Modularity and the organization of international production

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Abstract

In recent decades, the global electronics industry has experienced a large reorganization. U.S. electronics firms have on a large scale off-shored and outsourced their manufacturing activities. Japanese electronics firms have offshored a large portion of their manufacturing, but have remained vertically integrated. To account for these industry trends, we build an two-country industry-equilibrium model in which firms concurrently choose (i) a product architecture, (ii) an ownership structure and (iii) a location for production. We demonstrate that technological advances that allow firms to more easily modularize their products can explain the co-evolving trends of offshoring and outsourcing. We also assess the role of technology on the different patterns of reorganization between Japanese and U.S. firms.

Keywords: Modularity; Input specificity; Outsourcing; Offshoring; Co-evolution

1. Introduction

In the past few decades, many U.S. and Japanese electronics companies have experienced a large reorganization of their international production activities. Both U.S. and Japanese electronics firms have fragmented their production processes internationally by offshoring labor-intensive production stages to developing East Asia (Dedrick and Kraemer, 1998; Bonham et al., 2007). While Japanese firms have largely remained vertically integrated throughout this process (Ernst, 2006; Sturgeon, 2006), U.S. electronics firms have in addition outsourced a rising share of their manufacturing activities to specialized contract manufacturing
firms (Sturgeon, 2002). In this paper, we develop a theoretical model to explain the driving forces behind the reorganization of international production that has characterized the electronics industry. This allows us to account for the different patterns of reorganization between Japanese and U.S. firms.

Two largely separate literatures have analyzed the driving forces behind outsourcing and offshoring. The international trade literature has introduced elements of the theory of the firm into industry-equilibrium trade models to analyze changes in the organization of international production (see Spencer, 2005; Helpman, 2006 for a review of this literature). In this type of studies, a firm concurrently makes a two-dimensional choice: (i) whether to produce its components in-house or to outsource its production to another firm, and (ii) whether to make its components domestically or offshore. The trade studies unveil three primary explanations for the rise of international outsourcing: lower costs of foreign production, improvements in foreign institutions, and reduced costs of international transactions due to greater integration in world markets.

A shortcoming of the trade literature is that it does not account for the role of technological change on the reorganization of international production. This runs counter to the global value chain literature’s argument that product modularization is an important driver behind the co-evolving trends of offshoring and outsourcing in the U.S. electronics industry (Sturgeon and Lee, 2001; Sturgeon, 2002; Gereffi et al., 2005). Modularity is a technological property of a product that is related to the way different components of a final good interact with one another (Baldwin and Clark, 2000). When a product is non-modular, components need to be specifically adjusted to one other in order to fully elicit the performance of the final product. On the contrary, modular products consist of loosely coupled components that interact with one another through well-defined and codified architectural standards. According to Sturgeon and Lee (2001) and Sturgeon (2002), advances in information technology have enabled electronics firms to more easily standardize the interfaces between components. As a consequence, more electronics firms have modularized their products. In turn, product modularization has made outsourcing more attractive since it allows multiple firms to share the same generic components, thus lowering the component costs due to economies of scale. Finally, product modularization has increased global competition, thus inducing firms to save labor costs by offshoring their labor-intensive production activities.

The main limitation of the global value chain literature is that it lacks a formal theoretical underpinning to identify the mechanisms through which offshoring and outsourcing are related to product modularization. This represents a critical impediment for understanding the driving forces behind the electronics industry’s reorganization of international production, and the different patterns between Japanese and U.S. firms. To address these issues, we in this paper formalize the idea that firms have the technological choice between different types of product architectures when producing a final good. We introduce the architectural choice framework into a two-country industry-equilibrium model and we use this model to analyze the link between outsourcing, offshoring and product modularization. This allows us to account for the different patterns of reorganization between Japanese and U.S. electronics firms.

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1 See, for example, Antràs (2003) and Antràs and Helpman (2004).

2 A PC is a good example of a modular product. It is composed of a limited number of standard components (e.g., resistors, capacitors and memory chips), which are mounted onto printed circuit boards in different combinations.
2. Choice of product architecture

A product’s architecture determines how components interact with one another to elicit the full potential of a final product. Ulrich (1995) and Schilling (2000) argue that firms can choose from a variety of product architectures to produce a final good depending on the degree of specificity of components. On the one extreme, it can adopt an *integral product architecture* to produce a final product. In this case, components are required to be specifically adjusted to each other. On the other extreme, a firm can adopt a *modular product architecture*. In this case, components are designed to interact with one another through standardized and codified interfaces.

Firms face an important trade off when choosing between an integral and modular product architecture. Even though there are synergistic productivity gains related to components being specific to one another (Schilling, 2000), firms might opt for a modular product architecture because it allows taking advantage of issues related to reduced input specificity. Garud and Kumaraswamy (1995), for example, argue that adopting a modular product architecture can stimulate technological progress by allowing firms to easily substitute certain components of a technological system while reusing others. Baldwin and Clark (2000) suggest that adopting a modular product architecture can be beneficial since it allows the sharing of the same generic components across multiple product families, thus lowering the component costs due to economies of scale. Schwartz and Van Assche (2006) indicate that it allows a firm to reduce the hold-up friction in arm’s length relations.

In this paper, we build on Baldwin and Clark (2000) and Schwartz and Van Assche (2006) by setting up a simple framework in which *n* symmetric final good firms can choose between an integral and a modular product architecture to produce their product varieties. If a firm adopts an integral product architecture, it is required to adopt a unit of a completely specific “ideal” input to produce a final good. If a firm adopts a modular product architecture, it can adopt a non-ideal input to produce a final good, but needs to spend additional customization costs $d$ per unit of input to make this input compatible to the final good requirements.

To make customization costs endogenous in the model, we assume that inputs and final goods are located on two separate concentric circles. All final goods are symmetrically and uniformly distributed along the circumference of a unit circle. All inputs are arrayed along the circumference of a concentric circle of length $γ$, with $γ ≥ 0$. An input is considered ideal for a final good if it lies on the same ray from the origin as the final good. If it does not lie on the same ray, then customization cost $d$ arises, where $d$ equals the input circle’s arc distance between the input in question and the ideal input. An example is given in Fig. 1. Four final good firms $y_1$ to $y_4$ are uniformly distributed along the unit length final good circle. The ideal input for $y_1$ is $x_1$, the ideal input for $y_2$ is $x_2$ and so on. Suppose that final good firm $y_1$ decides to use the non-ideal input $x_{s1}$ to produce the final good. In this case, customization cost $d$ arises, where $d$ equals the arc distance between $x_1$ and $x_{s1}$.

We take on the simplifying assumption that each input provider can only produce a single input variety. To ensure symmetry in the model, we also assume that each input provider can sell his input to at most two final good firms. In a model with economies of scale in input production, this setup implies that final good firms face the following tradeoff when choosing a product.

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3 If an input provider is allowed to sell to more than two final good firms, customization costs cannot be equal for all final good firms.
architecture: even though adopting an integral product architecture circumvents customization costs, a final good firm might opt for a modular product architecture since it leads to lower input prices due to economies of scale.

To evaluate the determinants of a final good firm’s product architecture choice, we can consider the equilibrium customization costs related to adopting a modular product architecture. When all symmetric final good firms adopt modular product architectures, each input provider locates its input equidistantly between the ideal inputs of two final goods and becomes the sole “generic” input provider for two final good firms. Consider once again Fig. 1. If all four final good firms adopt modular product architectures, then one of the following two situations would occur: (i) \( x_{s1} \) is produced for \( y_1 \) and \( y_2 \) and \( x_{s3} \) is produced for \( y_3 \) and \( y_4 \); (ii) \( x_{s2} \) is produced for \( y_2 \) and \( y_3 \) and \( x_{s4} \) is produced for \( y_1 \) and \( y_4 \). Note that under both situations each input provider is the sole supplier of inputs for two final good firms. In this modular product architecture equilibrium, each final good firm faces the following customization cost:

\[
d = \frac{\gamma}{2n},
\]

where \( \gamma \) is the length of the input circle and \( n \) is the number of final good firms. Eq. (1) implies that, all else equal, the equilibrium customization cost \( d \) that a firm faces when adopting a modular product architecture increases with \( \gamma \) and decreases with \( n \). First, an increase in \( n \) reduces the equilibrium customization cost of adopting generic inputs because it induces firms’ ideal inputs to locate closer to one another on the input circle. We will define this to be the market

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4 A situation where \( n \) input providers all are located between two ideal inputs cannot constitute an equilibrium because input providers would have the incentive to start producing ideal inputs to get rid of the required customization costs.

5 To guarantee symmetry in the model, we are required to assume that the number of final good firms is an even number. If there is an uneven number of final good firms, one input provider in theory would have to provide an ideal input to a final good firm.
thickness effect on customization costs. Second, a reduction in $\gamma$ reduces the equilibrium customization cost because it reduces the arc distance between ideal inputs.\footnote{Take Fig. 1 as an example. Suppose the input circle becomes smaller due to a reduction in $\gamma$. In that case, the customization cost of using $x_3$ in the production of $y_1$ and $y_2$ reduces.} The effect of a reduction in $\gamma$ is similar to the effect of an industry-wide technological innovation that reduces the cost of adopting generic inputs. We argue that this captures well Sturgeon and Lee (2001) and Sturgeon’s (2002) notion that advances in information technology have enabled firms to more easily standardize the interfaces between components, thus reducing the technological cost of adopting generic inputs. We will thus define the effect of a reduction in $\gamma$ as the standardization technology effect.

The goal of this paper is to analyze the role of the choice of product architecture on the organization of international production. For this purpose, we will in the next section insert our architectural choice framework into a two-country industry-equilibrium model.

3. Two-country model

Consider a world with two countries – the North and the South – and a single industry with Dixit–Stiglitz monopolistic competition.\footnote{See Dixit and Stiglitz (1977).} Global consumers have CES preferences for the industry’s products

$$U = \left( \sum_{0}^{n} y_i^{1/2} \right)^2,$$

where $y_i$ is the quantity demanded of final good $i$ and the elasticity of substitution is set equal to 2.\footnote{Our model can easily be expanded by taking a more general CES utility function. However, it comes at the cost of expositional clarity.} In the industry, there are $n$ symmetric final good firms that each produce one final good variety $i$. The global consumers spend a fixed portion $\xi$ of their aggregate income on the industry. Consumer preferences given by Eq. (2) lead to the following inverse demand function faced by the producer of good $y_i$:

$$p_i = A^{1/2} y_i^{-1/2},$$

where $p_i$ is the price of the good and

$$A = \left( \frac{\xi}{\sum_{0}^{n} y_i^{1/2}} \right)^2$$

is the aggregate consumption index. We take on the standard assumption in Dixit–Stiglitz monopolistic competition models that the number of final good firms is sufficiently large so that each final good firm takes the aggregate consumption index $A$ as given.

The production of a unit of a final good requires a unit of a specialized input:

$$y_i = x_i.$$  

To obtain the required inputs $x_i$, a final good firm needs to form a relation with an input provider in the North or South. We assume that there is a perfectly elastic supply of potential input
providers in both the North (N) and the South (S) and that there is free entry and exit in the input market. This implies that the input market is contestable in both countries. Each input provider can produce a unit of input \( x_i \) with one unit of labor. The industry is considered to be sufficiently small so that wages can be treated as exogenous in both countries. Southern wages \( \omega^S \) are strictly lower than Northern wages \( \omega^N \) and we normalize the latter to 1: \( \omega^S < \omega^N = 1 \).

Final good firms can source their inputs within the boundaries of the firm (vertical integration) or from an external input provider (outsourcing). Under vertical integration, each final good firm needs to pay both a fixed cost \( k_y \) of setting up and operating the final good firm and a fixed cost \( k_x \) of setting up and operating its subsidiary. Under outsourcing, a final good firm bears the fixed cost \( k_x \) of setting up and operating the final good firm and purchases its inputs from an external input provider. Since each input provider on its part bears a fixed cost \( k_x \) of setting up and operating the intermediate good firm, inputs are charged above marginal cost in order for the input provider to break even.\(^9\) This setup creates a standard double-marginalization distortion under outsourcing (Spengler, 1950). We assume that all fixed costs are paid in Northern wages and that the fixed cost of setting up and operating a final good firm is at least 1.5 times that of operating an intermediate good firm, i.e., \( k_x/k_y \leq 2/3 \).

It is a stylized fact that the costs of governing relations across border are higher than those of governing relations within borders. This can be due to extra search costs, coordination costs, and communication costs. To reflect this, we assume that a final good firm faces an extra fixed internationalization cost \( k_I \) when dealing with an input provider in the South. This implies that, all else equal, a final good firm trades off a higher fixed costs of operating in the South with a higher marginal cost of operating in the North when choosing the location of production.

Finally, we introduce Section 2’s framework of architectural choice into our two-country industry equilibrium model. Specifically, a final good firm has the technological choice between adopting an integral or a modular product architecture. If it adopts an integral product architecture, it is required to adopt completely specific “ideal” inputs for final good production. If it adopts a modular product architecture, it can adopt non-ideal inputs, but it needs to spend additional units of Northern labor \( d = \gamma/2n \) per unit of input to make the input compatible to the final good requirements.

The model is characterized by two sequences of moves. In the first stage, final good firms simultaneously choose from three choice variables: product architecture (i.e., whether to adopt an integral or a modular product architecture), ownership structure (vertical integration or outsourcing) and location of production (North or South). To simplify our exposition, we define production structure to comprise both a firm’s choice of product architecture and ownership structure. In particular, each firm can choose from three feasible production structures: vertical integration (V), ideal outsourcing (O) and generic outsourcing (G).\(^10\) We define organizational form \((k,l)\) to comprise a final good firm’s production structure \( k \in K = \{V,O,G\} \) and location of input production \( l \in L = \{N,S\} \). In the second stage, the input provider produces the inputs, the final good firm uses the inputs to produce final goods, and sells the final goods on the market.

In Sections 3.1, 3.2 and 3.3, we will solve the model by first deriving the equilibrium conditions for each organizational form \((k,l)\) separately (stage 2). In Section 3.4, we will then move backwards to solve for the equilibrium organizational form (stage 1).

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\(^9\) In the interest of tractability, I do not consider nonlinear pricing of the inputs.

\(^10\) Vertical integration with the adoption of a modular product architecture is never feasible since we do not allow subsidiaries to sell inputs to an external final good firm.
3.1. Vertical integration in the North and South

We start off by describing an equilibrium where vertical integration in the North (V,N) or South (V,S) is pervasive. To simplify notation, we from now on will drop the $i$'s. In both cases, all symmetric final good firms choose to produce the ideal inputs $x$ exclusively for themselves. By using Eqs. (3) and (5), each final good firm’s profit function takes the following form:

$$\max_x \Pi_v^l = \left( A_v^l x^l \right)^{1/2} - \omega_v^l x^l - (\kappa_x + \kappa_y + \kappa_1^l),$$  \hfill (6)$$

where $\Pi_v$ denotes the vertically integrated final good firm’s profits and $l \in \{N,S\}$ indicates the location of production. When $l = N$, then $\omega_N = 1$ and $\kappa_1^N = 0$. When $l = S$, then $\omega_S < 1$ and $\kappa_1^S > 0$. It is straightforward to derive that this program yields the following profits for each symmetric vertically integrated final good firm:

$$\Pi_v^l = \frac{A_v^l}{4\omega_v^l} - (\kappa_x + \kappa_y + \kappa_1^l).$$  \hfill (7)$$

Free entry and exit in the final good sector implies that all vertically integrated firms in industry equilibrium have zero profits. We can use the zero profit condition to derive the aggregate consumption index from Eq. (7):

$$A_v^l = 4\omega_v^l (\kappa_x + \kappa_y + \kappa_1^l).$$  \hfill (8)$$

In Section 3.4, we will use the aggregate consumption index $A_v^l$ to determine the equilibrium organizational form in the industry.

3.2. Ideal outsourcing to the North and South

When ideal outsourcing to the North (O,N) or South (O,S) is pervasive, each final good firm relies on an external input provider to exclusively produce ideal inputs for him. Since the input provider and final good firm are independent, we need to consider their profit-maximization problems separately. We start with the optimization decision for the final good firms. Each final good firm purchases its ideal inputs from an external provider at price $q_o$. It thus faces the following profit maximization problem:

$$\max_x \Pi_o^l (A_o^l x_o^l)^{1/2} - q_o^l x_o^l - (\kappa_y + \kappa_1^l).$$  \hfill (9)$$

Solving the final good firm’s profit maximization problem yields the following level of inputs:

$$x_o^l = \frac{A_o^l}{4q_o^l}.$$  \hfill (10)$$

By inserting Eq. (10) into Eq. (9), we can then derive the final good firm’s profit-maximizing level of profits

$$\Pi_o^l = \frac{A_o^l}{4q_o^l} - (\kappa_y + \kappa_1^l).$$  \hfill (11)$$
Free entry and exit in the final good sector then implies that

$$A_o^I = 4q_o^I(k_y + k_1^I).$$  \hspace{1cm} (12)

Next, we need to derive the input price $q_o^I$ that an input provider charges. Since each input provider exclusively sells his inputs to a single final good firm, its level of input production is $x_o^r$. It thus has the following profit function:

$$\pi_o^I = (q_o^I - \omega) x_o^r - \kappa_x,$$  \hspace{1cm} (13)

where $\pi_o$ is the input provider’s profits. Since in both the North and South there is free entry and exit and an infinitely elastic supply of potential input providers, the market for inputs is contestable. We can thus use the zero profit condition together with Eqs. (10) and (12) to calculate the input provider’s price

$$q_o^I = \frac{\omega (k_y + k_1^I)}{k_y + k_1^I - \kappa_x}$$  \hspace{1cm} (14)

We can then calculate the aggregate consumption index $A_o^I$ by inserting Eq. (14) into Eq. (12):

$$A_o^I = \frac{4\omega (k_y + k_1^I)^2}{k_y + k_1^I - \kappa_x}.$$  \hspace{1cm} (15)

### 3.3. Generic outsourcing to the North and South

When generic outsourcing to the North (G,N) or South (G,S) is pervasive, two final good firms rely on the same external input provider to produce common generic inputs for them. In that case, each final good firm purchases inputs at $q_g^I$ and spends additional resources $d_g^I$ per unit of input to customize the inputs to final good use. Each final good firm thus faces the following profit maximization problem:

$$\max_x \Pi_g^I = \left(A_g^I x_g^I\right)^{1/2} - (q_g^I + d_g^I) x_g^I - (k_y + k_1^I),$$  \hspace{1cm} (16)

Solving the profit-maximization problem yields the following level of inputs:

$$x_g^r = \frac{A_g^I}{4(q_g^I + d_g^I)^{1/2}}.$$  \hspace{1cm} (17)

By inserting Eq. (17) into Eq. (16), the final good firm’s profit maximizing level of profits equals

$$\Pi_g^I = \frac{A_g^I}{4(q_g^I + d_g^I)^{1/2}} - (k_y + k_1^I).$$  \hspace{1cm} (18)

Free entry and exit in the final good sector then implies that

$$A_g^I = 4(q_g^I + d_g^I)(k_y + k_1^I)$$  \hspace{1cm} (19)

In Eq. (19), the input price $q_g^I$ and the customization cost $d_g^I$ are endogenous variables that need to be derived. We will first derive $d_g^I$. From Eq. (1), we know that $d_g^I$ is a function of the equilibrium number of final good firms $n$ in the industry. By relying on the symmetry assumption and by
combining Eqs. (4), (5), (17) and (19), we can derive the equilibrium number of final good firms

\[ n^f_g = \frac{\xi}{2(k_y + k_l^1)}. \]  

(20)

By inserting Eq. (20) into Eq. (1), we can determine the equilibrium customization costs

\[ d^*_g = \frac{\gamma(k_y + k_l^1)}{\xi}. \]  

(21)

Eq. (21) indicates that, all else equal, final good firms under (G,S) face a higher customization cost than final good firms under (G,N). As we can see from Eq. (20), this is due to a negative market thickness effect. Final good firms under (G,S) need to pay an extra fixed internationalization costs \( k_l^1 \). This reduces the equilibrium number of final good firms \( n \) and thus increases customization costs \( d \). It is straightforward to derive from Eq. (21) that the size of the market thickness effect is increasing in \( \gamma \) and \( k_y \), while decreasing in \( \xi \).

Next, we can derive \( q^*_g \) by making use of the input provider’s profit maximization condition. Each input provider under generic outsourcing sells his inputs to two symmetric final good firms. As a result, it produces \( 2x^*_g \) inputs and faces the following profit function:

\[ \pi^*_g = 2(q^*_g - \omega^*_g)x^*_g - \kappa_x. \]  

(22)

Since the input provider is contestable, we can use the zero profit condition together with Eqs. (17) and (19) to calculate the input provider’s profit-maximizing input price

\[ q^*_g = \frac{(2\omega^*_g + \gamma \kappa_x)(\kappa_y + k_l^1)}{\xi(2(k_y + k_l^1) - \kappa_x)}. \]  

(23)

It is straightforward to derive from Eq. (23) that, all else equal, final good firms under (G,S) face a lower input price than final good firms under (G,N). The reason for this is two-fold. First, final good firms under (G,S) face lower labor costs \( \omega \). Second, input providers under (G,S) produce a larger number of inputs, thus reducing the average cost of producing inputs. The size of this positive scale effect is a positive function of \( \kappa_x \) and \( \gamma \), and a negative function of \( \xi \).

We can then derive \( A^*_g \) by inserting Eqs. (23) and (21) into Eq. (22):

\[ A^*_g = \frac{8(\xi \omega^*_g + \gamma(k_y + k_l^1))(\kappa_y + k_l^1)^2}{\xi(2(\kappa_y + k_l^1) - \kappa_x)}. \]  

(24)

3.4. Equilibrium organizational form

We now roll back to stage 1 in which final good firms choose their optimal organizational form. Our model setup is similar to that of Grossman and Helpman (2002) and we will therefore heavily rely on their exposition to determine the industry equilibrium. In our model, two types of equilibria are possible: (i) a mixed equilibrium with more than one organizational form co-existing; and (ii) an equilibrium with a single pervasive organizational form. For a mixed equilibrium to occur, a strictly positive number of final good firms of at least two organizational forms must concurrently face non-negative profits. In a model with free entry and exit, this will only occur when the zero-profit-yielding
aggregate consumption indexes $A_k$ of two types of organizational forms in equilibrium are identical.\footnote{In our discussion above, Eq. (8) provided the zero-profit-yielding aggregate consumption index under vertical integration in the North and South, Eq. (15) provided the zero-profit-yielding aggregate consumption index under ideal outsourcing in the North and South, and Eq. (24) provided the zero-profit-yielding aggregate consumption index under generic outsourcing in the North and South.} This will only happen in the knife-edge case where the industry parameters happen to equalize the zero-profit-yielding aggregate consumption indexes for two organizational forms. As a result, a mixed equilibrium thus generically does not exist in this type of model setting (Grossman and Helpman, 2002). In our exposition below, we will focus on the determinants of the equilibria in which a single organizational form is pervasive.

For an organizational form to be pervasive in equilibrium, it must be the case that any firm with another organizational form faces negative profits if it enters the market. Let us denote the aggregate consumption index of the prevalent organizational form with $A^*$ and an entrant’s zero-profit-yielding aggregate consumption index $A_k$, where $k$ is the firm production structure and $l$ is his location of production. When entering the market, an entrant faces the same aggregate consumption index $A^*$ as the existing firms in the market. In that case, the entrant’s profits will be positive if $A_k < A^*$ and will be negative if $A_k < A^*$. If any entrant regardless of his organizational form ends up with negative profits, then the prevalent organizational form is in equilibrium. We will state this in the following proposition.\footnote{Grossman and Helpman (2002) demonstrate that this type of equilibrium is also stable.}

**Proposition 1.** An organizational form will form a stable equilibrium if and only if its aggregate consumption index

$$A^*_k = \min[A_k].$$

Proposition 1 implies that it is sufficient to compare the zero-profit-yielding aggregate consumption indexes $A_k$ of all organizational forms to determine which is optimal.

We can use Proposition 1 to rule out ideal outsourcing to the North (O,N) and South (O,S) as optimal organizational forms: by comparing Eqs. (8) and (15), it is straightforward to derive that for any parameter combination $A^*_V \leq A^*_O$, thus implying that vertical integration always dominates ideal outsourcing. This is because vertical integration avoids the double marginalization problem that firms face under ideal outsourcing.

In Appendix A to this paper, we use Proposition 1 to determine the range of parameter values for which each organizational form is optimal. The results of this analysis are depicted in Figs. 2 and 3.

Fig. 2 focuses on variations in $\gamma/\xi$ and variations in $\kappa_1$ in the scenario where

$$\frac{1 - \omega^S}{\omega^S} \geq \frac{\kappa_x/\kappa_y}{2(1 - (\kappa_x/\kappa_y)^2)}.$$ (25)

Eq. (25) holds when $\omega^S$ is small and $\kappa_x/\kappa_y$ is large. Fig. 3 focuses on variations in $\gamma/\xi$ and $\kappa_1$ the scenario where Eq. (25) does not hold.

The results depicted in both figures are similar in most respects. In both figures, there are four regions, (V,S), (V,N), (G,S) and (G,N), each identifying the area where the corresponding organizational form is optimal. The figures provide a number of obvious results. First, vertical integration is preferred over generic outsourcing in industries with a high $\gamma/\xi$. This result is a direct consequence of Eq. (21). Both a high value of synergistic specificity $\gamma$ and a low value of
industry demand $\xi$ lead to a high customization cost $d$, thus making generic outsourcing less attractive. Second, firms prefer to source their inputs from the North rather than the South when $k_1$ is high. This is because final good firms are unwilling to take advantage of lower wages in the South if the extra fixed cost of sourcing internationally is too high.

Fig. 2. Optimal organizational form if $(1 - \omega^S)/\omega^S \geq (k_1/k_2)/2(1 - (k_1/k_2)^2)$.

Fig. 3. Optimal organizational form if $(1 - \omega^S)/\omega^S < (k_1/k_2)/2(1 - (k_1/k_2)^2)$. 
More interestingly, both figures suggest that offshoring can be a substitute or complement to outsourcing and product modularization depending on the parameters of the model. When condition (25) holds, offshoring is a substitute for outsourcing. Two characteristics of Fig. 2 illustrate this. First, the boundary between (V,S) and (G,S) lies lower than the boundary between (V,S) and (G,N) for all values of $k_I$. This suggests that final good firms that source offshore (i.e., from the South) require a lower $\gamma/\xi$ before shifting from vertical integration to generic outsourcing than final good firms sourcing from the North. Second, the boundary between (G,N) and (G,S) lies to the left of the boundary between (V,S) and (V,S) for all values of $\gamma/\xi$. This indicates that final good firms that are vertically integrated will shift production to the South at a higher $k_I$ than final good firms under generic outsourcing. The reason for this substitution effect is that final good firms do not only trade off the lower wages in the South $\omega^S$ to the extra fixed cost of internationalizing $k_I$ when choosing between (G,S) and (G,N). They also need to take into account two additional effects. On the one hand, from Eq. (21), shifting to (G,S) entails a negative market thickness effect, thus increasing the customization costs that final good firms face. On the other hand, from Eq. (23), shifting to (G,S) leads to a positive scale effect, thus lowering the input price $q_g$. When condition (25) holds, the higher customization cost dominates the lower input price, thus implying that final good firms treat offshoring as a substitute to outsourcing.

When condition (25) does not hold, then offshoring is a substitute for outsourcing if $\gamma/\xi$ is high, but becomes a complement when $\gamma/\xi$ is low. In Fig. 3, the boundary between (G,N) and (G,S) lies to the left of the boundary between (V,S) and (V,S) for high values of $\gamma/\xi$, thus implying that offshoring is a substitute for outsourcing and product modularization. For low values of $\gamma/\xi$, the boundary between (G,N) and (G,S) lies to the right of the boundary between (V,S) and (V,S), thus implying that final good firms under generic outsourcing shift input production to the South at a lower $k_I$ than vertically integrated firms. The logic behind the complementarity at low values of $\gamma/\xi$ is that the reduction in input price $q_g$ when shifting from (G,N) to (G,S) dominates the increase in customization cost $d_g$.

Sturgeon and Lee (2001) and Sturgeon (2002) have attributed the co-evolving trends of offshoring and outsourcing in the U.S. electronics industry to advances in information technology that have enabled electronics firms to more easily standardize the interfaces between components. In our model, we capture the effect of an improvement in standardization technology through a reduction in $\gamma$. Our model suggests that a reduction in $\gamma$ can induce an industry to move from (V,S) to (G,S) when offshoring is a complement to outsourcing and product modularization. This will be the case in industries with characteristics consistent with the electronics industry: high economies of scale in input production (high $\kappa_x/\kappa_y$), high industry demand (high $j$), and high standardization technology (low $\gamma$). The speed of this industry reorganization will be accelerated even more if a reduction in $\gamma$ is combined with another characteristic that is generally linked to advances in information technology: the reduction in fixed cost $k_I$ of coordinating activities across borders.

Besides through a reduction in $\gamma$, our model suggests that the industry reorganization from (V,S) to (G,S) can also be explained by an increase in industry demand $\xi$ in a sector where offshoring is a complement to outsourcing and product modularization. An increase in $\xi$ increases market thickness in the final good sector, thus reducing equilibrium customization costs under generic outsourcing. This puts in motion the complementary forces between outsourcing and offshoring.

Finally, we can use our model to provide an explanation why Japanese firms have remained vertically integrated, while U.S. firms have outsourced many of their production activities. In an
overview of Japan’s electronics industry, Sturgeon (2006) highlights that Japanese electronics firms produce different types of electronics products than U.S. firms. While U.S. firms are the market leaders in nearly all internet-related electronics hardware and software product categories, Japanese firms focus on the production of stand-alone consumer electronics devices and proprietary enterprise computing systems. For the production of this type of products, one arguably needs more dense interactions in the design and manufacturing. As a result, it is less easy to standardize interface, thus leading to a higher $\gamma$. This can explain why a combined reduction in $\gamma$ and $\kappa_1$ can induce U.S. electronics firms to move from $(V,S)$ to $(G,S)$, while Japanese electronics firms move from $(V,S)$ to $(V,S)$.

4. Conclusion

In this paper, we developed a theoretical framework to analyze whether the modularization of electronics products can explain the concurrent trends of production offshoring and outsourcing witnessed in the U.S. electronics industry. For this purpose, we formalized the notion that final good firms can choose between an integral and modular product architecture to produce final goods. Next, we introduced this notion into a two-country industry-equilibrium model where symmetric final good firms can concurrently choose their product architecture, ownership structure and location of production.

Using this setup, we established that offshoring can be both a complement or substitute of outsourcing depending on the parameters of the model. In an industry with high aggregate demand, high standardization technology, and high economies of scale in the intermediate good sector, offshoring and outsourcing are more likely to go hand-in-hand. Otherwise, offshoring is a substitute of outsourcing.

In industries where offshoring is a complement of outsourcing, we found that both an improvement in standardization technology and a increase in industry demand can explain the concurrent trends of production offshoring and outsourcing witnessed in the U.S. electronics industry. Our model also provides a technological explanation why Japanese firms have remained vertically integrated, while U.S. firms have outsourced many of their production activities. Since Japanese electronics firms have primarily focused on the production of goods that need more dense interactions in the design and manufacturing, the cost of adopting a modular product architecture has been higher. As a result, the complementary forces between offshoring and outsourcing have not come into play in Japan’s electronics industry.

We have applied our model to understanding the reorganization of international production in the electronics industry. Our model, however, is general enough so that it can be used to analyze the organizational structure of many other industry. Indeed, our theoretical model can be easily applied to assess Sturgeon’s (2002) argument that similar trends in the organization of international production are underway in other industries such as apparel and footwear, toys, furniture, automotive parts and pharmaceutical production.

A challenge for future research will be to empirically evaluate the relative importance of the various factors that we and other trade studies have identified as drivers of the reorganization in international production. Except for the case study research by the global value chain literature, existing empirical work in this area is limited. A fundamental challenge will be to identify and measure the role of technological factors such as standardization technology on the organization of international production. We leave this for future research.
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Appendix A. Construction of Figs. 2 and 3

From our discussion in Section 3.4, there are four possible organizational forms in equilibrium, indexed by (V,S), (V,S), (G,S) and (G,N). In Sections 3.1 and 3.3, we have derived the corresponding zero-profit-yielding aggregate consumption indexes to be (8) and (24). To calculate the parameter range in which each organizational form is optimal in \((g/j, k_I)\)-space, we take the following three steps. First, we derive the cutoff line \(C\) of each pair of organizational forms by equating their corresponding aggregate consumption index functions and solving for \(g/j\). For example, to derive the cutoff line \(C_{V;S;N}\) between (V,S) and (G,N), we equate \(A_N^V = A_S^G\) and solve for \(g/j\). Second, we determine the range of parameters in \((g/j, k_I)\)-space for which each of the two organizational forms is dominant. In our example, the area where \(A_N^V > A_S^G\) is dominant is the side of the cutoff line where \(A_N^V < A_S^G\). Finally, by relying on Proposition 1, we can identify the region were an organizational form is optimal as the area where the organizational form in question dominates all other organizational forms. In our example, this will be the area where the following three conditions hold:

1. \(A_N^V > A_S^G\)
2. \(A_N^V > A_N^G\)
3. \(A_N^V > A_S^G\)

We will proceed to derive the shape of each cutoff line below.

The cutoff line \(C_{V;S;N}\) between (V,S) and (V,S) can be determined by equating the corresponding aggregate consumption index functions \(A_N^V = A_V^S\) and solving for \(k_I\):

\[
 k_I = \frac{1 - \omega S}{\omega S} (\kappa_x + \kappa_y). \tag{A.1}
\]

This expression does not depend on \(g/j\). Therefore, the corresponding boundary in \((g/j, k_I)\) space is a vertical line. It is straightforward to derive and intuitive to verify that (V,S) dominates (V,S) on the right of the cutoff line. (V,S) dominates (V,S) on the left of the cutoff line.

The cutoff line \(C_{V;S;N}\) between (V,S) and (V,S) can similarly be derived as

\[
 k_I = \frac{1 - \omega S}{\omega S} (\kappa_x + \kappa_y). \tag{A.1}
\]

This expression does not depend on \(k_I\). Therefore, the corresponding boundary in \((g/j, k_I)\) space is a horizontal line. (V,S) dominates (V,S) above the cutoff line. (V,S) dominates (V,S) below the cutoff line.

The cutoff line \(C_{V;S;N}\) between (V,S) and (V,N) can be determined by equating \(A_V^N = A_V^G\) and solving for \(g/j\):

\[
 \frac{g}{j} = \frac{k_x (\kappa_y - \kappa_x)}{2k_y^3}. \tag{A.2}
\]

This expression does not depend on \(k_I\). Therefore, the corresponding boundary in \((g/j, k_I)\) space is a horizontal line. (V,S) dominates (V,N) above the cutoff line. (V,S) dominates (V,N) below the cutoff line.

The cutoff line \(C_{V;S;N}\) between (V,S) and (G,N) can be similarly derived as

\[
 \frac{g}{j} = \frac{(2(\kappa_y + k_I) - \kappa_x)(\kappa_x + \kappa_y) - 2\omega S(\kappa_y + k_I)^2}{2(\kappa_y + k_I)^3}. \tag{A.3}
\]

It is straightforward to derive that the line is a negative and concave function of \(k_I\): \(d^2(g/j)/dk_I^2 \leq 0\) and \((d^2 g/j)/dk_I^2 \leq 0\). It intercepts the y-axis at \(g/j = (\kappa_x (\kappa_y - \kappa_x) + 2(1 - \omega S)k_I^2)/2k_y^3\). (V,S) dominates (G,S) above the cutoff line. (G,S) dominates (V,S) below the cutoff line. If we equate
$A_V^S = A_G^N$, we can derive the cutoff line $\Psi_{V,S}^{G,N}$ as

$$\frac{\gamma}{\xi} = \frac{1}{2\kappa_3^2} (\omega^S (\kappa_x + \kappa_y + \kappa_1)(2\kappa_y - \kappa_x) - 2\kappa_y^2).$$ (A.4)

The cutoff line is a positively sloping straight line: $(\partial \gamma/\partial \xi) \geq 0$ and $(\partial^2 \gamma/\partial \xi^2) = 0$. It crosses the $y$-axis at $\gamma/\xi = \omega^S \kappa_x (\kappa_y - \kappa_x) - 2(1 - \omega^S) \kappa_y^2 / 2\kappa_3^2$. This intercept may lie above or below the $x$-axis. ($V,S$) dominates ($G,N$) above the cutoff line. ($G,N$) dominates ($V,S$) below the cutoff line.

If we equate $A_V^S = A_S^G$, we can derive the cutoff line $\Psi_{V,S}^{G,S}$ as

$$\frac{\gamma}{\xi} = \frac{\omega^S \kappa_x}{2(\kappa_y + \kappa_1)} (\kappa_y + \kappa_1 - \kappa_x)$$ (A.5)

The cutoff line is unambiguously decreasing in $\kappa_1$: $(\partial \gamma/\partial \xi) \leq 0$. For low values of $\kappa_1$ the second-order condition is ambiguous. For high values of $\kappa_1$, however, $(\partial^2 \gamma/\partial \xi^2) \geq 0$. The cutoff line crosses the $y$-axis at $\gamma/\xi = (\omega^S \kappa_x (\kappa_y - \kappa_x))/2\kappa_3^2$ does not cross $x$-axis, but rather approaches 0 as $\kappa_1$ goes to infinity. ($V,S$) dominates ($G,S$) above the cutoff line. ($G,S$) dominates ($V,S$) below the cutoff line.

If we equate $A_G^N = A_S^G$, we can derive the cutoff line $\Psi_{G,N}^{G,S}$ as

$$\frac{\gamma}{\xi} = \frac{\omega^S (\kappa_x + \kappa_y + \kappa_1)^2 (2\kappa_y - \kappa_x) - \kappa_y^2 (2(\kappa_y + \kappa_1) - \kappa_x)}{\kappa_3^2 (2(\kappa_y + \kappa_1) - \kappa_x) - (\kappa_y + \kappa_1)^3 (2\kappa_y - \kappa_x)}$$ (A.6)

The cutoff line is a negative and convex function of $\kappa_1$: $(\partial \gamma/\partial \xi) \leq 0$ and $(\partial^2 \gamma/\partial \xi^2) \geq 0$. It crosses the $x$-axis at $\gamma/\xi = \kappa_x \kappa_y / 2\kappa_y - \kappa_x$. It does not cross the $y$-axis, but rather approaches it as $\gamma/\xi$ approaches infinity. ($G,N$) dominates ($G,S$) above the cutoff line. ($G,S$) dominates ($G,N$) below the cutoff line.

Once the shapes of all six cutoff lines have been derived, we can plot them in $(\gamma/\xi, \kappa_1)$-space to determine the range in which each organizational form is optimal. In plotting the cutoff lines, a number of issues need to be considered. First, when drawing the cutoff lines, it is important to respect the transitivity properties. Consider, for example, the intersection point in $(\gamma/\xi, \kappa_1)$-space where the cutoff lines $\Psi_{V,S}^{G,N}$ and $\Psi_{G,N}^{G,N}$ intersect. Since at this point $A_V^S = A_S^G$ and $A_G^N = A_N^G$, the transitivity property requires that $A_V^S = A_G^N$. As a result, the cutoff line $\Psi_{V,S}^{G,N}$ also needs to intersect with the other two cutoff lines in that point.

Second, the $y$-axis intercepts of the cutoff lines can be unambiguously ranked regardless of the parameter values of the model:

$$\Psi_{V,S}^{G,N}(0) \leq \Psi_{V,S}^{G,S}(0) \leq \Psi_{V,N}^{G,N}(0) \leq \Psi_{V,N}^{G,S}(0).$$

The ranking of the cutoff lines’ $x$-axis intercepts however, depends on the parameters of the model. There are two lines that we need to consider that intersect the $x$-axis: $\Psi_{V,N}^{G,N}$ and $\Psi_{G,N}^{G,S}$. If

$$\frac{1 - \omega^S}{\omega^S} \geq \frac{\kappa_x}{\kappa_y} = \frac{1}{2(1 - (\kappa_x/\kappa_y)^2)},$$

then $\Psi_{G,N}^{G,S}$ crosses the $x$-axis at a lower value of $\kappa_1$ than $\Psi_{G,N}^{G,N}$. Otherwise, $\Psi_{V,N}^{V,S}$ crosses the $x$-axis at a lower value of $\kappa_1$ than $\Psi_{G,N}^{G,S}$. In Fig. 2, we plot Scenario 1 in which condition (A.7) holds. In Fig. 3, we plot Scenario 2 in which condition (A.7) does not hold.
Once all the cutoff lines have been drawn, we can determine the region in which an organizational form is optimal by identifying in which area this organizational form dominates all other organizational forms.

References