possible cost differences and inefficiencies attributable to misallocation are $MC_{n,z}(\infty, S(\infty)) - MC_{n,z}(0, S(0))$.

Finally, for the estimated value of $\hat{\varphi}$, the marginal costs are equal to $MC_{n,z}(\hat{\varphi}, S(\hat{\varphi}))$.

Note that these costs are higher than $MC_{n,z}(0, S(0))$ for two reasons: first, as discussed in Section 2.3.2, allocation $S(\hat{\varphi})$ does not allow a firm to utilise productivity differences between countries in the most efficient way and leads to a sub-optimal allocation of resources compared to $S(0)$. Second, nonzero unbundling costs are included in the cost function, so marginal costs are higher for allocation $S(\hat{\varphi})$.

Since we are interested in the degree of misallocation that is caused by the presence of the unbundling costs, we focus on the former channel and consider marginal costs for allocation $S(\hat{\varphi})$ and ignore the additional unbundling costs when deriving a comparable marginal costs: $MC_{n,z}(0, S(\hat{\varphi}))$. The value of the actual level of misallocation is then $MC_{n,z}(0, S(\hat{\varphi})) - MC_{n,z}(0, S(0))$, which is the largest possible production cost savings that can be achieved by switching from autarky to international production.

We then define the allocation efficiency measure as one minus the ratio of the actual extent of inefficiency to the largest possible value of inefficiency:

$$AEM_{n,z}(\hat{\varphi}) = 1 - \frac{MC_{n,z}(0, S(\hat{\varphi})) - MC_{n,z}(0, S(0))}{MC_{n,z}(0, S(\infty)) - MC_{n,z}(0, S(0))} \quad (3)$$

This measure is equal to 1 when the allocation at $\hat{\varphi}$ coincides with the case of no unbundling costs $\varphi = 0$, and equal to 0 if the optimal allocation under $\hat{\varphi}$ is the same as the allocation under prohibitively high unbundling costs. If the allocations under zero and infinite trade costs coincide, then $MC_{n,z}(0, S(\infty)) = MC_{n,z}(0, S(0))$ and we assume that $AEM = 1$ because there is no misallocation for any value of φ .

Note that this particular AEM is calculated individually for a firm z in industry n . We can now obtain sector-level AEM as a summation of firm-level AEM weighted by their market share,

$$AEM_n(\hat{\varphi}) = \sum_z \frac{q_{n,z}^1(\hat{\varphi})}{Q_n^1(\hat{\varphi})} AEM_{n,z}(\hat{\varphi}), \quad (4)$$

where $\frac{q_{n,z}^1(\hat{\varphi})}{Q_n^1(\hat{\varphi})}$ is firm z 's market share in sector n among all country 1 firms under $\varphi = \hat{\varphi}$. The aggregate AEM for the home country is then

$$AEM(\hat{\varphi}) = \sum_{n=1}^N \alpha_n AEM_n(\hat{\varphi}), \quad (5)$$

where α_n regulates the contribution of each sector based on its relative size in the economy.

A higher value of AEM indicates that the economy is closer to the state of free trade, which is associated with the highest level of efficiency in terms of allocation decisions. $AEM = 0$ coincides with a closed economy where all production tasks occur within the

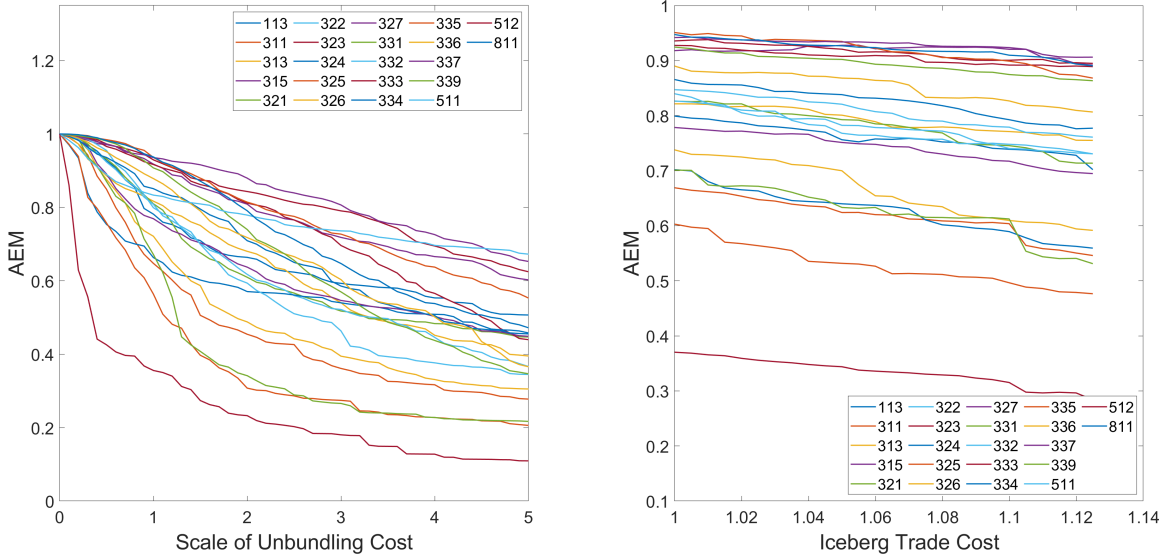


Figure 2: Paths of sector-level AEM as φ and τ change

same location, meaning that no cost reduction potential is exploited through trade.

If the scale of complementarity cost φ decreases, an industry's AEM will likely increase, reflecting the marginal cost converging to that of the frictionless trade state. The top panel of Figure 2 presents the path of sector-level AEM against the magnitude of unbundling costs, with scale of 1 coinciding with the calibrated level of unbundling costs in the data. In the bottom panel of Figure 2, we plot industry-level, φ -based AEM measures, evaluated at the calibrated $\varphi = (0.0008, 0.0002)$ as τ changes. The AEM values remain robust to changes τ , as this measure captures misallocation through unbundling costs rather than iceberg trade costs.

4.1.2 Import Measure

To further analyse and contextualise the behaviour of AEM , we introduce a measure that is close to conventional measures of offshoring. Since there is no sequential production in our model, such measures as value added to exports (VAX) become redundant and are always equal to 1.

The measure we need has to account for the importance of imported intermediate inputs in overall production. For some $\bar{\varphi}$, we solve for every firm's optimal allocation strategy and find the total factor payments, or the net value added, $VA_{n,z}(\bar{\varphi}) = \sum_{m=1}^N s_{mn,z} c_{mn,z}^1 + \tau(1 - s_{mn,z}) c_{mn,z}^2 = MC_{n,z}(0, S(\bar{\varphi}))$, as well as the value of intermediate inputs sourced from abroad, $IM_{n,z}(\bar{\varphi}) = \sum_{m=1}^N (1 - s_{mn,z}) \tau c_{mn,z}^2$ for firms in country 1. For given $\bar{\varphi}$, we calculate

the import to total volume measure (*ITVM*) for individual home firm z

$$ITVM_{n,z}(\bar{\varphi}) = \frac{IM_{n,z}(\bar{\varphi})}{VA_{n,z}(\bar{\varphi})}.$$

Aggregate the firm-level measure across all sector n firms in country 1 based on their respective market share:

$$ITVM_n(\bar{\varphi}) = \sum_z \frac{q_{n,z}^1(\bar{\varphi})}{Q_{n,z}^1(\bar{\varphi})} ITVM_{n,z}(\bar{\varphi}). \quad (6)$$

We can further aggregate the measure to the economy level:

$$ITVM(\bar{\varphi}) = \sum_{n=1}^N \alpha_n ITVM_n(\bar{\varphi}). \quad (7)$$

Table 4 presents the two measures for the benchmark model, with *ITVM* in column 3 and *AEM* in column 4. There is significant industrial heterogeneity in both measures. Among NAICS manufacturing industries, the highest *AEM* value is 0.9361 for Electrical Equipment, Appliance, and Component Manufacturing, and the lowest value is 0.5637 for Chemical Manufacturing; and the highest *ITVM* value is 0.4554 for Apparel Manufacturing and Leather and Allied Product Manufacturing, with the lowest value of 0.2215 in Paper Manufacturing.

It is interesting to note that manufacturing industries with a focus on final goods, such as Computer and Electronic Product Engineering (334), Electrical Equipment, Appliance, and Component (335), Transportation Equipment Manufacturing (336), and Furniture and Related Products (337), have higher *AEM* than other manufacturing industries.

Furthermore, the values of *AEM* do not correspond to the share of complementarity cost in Table 3: for instance, Textile Mills and Textile Product Mills (313) has the third lowest complementarity cost share but a relatively high *AEM*, while Chemical Engineering (325) has the lowest manufacturing sector *AEM* even though it has a similar level of complementarity cost share. This reflects the fact that the most efficient allocation differs across industries, it may be clustered for some but not for others.

4.1.3 A Simplified Allocation Efficiency Measure

While *AEM* effectively captures the extent of production efficiency, the derivation process requires extensive calculation and simulation of the framework in three different states: unbundling costs at zero level, prohibitively high level, and the desired level being examined.

Table 4: Measures from Calibrated Model, by Sector

Sector	Description	<i>ITVM</i>	<i>AEM</i>	<i>SAEM</i>
113	Forestry and Logging	0.4195	0.7816	0.1800
311	Food Manufacturing and Beverage and Tobacco Product Manufacturing (inc. 312)	0.2325	0.6474	0.1102
313	Textile Mills and Textile Product Mills (inc.314)	0.3635	0.8169	0.1687
315	Apparel Manufacturing and Leather and Allied Product Manufacturing (inc. 316)	0.4554	0.9178	0.2183
321	Wood Product Manufacturing	0.3586	0.8097	0.1718
322	Paper Manufacturing	0.2215	0.7991	0.1067
323	Printing and Related Support Activities	0.2935	0.9168	0.1465
324	Petroleum and Coal Products Manufacturing	0.3431	0.6632	0.1450
325	Chemical Manufacturing	0.315	0.5637	0.1205
326	Plastics and Rubber Products Manufacturing	0.3187	0.7213	0.1446
327	Non-metallic Mineral Product Manufacturing	0.3358	0.7691	0.1615
331	Primary Metal Manufacturing	0.2935	0.6716	0.1333
332	Fabricated Metal Product Manufacturing	0.3003	0.8083	0.1465
333	Machinery Manufacturing	0.3945	0.9294	0.2034
334	Computer and Electronic Product Manufacturing	0.4552	0.8510	0.1977
335	Electrical Equipment, Appliance, and Component Manufacturing	0.3757	0.9361	0.1933
336	Transportation Equipment Manufacturing	0.3705	0.8784	0.1805
337	Furniture and Related Product Manufacturing	0.3734	0.9356	0.1855
339	Miscellaneous Manufacturing	0.3176	0.9075	0.1651
511	Publishing Industries (except Internet)	0.3571	0.8334	0.1628
512	Motion Picture and Sound Recording Industries	0.1384	0.3557	0.0578
811	Repair and Maintenance	0.3386	0.9374	0.1778
Aggregate		0.3250	0.7815	

Notes: Column 1 lists the 2012 NAICS classification of the sector that corresponds to the description in Column 2. The measures are from baseline simulation with calibrated parameters $\varphi^L = 0.0008$, $\varphi^T = 0.0002$, and $\tau = 1.025$.

We thus propose a simplified allocation efficiency measure that follows the spirit of *AEM* while being less computationally demanding.

The amount of complementary cost that a firm incurs can be used to approximate how fragmented its production allocation is. At a given level of φ and complementarity cost matrix \mathbf{C} , there exists a maximum amount of complementarity cost that a firm may incur. While the most efficient production allocation decision doesn't necessarily coincide with the allocation decision with the highest complementarity cost, a firm will begin to incur increasing complementarity costs as it outsources more components to take advantage of better productivity elsewhere.

We thus propose a simplified allocation efficiency measure (*SAEM*) based on the ratio of a firm's complementarity cost against the largest possible complementarity cost, $CompCost(\varphi, \mathbf{C})$,

$$SAEM_{n,z}(\hat{\varphi}) = \frac{\sum_{m=2}^N \varphi |s_{mn,z} - s_{(m-1)n,z}| \mathbf{C}_{m,m-1}}{CompCost(\varphi, \mathbf{C})}. \quad (8)$$

This measure can be similarly aggregated to the industry level based on each firm's respective market share. While easy to calculate, a downside to the simplified measure is that it focuses exclusively on unbundling costs and ignores industrial cost draws, which are also an important driver of international organisation.²² In other words, *AEM* measures the degree of production distortions in the presence of both complementarity costs and differential production costs between countries, while *SAEM* focuses exclusively on the former channel.²³

The aggregated industry-level *SAEM* is shown in Column 5 of Table 5. While the correspondence is not perfect, the *SAEM* does tend to move in sympathy with *AEM*: the correlation coefficient across the 22 industries is 0.838.

4.1.4 Measures under Trade Liberalisation

In this section, we examine how the two measures introduced above respond to changes in trade barriers. While both measures can be used to measure the extent of offshoring, they behave differently to changes in trade barriers, and this also depends on whether trade liberalisation takes place through iceberg trade costs, or complementarity costs.

In the top panel of Figure 3, we plot the change in these two measures for the scale of complementarity cost from 0% to 500% of the calibrated values. Every sector contains 200 firms in each country. The calibrated $\varphi^L = 0.0008$ and $\varphi^T = 0.0002$. In the bottom panel

²²It is impossible to obtain the estimates of industrial productivity shifters without simulating the whole model.

²³As a result, the *SAEM* can be smaller than 1 for the most efficient allocations.

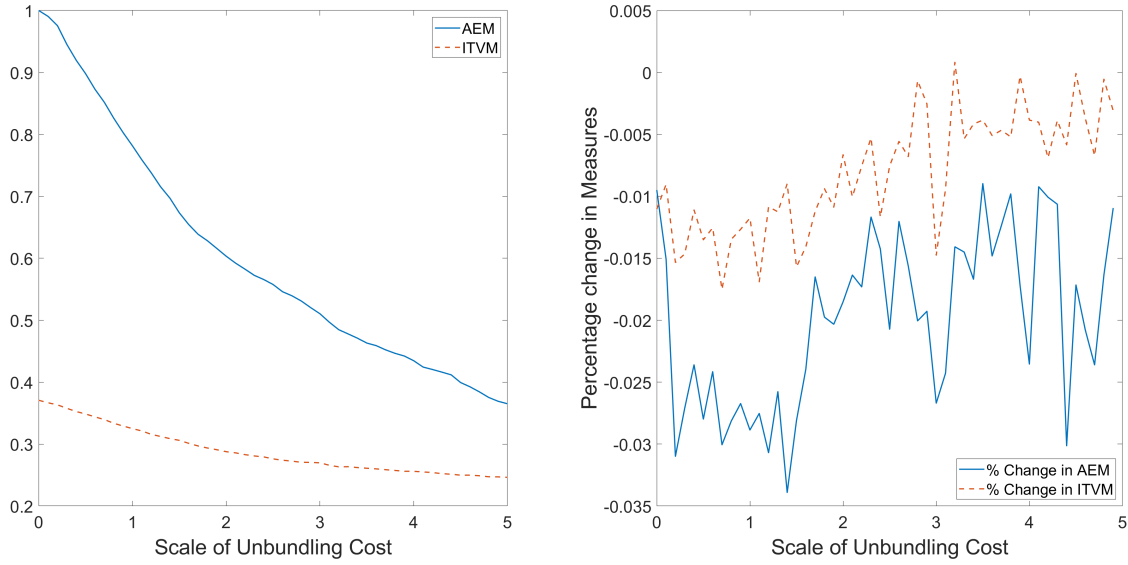


Figure 3: Changes and percentage changes in the two measures between 0% and 500% of calibrated complementarity cost parameters

of Figure 3, we plot the percentage change in both measures. The bottom panel of Figure 3 indicates that even though both measures are decreasing in φ , the percentage change in *AEM* is consistently higher and more volatile than that of *ITVM*, indicating that *AEM* is more sensitive to changes in φ . Interestingly, changes in *AEM* exhibit a strong non-monotone pattern, reflecting the non-trivial effect of clustering discussed in Section 2.3.2.

Table 5 supplements the top panels of Figures 1 and 2 by comparing the counterfactual with 10% lower unbundling costs against the baseline results. The last two columns of Table 5 are consistent with Proposition 3: decrease in φ can have an ambiguous effect on the cost share of complementarity activities. In this counterfactual exercise, a 10% decrease in φ leads to a decrease in the complementarity cost share in 20 industries and an increase in this share in 2 industries. If complementarity tasks are associated with non-production activities such as high-skilled intensive managerial tasks, trade liberalisation can lead to an increase in within-industry inequality in some industries and to a decrease in others.

In this paper, we focus on analysing the consequences of changes in unbundling costs. However, the presence of unbundling costs affects the model's response to changes in iceberg trade costs. To show this interaction, we then simulate the model with different levels of iceberg trade costs and again construct the two measures. The construction of the *AEM* measure is almost identical to the process described by Equation 5, other than the parameter of interest for the derivation of *AEM* instead being τ , and the frictionless state of the world (with unbundling cost held constant at some non zero φ as calibrated) is represented as

Table 5: Measures from Model with 10% Lower Unbundling Cost

Sector	<i>AEM</i>	% Change	Cost Share	% Change
113	0.7971	1.993%	0.966%	-5.072%
311	0.6722	3.825%	1.236%	-4.169%
313	0.8302	1.622%	1.317%	-5.910%
315	0.9331	1.667%	1.464%	-3.049%
321	0.8347	3.083%	1.948%	-1.721%
322	0.8350	4.495%	1.605%	-0.289%
323	0.9245	0.845%	2.198%	-7.900%
324	0.6947	4.752%	0.914%	0.888%
325	0.6086	7.958%	1.329%	-4.338%
326	0.7364	2.097%	1.634%	-6.506%
327	0.7782	1.180%	1.610%	-6.360%
331	0.7145	6.386%	1.609%	4.566%
332	0.8283	2.474%	1.498%	-5.830%
333	0.9449	1.662%	2.200%	-5.331%
334	0.8575	0.763%	1.520%	-6.902%
335	0.9555	2.068%	2.078%	-5.491%
336	0.8918	1.526%	2.109%	-5.786%
337	0.9432	0.814%	2.045%	-6.850%
339	0.9272	2.170%	2.693%	-5.483%
511	0.8409	0.908%	1.231%	-4.869%
512	0.3680	3.465%	0.223%	-7.133%
811	0.9461	0.932%	3.046%	-7.204%

Notes: The measures are derived after lowering parameter $\varphi = (0.0008, 0.0002)$ by 10%. Aggregate statistics are calculated from expenditure-weighted sums. Column 3 shows the percentage change in *AEM* compared to the baseline results. Column 4 contains the complementarity cost shares under this specification. Column 5 shows the percentage change in complementarity cost shares against the baseline results.

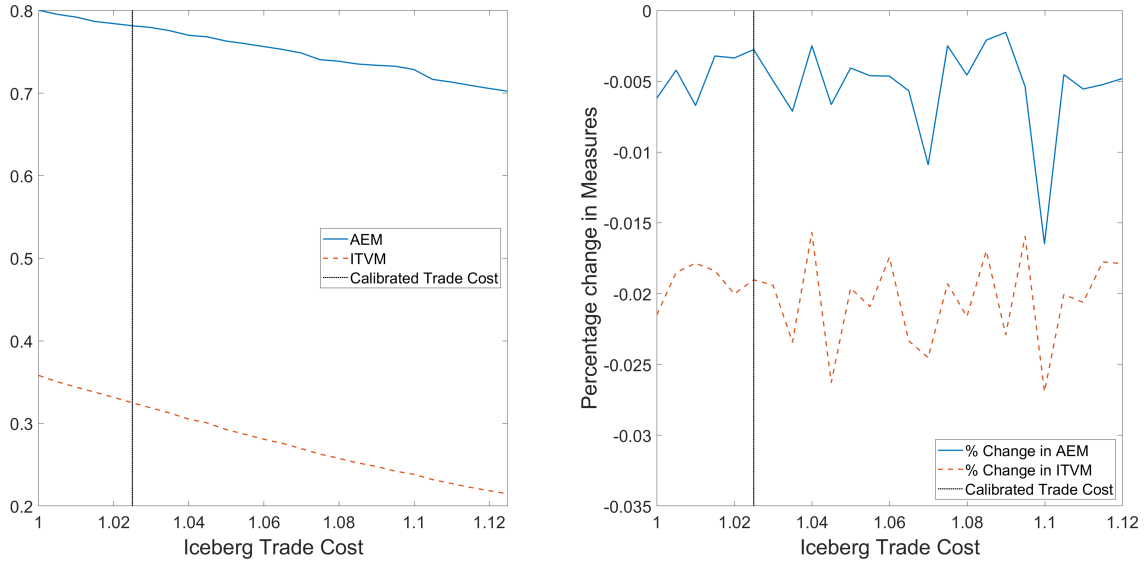


Figure 4: Changes and percentage changes in the two measures for τ between 1 and 1.125

$\tau = 1$.

In the bottom panel of Figure 2, we plot industry-level, φ -based *AEM* measures, evaluated at the calibrated $\varphi = (0.0008, 0.0002)$ as τ changes. The *AEM* values remain robust to changes τ , as this measure captures misallocation through unbundling costs rather than iceberg trade costs.

In Figure 4, we plot the levels and percentage changes in the two measures as the iceberg trade costs increase from 1 to 1.125, with the calibrated $\tau = 1.025$. Both measures monotonically decrease as iceberg cost increases, similar to the patterns demonstrated in Figure 3. However, as expected, in the presence of unbundling costs, *ITVM* is more sensitive than *AEM* to changes in τ . Moreover, as in the case with changes in φ , albeit to a lesser extent, changes in both measures exhibit non-monotone behaviour, indicating that complementarity-induced clustering is a relevant mechanism for the case of trade liberalisation in τ .

4.2 Aggregate Outcomes under Trade Liberalisation

In this section we consider how key economic indicators respond under a counterfactual exercise - a uniform decrease in unbundling costs (φ) by 10%, i.e. $\varphi^L = 0.0008$ and $\varphi^T = 0.0002$ both decreasing by 10%. Sector-level and aggregate results are provided in Table 6. Such a decrease in unbundling costs increases gross output in all industries and is highly heterogeneous among the included industries with Apparel Manufacturing and Leather and

Allied Product Manufacturing (315-316) among the least and Transportation Equipment Manufacturing (336) among the most affected in manufacturing sectors. Our counterfactual results indicate that a 10% decrease in φ leads to a significant increase in aggregate output of 75.5 billion dollars.

Not surprisingly, a decrease in φ leads to sizeable changes in employment, which is also heterogeneous across sectors. We estimate an aggregate change in production employment of 28,450 people. Interestingly, while production employment (employment associated with production costs) increased in all sectors, the sign of the effect on non-production employment associated with unbundling tasks is ambiguous, which is consistent with Proposition 3. The total number of newly hired or displaced workers involved in unbundling tasks is 15,092, which is the same order of magnitude as changes in production employment (43,545) despite unbundling costs only accounting for 1.86% of the total costs of production.²⁴

4.3 Welfare Analysis

In this section, we provide a welfare analysis. We define welfare as the inverse of the aggregated price level of final goods in the economy. A comparison of standard elasticity measures for the cases of tariff and non-tariff liberalisation can be misleading because of differences in absolute values and variation in φ and τ . Instead, we compute the standard deviation of each parameter using their values from the model calibrated for the years 2003 to 2020. In this section it is useful to separately consider labour and technology complementarity, φ^L and φ^T , as they may affect the aggregate outcome in different ways.

Despite the small absolute value of the complementarity cost scalar, it has a meaningful impact on firm behaviour and welfare outcomes. Table 7 indicates that the elasticity of welfare is much higher in case of a 1 standard deviation change in φ^L than changes in tariff barriers τ or φ^T . In the absence of unbundling costs, with $\varphi = 0$, tariff liberalisation will lead to a more pronounced welfare gain. In other words, the presence of unbundling costs prevents the effect of trade liberalisation from being fully realised: the cost difference will have to be large enough to offset the additional unbundling costs to justify changing production decisions.

²⁴These findings are consistent with [Eckert \(2019\)](#), who finds that the fall in communication costs can explain up to a 30% increase in the US college wage premium between 1980 and 2010.

Table 6: Sector Outcomes with 10% Lower Unbundling Cost

Sector	Δ GO	% Change	Δ Non-prod.	EMP	% Change	Δ Prod.	EMP	% Change	Δ Emp
113	328.2	0.097%	-0.02		-4.980%	0.07		0.150%	0.05
311	6978.1	0.127%	-0.99		-4.047%	3.42		0.182%	2.42
313	395.5	0.138%	-0.18		-5.779%	0.49		0.223%	0.31
315	161.4	0.153%	-0.06		-2.901%	0.27		0.200%	0.21
321	1285.9	0.203%	-0.12		-1.521%	0.95		0.238%	0.83
322	1779.7	0.166%	-0.01		-0.124%	0.61		0.171%	0.61
323	1166.7	0.238%	-0.79		-7.681%	1.81		0.431%	1.02
324	3280.1	0.092%	0.01		0.981%	0.09		0.084%	0.10
325	5490.7	0.128%	-0.49		-4.216%	1.56		0.189%	1.07
326	2351.9	0.171%	-0.81		-6.347%	2.06		0.287%	1.25
327	1277.9	0.171%	-0.45		-6.200%	1.16		0.282%	0.72
331	1963.1	0.140%	0.28		4.713%	0.26		0.069%	0.54
332	3272.8	0.155%	-1.34		-5.684%	3.65		0.250%	2.30
333	4875.7	0.234%	-1.33		-5.109%	3.96		0.361%	2.63
334	2838.0	0.156%	-1.15		-6.757%	2.77		0.271%	1.62
335	1572.3	0.225%	-0.46		-5.279%	1.34		0.349%	0.89
336	12749.5	0.222%	-2.15		-5.577%	5.96		0.354%	3.81
337	906.0	0.221%	-0.57		-6.645%	1.42		0.375%	0.86
339	2503.5	0.291%	-0.91		-5.208%	2.68		0.452%	1.77
511	2771.4	0.127%	-0.45		-4.748%	1.39		0.191%	0.94
512	109.8	0.022%	-0.08		-7.113%	0.17		0.039%	0.10
811	17443.4	0.330%	-3.03		-6.898%	7.45		0.576%	4.42
Aggregate	75501.7	0.182%	-15.09		-5.254%	43.54		0.290%	28.45

Notes: The sector outcomes are derived after reducing parameter $\varphi = (0.0008, 0.0002)$ by 10%. Column 2 shows the change in gross output, in millions of US dollars. Column 4 shows the change in the number of employees, in thousands, engaged in unbundling, non-production, activities. Column 5 shows the percentage change in the number of employees engaged in unbundling activities relative to the baseline specification of the model. Column 6 shows the change in the number of employees, in thousands, engaged in production activities. Column 8 shows the change in the total number of employees engaged in each sector.

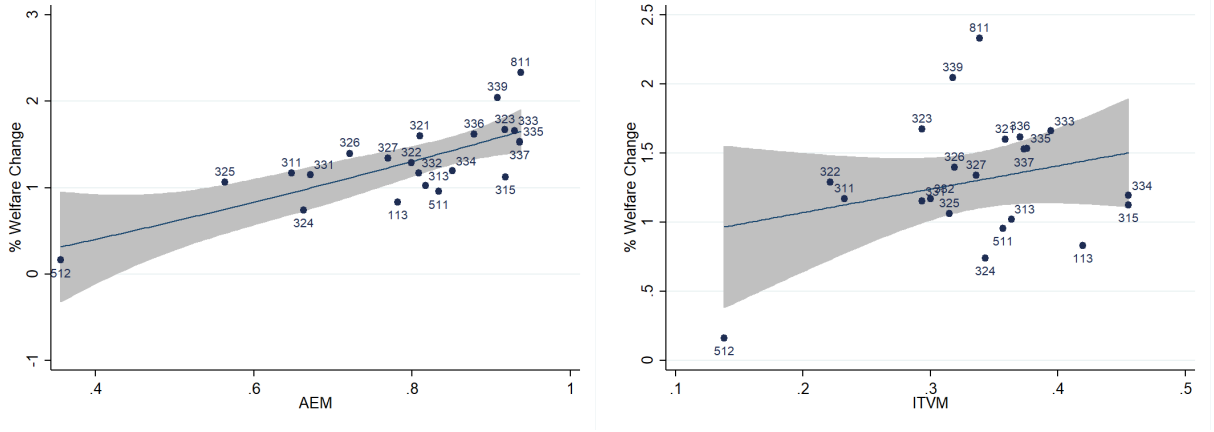


Figure 5: Welfare Elasticity, AEM and $ITVM$

Table 7: Elasticity of Welfare

Parameter	-1 s.d.	+1 s.d.
φ^L	1.390%	0.931%
φ^T	0.081%	0.079%
τ	0.875%	0.786%
τ (with $\varphi = 0$)	0.986%	0.902%

Notes: Welfare is calculated as the inverse of the aggregated price level in the economy. Calibrated $\varphi^L = 0.0008$, 1 s.d. = 0.00052, $\varphi^T = 0.0002$, 1 s.d. = 0.00035, and $\tau = 1.025$, 1 s.d. = 0.025.

Moreover, in the case of non-tariff liberalisation, an increase and a decrease in the value of labour demand complementarity cost leads to asymmetric changes in welfare with the effect associated with the decrease in φ^L being 50% larger than the effect of an increase in φ^L . The explanation follows from the top panel of Figure 3: the curve has a convex shape, and the estimated value of φ is relatively high, so its increase will not result in a substantial increase in misallocation. Conversely, a decrease in φ has greater potential to decrease misallocation and hence leads to higher welfare gains. Lower complementarity cost can first of all reduce the total amount of unbundling costs, holding constant the production allocation decision. At the same time, it can also enable the lead firm to choose a more efficient production decision. Consider an input that can be sourced at different costs from two countries, the lead firm is currently purchasing from the more expensive source: the associated increase in unbundling costs is high enough to discourage the firm from moving to the cheaper source. Lower unbundling costs may mean that the firm can now source instead from the cheaper source and further improve the efficiency of its production allocation decisions.

We evaluate welfare gains on the sector level (decrease in sector-level price index) for the case of non-tariff trade liberalisation in labour complementarity and plot it against our measures of offshoring. The results are presented in Figure 5. It is apparent that the values of *AEM* are strongly associated with welfare gains, while *ITVM* has no significant relationship with changes in welfare.

5 Conclusion

This paper introduces a multi-sector quantifiable model in which firms' production of inputs exhibits a general form of cost complementarity when they are produced in the same country. We show that the presence of such complementarity affects the optimal allocation of a firm and affects gains from trade. We use the US data to estimate the extent of complementarity and calibrate the model, and find that unbundling costs that we link to non-tariff trade barriers account for 1.86% of total costs and can be as high as 3.28% in some industries.

To quantify the strength of the complementarity effects, we introduce a new index of offshoring that accounts not only for volumes of imports but also for what parts and how complementary the inputs produced overseas are. We find that this index is a good predictor of gains from trade when non-tariff trade barriers decrease.

Our counterfactual exercises suggest that output and employment are sensitive to changes in unbundling costs, so a 10% uniform decrease in the value of unbundling costs leads to an increase in total US output by 75.5 billion dollars. We also find that the effects of such liberalisation exhibit a high degree of sectoral heterogeneity and are asymmetric for the cases of an increase and a decrease in unbundling costs.

References

- P. Antràs. *Conceptual aspects of global value chains*. The World Bank, 2020.
- P. Antràs and A. De Gortari. On the geography of global value chains. *Econometrica*, 88(4):1553–1598, 2020.
- P. Antràs, E. Rossi-Hansberg, and L. Garicano. *Organizing Offshoring: Middle Managers and Communication Costs*, pages 311–39. Harvard University Press, Cambridge, MA, 2008.
- P. Antras, T. C. Fort, and F. Tintelnot. The margins of global sourcing: Theory and evidence from us firms. *American Economic Review*, 107(9):2514–64, 2017.
- C. Arkolakis, F. Eckert, and S. Rowan. Combinatorial discrete choice: A quantitative model of multinational location decision. *Available at SSRN*, 2022.
- R. Baldwin and A. J. Venables. Spiders and snakes: Offshoring and agglomeration in the global economy. *Journal of International Economics*, 90(2):245–254, 2013.
- R. E. Baldwin. Globalisation: the great unbundling (s). Technical report, Economic council of Finland, 2006.
- J. V. Biesebroeck. Complementarities in automobile production. *Journal of Applied Econometrics*, 22(7):1315–1345, 2007.
- D. Chor. Modeling global value chains: approaches and insights from economics. In *Handbook on Global Value Chains*. Edward Elgar Publishing, 2019.
- A. Costinot. An elementary theory of comparative advantage. *Econometrica*, 77(4):1165–1192, 2009a.
- A. Costinot. On the origins of comparative advantage. *Journal of International Economics*, 77(2):255–264, 2009b.
- A. De Gortari. Disentangling global value chains. Technical report, National Bureau of Economic Research, 2019.
- S. Dhingra, R. Freeman, and H. Huang. The impact of non-tariff barriers on trade and welfare. *Economica*, 90(357):140–177, 2023.
- X. Ding, T. C. Fort, S. J. Redding, and P. K. Schott. Structural change within versus across firms: Evidence from the united states. Technical report, Technical Report, Discussion Paper). Dartmouth College, 2019.
- J. Eaton and S. Kortum. Technology, geography, and trade. *Econometrica*, 70(5):1741–1779, 2002.
- F. Eckert. Growing apart: Tradable services and the fragmentation of the us economy. *mimeograph, Yale University*, 2019.

- G. Ellison, E. L. Glaeser, and W. R. Kerr. What causes industry agglomeration? evidence from coagglomeration patterns. *American Economic Review*, 100(3):1195–1213, 2010.
- T. Fally and R. Hillberry. *A coasian model of international production chains*. The World Bank, 2015.
- R. C. Feenstra and G. H. Hanson. Globalization, outsourcing, and wage inequality. *The American Economic Review*, 86(2):240, 1996.
- T. C. Fort. Technology and production fragmentation: Domestic versus foreign sourcing. *The Review of Economic Studies*, 84(2):650–687, 2017.
- A. F. Friedlaender, C. Winston, and K. Wang. Costs, technology, and productivity in the us automobile industry. *The Bell Journal of Economics*, pages 1–20, 1983.
- G. M. Grossman and E. Rossi-Hansberg. Trading tasks: A simple theory of offshoring. *American Economic Review*, 98(5):1978–97, 2008.
- G. M. Grossman and E. Rossi-Hansberg. Task trade between similar countries. *Econometrica*, 80(2):593–629, 2012.
- P. Harms, O. Lorz, and D. Urban. Offshoring along the production chain. *Canadian Journal of Economics/Revue canadienne d’économique*, 45(1):93–106, 2012.
- K. Head and T. Mayer. Brands in motion: How frictions shape multinational production. *American Economic Review*, 109(9):3073–3124, 2019.
- P. Jia. What happens when wal-mart comes to town: An empirical analysis of the discount retailing industry. *Econometrica*, 76(6):1263–1316, 2008.
- R. C. Johnson and A. Moxnes. Gvcs and trade elasticities with multistage production. Technical report, National Bureau of Economic Research, 2019.
- R. C. Johnson and G. Noguera. Accounting for intermediates: Production sharing and trade in value added. *Journal of international Economics*, 86(2):224–236, 2012.
- F. Lopez-de Silanes, J. R. Markusen, and T. F. Rutherford. Complementarity and increasing returns in intermediate inputs. *Journal of Development Economics*, 45(1):101–119, 1994.
- J. R. Markusen. Trade in producer services and in other specialized intermediate inputs. *The American Economic Review*, pages 85–95, 1989.
- M. J. Melitz. The impact of trade on intra-industry reallocations and aggregate industry productivity. *econometrica*, 71(6):1695–1725, 2003.
- P. Milgrom, J. Roberts, et al. The economics of modern manufacturing: Technology, strategy, and organization. *American economic review*, 80(3):511–528, 1990.
- E. Oberfield, E. Rossi-Hansberg, P.-D. Sarte, and N. Trachter. Plants in space. Technical report, National Bureau of Economic Research, 2020.

- N. Ramondo and A. Rodríguez-Clare. Trade, multinational production, and the gains from openness. *Journal of Political Economy*, 121(2):273–322, 2013.
- F. M. Scherer. Inter-industry technology flows in the united states. *Research policy*, 11(4): 227–245, 1982.
- I. Simonovska and M. E. Waugh. The elasticity of trade: Estimates and evidence. *Journal of international Economics*, 92(1):34–50, 2014.
- H. Thompson. Complementarity in a simple general equilibrium production model. *Canadian Journal of Economics*, pages 616–621, 1985.
- F. Tintelnot. Global production with export platforms. *The Quarterly Journal of Economics*, 132(1):157–209, 2017.
- V. Tyazhelnikov. Production clustering and offshoring. *American Economic Journal: Microeconomics*, 14(3):700–732, 2022.