Coordinating Supply Chains

Robert Akerlof and Richard Holden*†

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Abstract

Many complex final goods require a large number of inputs to come together in a timely and efficient manner for production to be successful. Notable examples include lithography machines used to make semiconductors, airplanes, and lasers. We build a model to analyze this coordination problem and show how coordination can be achieved. There is a manufacturer endowed with capital who needs an input from each of n suppliers to produce a final good. The manufacturer may pay a markup to overcome supplier reluctance and achieve coordination. Coordination can also be achieved through integration, but integration inflates costs due to a lack of congruence between manufacturer and supplier. We model integration and the associated cost inflation along the lines of Aghion and Tirole (1997). We derive sharp predictions about firm structure and apply our model to a number of applications including International Trade and Industry Policy.

Keywords: Coordination, Supply Chains, Theory of the Firm.

*Akerlof: University of Warwick and CEPR. r.akerlof@warwick.ac.uk. Holden: UNSW Business School. richard.holden@unsw.edu.au

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1 Introduction

A crucial but underappreciated feature of supply chains is the need for coordination. Bringing together multiple suppliers to create complementary components of a product that fit together in a timely and efficient manner is, at its core, a matter of coordination. Indeed, without effective coordination a supply chain does not even exist.

To get a sense of the importance of coordination in supply chains, consider the following example from the semiconductor industry, which produces the chips used in a vast range of electronic devices from smartphones and computers, to cars and household appliances, to missiles and aircraft.

Dutch company ASML is the world's leading manufacturer of photolithography machines used to fabricate advanced semi-conductors. Indeed, it has 100% market share in extreme ultraviolet (EUV) lithography machines, which are essential for the production of the most advanced chips used in mobile phones and other devices.

The essence of producing chips is to carve transistors into silicon. The smaller the transistor, the more transistors can be placed onto a given size piece of silicon, and the more powerful and energy efficient the chip is.

The first semiconductors were made with a microscope, visible light, and photoresists (a light-sensitive material that produces a pattern). But as transistors became smaller and smaller, chip producers ran into a problem. The wavelength of visible light is several hundred nonometers (depending on the color of light). To continue to make transistors smaller, manufacturers moved to ultraviolet light, with wavelengths as small as 193nm. To make more efficient chips, manufacturers needed to make use of EUV, which has a wavelength of 13.5nm.[1]

[1]The interested reader may wonder how 7nm, 5nm, and even 3nm transistors can be produced with EUV light having a wavelength of 13.5nm. In 1873 Ernst Abbe showed that the smallest resolvable distance between two features of a sample–the *optical resolution* of a microscope–is proportional to the wavelength of light used to illuminate the sample and inversely proportional to the refractive index of the medium between the lens and the sample. Denoting the wavelength as λ and NA as the *numerical aperture* given by the sine of the half angle multiplied by the refractive index of the medium, Abbe showed that $d = \lambda/2NA$. This principle applies to any light-based

But as Miller (2022) notes: one "can't simply buy an EUV lightbulb. Producing enough EUV light requires pulverizing a small ball of tin with a laser." ASML's search for a supplier of EUV light focused on Cymer, founded and based in San Diego, CA. ASML announced that they would acquire Cymer in October 2012 and the deal closed in May 2013.[2] Cymer engineers devised a method to propel a 1/30,000 mm wide ball of tin through a vacuum at 200 miles per hour. They then fire a laser once at the tin to warm it up, and then a second time turn it into a plasma 40-50 times hotter than the surface of the sun. This is repeated 50,000 times per second, to produce the required EUV light.

The lasers required to perform this task didn't exist, so Cymer approached German precision tooling company Trumpf to develop such a laser. Trumpf's accomplishment in doing so is a story in and of itself, involving specialized gases in the laser chamber, and building a laser which itself had 457,329 individual components. Yet there was another problem to overcome. The tin droplets reflected light, which, if they shined back into the laser would wreak havoc.

To solve this problem, ASML approached German lens manufacturer Zeiss. The central issue was that EUV is hard to reflect. The 13.5nm wavelength of EUV is more like an X-ray than visible light. Just like with X-rays, many materials absorb EUV rather than reflecting it. So Zeiss developed mirrors made of one hundred alternating layers of molybdenum and silicon. Each of these layers was around 2nm thick.

As Miller (2002) puts it "building such a mirror with nanoscale precision proved almost impossible. Ultimately, Zeiss created mirrors that were the smoothest objects ever made, with impurities that were almost imperceptibly small. If the mirrors in an EUV system were scaled to the size of Germany, the company said, their biggest irregularities would be a tenth of a millimeter. To direct EUV light with precision, they must be held perfectly still, requiring mechanics and sensors so exact that Zeiss boasted they could be used to aim a laser to hit a golf ball as far

projection system, including semiconductor photolithography.

[2] https://www.asml.com/en/news/press-releases/2013/asml-completes-acquisition-of-cymer.

away as the moon."

In all, ASML uses more than 4,700 individual suppliers that go into the $200 million ASML machine used by semiconductor foundries like Taiwan Semiconductor Manufacturing Corporation (TSMC) and Intel to produce advanced chips.

There are a number of salient features from the above discussion of ASML and EUV photolithography. First, many of their suppliers had to develop entirely new products for ASML's purposes. Second, multiple components were essential for ASML. Trumpf's new laser and Cymer's method for creating EUV light in industrial quantities would have been useless to ASML without Zeiss's new mirrors. Third, ASML bought Cymer but not Trumpf or Zeiss.[3] Across its supply chain it is integrated with about 15% of its suppliers, but contracts with the remaining suppliers (Miller, 2022). Fourth, by being the first to successfully coordinate these suppliers–to build the requisite supply chain–ASML has, at least for now, a complete monopoly in the market for its advanced machines. In fact, ASML's stock price has risen from $154 in January 2019 to $546 at the end of 2022, or more than 350%.

We analyze a model of the supply-chain coordination problem. There is a Manufacturer (M) endowed with capital who needs an input from each of n suppliers to produce a final good. M makes a take-it-leave it offer to each supplier consisting of a price for the input and a fraction of M's capital that is payable if the supplier produces and M refuses to buy. Suppliers decide whether to accept this contract and produce. Finally M decides whether to buy the inputs produced or pay the penalty for not purchasing. If M buys all the inputs then M produces final goods.

[3] Our model provides a rationale for why ASML bought Cymer but not Trumpf or Zeiss. The value of Cymer's business was largely tied to the successful development of EUV lithography, and ASML had made a large bet on that prospect as well. In the context of our model they had high "congruence" (the parameter α in section 3). By contrast Trumpf made lasers more many other purposes and the lens Zeiss developed was a small part of its business. The two other acquisitions ASML made in this period were also companies whose products were strongly tied to the success of EUV lithography. Wijdeven Motion (acquired in September 2012) essentially determines the size of a nanometer; and Hermes Microvision (acquired June 16, 2016) tests the functioning of advanced chips.

We then characterize the set of equilibria of this game, using *Introspective Equilibrium* as our solution concept (Kets and Sandroni (2021)). Introspective equilibrium is based upon level-k thinking. Each player has an exogenously-given "impulse" which determines how they react at level 0; at level $k > 0$, players react according to the belief that other players are acting at level $k - 1$. Introspective equilibrium is defined as the limit of this process as $k \to \infty$.

We show that M uses its capital to provide insurance to the m suppliers who are most reticent to produce. These suppliers are paid marginal cost, while the remaining suppliers receive a markup. We offer an explicit expression for the markup as a function of marginal costs and impulses. If the size of the aggregate markups exceeds the surplus generated from final good production then coordination is not possible.

Armed with this we consider the decision for M to make input i in-house or buy it from a supplier. We use an approach in the spirit of Aghion and Tirole (1997) where M and supplier i decide ex ante on the allocation of formal authority. If M has formal authority then we describe them as being "integrated."

In the general case with n suppliers we show that supplier i is more likely to be integrated when the extent to which the cost increase under M-authority is lower, or their impulse is lower. The basic tradeoff is that M can pay a markup to overcome supplier reluctance and achieve coordination under non-integration. Alternatively coordination can be achieved through integration, but this increases costs through lack of congruence between manufacturer and supplier. The three key factors mentioned above affect this tradeoff.

One important point of comparison to our paper is Property Rights Theory (Grossman and Hart (1986), Hart and Moore (1990)). Since hold-up problems are not the focus of our analysis, we assume that investments are contractible. But it is useful to point out that our model makes two starkly different predictions than what PRT would within our framework. First, since investments are made by suppliers, PRT would predict that suppliers should own manufacturers. In our model it is only ever optimal for manufacturers to own suppliers, although non-integration may certainly be optimal. Second, integration can only ever be optimal in our model with two or more suppliers since, with only one supplier there is nothing to coordinate.

Scholars of international trade have, since the 1980s, focused on what have become known as “Global Value Chains” (GVCs). This literature concerns the size of trade flows within GVCs and how different countries and industries are positioned within GVCs. For an excellent survey see Antràs and Chor (2022).

Within this literature it is now customary to distinguish between two broad types of value chains: “snakes” and “spiders”.[4] Snakes involve a purely sequential production process where at each stage along the value chain a supplier produces an input which is then used by a different supplier at the next stage. This proceeds stage-by-stage until a manufacturer produces a final good. Following the earlier trade literature, beginning with Antràs (2003), models of snakes that speak to the organization of the production process typically take a PRT approach.

Sociologists such as Gereffi (1999) have long-emphasized the importance of coordination in supply (or “commodity”) chains. They also distinguish between “Producer-driven commodity chains” (essentially spiders) and “Buyer-driven commodity chains” (essentially snakes). As Gereffi (1999) puts it: “Producer-driven commodity chains are those in which large, usually transnational, manufacturers play the central roles in coordinating production networks.” Notable examples include “automobiles, aircraft, computers, semiconductors and heavy machinery.”

Our paper focuses squarely on spiders as we are principally concerned with the coordination-aspect of supply chains. We do not address sequential production processes, which are undoubtedly important in many industries, and we do not model the final goods market and thus cannot speak to issues driven by elasticities, which is the focus of much of the international trade literature. On the other hand, we put coordination of suppliers at the heart of the analysis. Indeed, we take a complete contracts approach, but focus on the coordination problem. This is consistent with our motivating example, and our results on which suppliers are integrated is consistent with the empirical evidence on “spiders” (see, for instance, Gereffi (1999))

[4] Baldwin and Venables (2013).

To get a more concrete sense of how incomplete-contracting models of snakes works, consider the pioneering work of Antràs and Chor (2013). They build on the Property Rights Theory (PRT), and follow a now venerable tradition of applying PRT to international trade, which includes Antràs (2003), Antràs (2005), Antràs and Helpman (2004), Acemoglu et al. (2007), and Antràs and Helpman (2008).

Antràs and Chor (2013) analyze a model in which final goods production requires a continuum of production stages, each performed by a different supplier. Each supplier makes a relationship-specific investment which affects compatibility with other components, but contracts cannot be written on compatibility. Importantly, production is necessarily sequential so that one stage must be performed before the next stage can commence, and there is a specific technologically-determined order in which this takes place.

The authors show that if final-good demand is sufficiently elastic, integration in production is determined by a cutoff in the production process. Early stages are non-integrated and later stages are integrated. Conversely, when demand in sufficiently inelastic early stages are integrated and later stages are not. This is a striking result, and the authors find empirical support for it in data on the share of intrafirm imports of total imports in U.S. data.[5]

Another strand of the international trade literature on value chains concerns "spiders", where production is non-sequential. Inputs from many suppliers are assembled by a manufacturer to produce a final good. For instance, an aircraft consists of many components (fuselage, wing assembly, engines, and so on) that are assembled by a manufacturer such a Boeing or Airbus. An illuminating incomplete-contracting model of spiders is offered by Chor and Ma (2021), and a complete-contracting approach by Antras et al. (2017).

Antras et al. (2017) interpret international trade flows as the "legs" of a spider. Firms that assemble inputs from the legs decide from which countries they source those inputs. A key ingredient in this framework is that countries differ in

[5]Alfaro et al. (2019) consider an environment where choices of organizational form have spillovers along the value chain. In particular relationship-specific investments upstream affect the incentives for specific investments by downstream suppliers. The authors show that the central results of Antràs and Chor (2013) go through in this richer setting.

their ability to reduce marginal costs for the assembling firm, but also in the fixed costs paid to important from a country. This implies that–in contrast to standard models of exports–whether it is optimal to import from one country depends on the other countries from which a firm is sourcing its inputs. That is, there is interdependence across suppliers. In fact, depending on elasticities of demand in the final goods market, different input-source countries can be complements or substitutes. The authors show how, despite this complexity, such a model can be structurally estimated. They show focus on how a change in the benefits of sourcing from a country like China affects the sourcing decisions of US firms and how this varies depending on firm productivity and the other countries from which they were initially sourcing.

Chor and Ma (2021) analyze a state-of-the-art multi-country, multi-industry model of sourcing inputs. Final good producers source a continuum of inputs from different suppliers. Both suppliers and the headquarters make relationship-specific investments, leading to the possibility of bilateral holdup. The key contribution of the paper is that for each input variety the firm chooses two things. One, from which country to source the input; and two, whether to vertically integrate with the supplier. In this environment, integration can be the optimal organizational form because of hold-up between firms and suppliers. These integration decisions can be made on a dyad-by-dyad basis since there are no relevant interactions among suppliers that affect integration decisions. The authors show how these firm-level decisions can be aggregated into a gravity equation by industry and organizational form. This has direct implications for the share of intra-firm trade. The authors also provide an expression for the welfare gains from trade.

Finally, a number of papers have emphasized the importance of coordination in investment decisions. Among these, Akerlof and Holden (2016) and Akerlof and Holden (2019) focus on the role of coordination in investment decisions, as does the literature on "catalytic finance" such as Corsetti et al. (2006) and Morris and Shin (2006).

The remainder of the paper proceeds as follows. Section 2 states the model of supply-chain coordination, and characterizes its equilibrium. Section 3 considers the manufacturer's make-or-buy decision and analyzes which suppliers will optimally be integrated. Section 4 provides some applications of our theory. Section 5 concludes by putting our "coordination-based theory of the firm", analyzed here, into context. Proofs not offered in the main text are contained in the appendix.

2 The Model

A manufacturer of widgets (M) is endowed with capital k. Selling widgets generates revenue R. There are n suppliers of production inputs. To make widgets, M needs an input from each supplier. M has no production costs aside from the cost of obtaining inputs. It costs supplier i (S_i for short) c_i to produce the input needed by M. The surplus from making widgets is strictly positive: $S \equiv R - \sum_i c_i > 0$.

The contracting environment is one where M makes take-it-or-leave-it offers to suppliers (and thus has all of the bargaining power). For reasons that will become clear momentarily, it makes sense for M to make offers to suppliers before they decide whether to produce. A contract between M and S_i takes the form of a price p_i that M offers to pay for input i, plus a claim over a fraction θ_i of M's capital if S_i produces the input and M fails to pay (with $\sum_i \theta_i \leq 1$). We assume that the suppliers have limited liability, so in the event they are unable to deliver inputs, it is not possible to penalize them.[6]

The timing of events is as follows:

1. M makes take-it-or-leave-it offers to each supplier i of the form (p_i, θ_i).

2. Suppliers simultaneously decide whether to accept the offers and produce inputs.

3. For each supplier i who produces, M decides whether to buy their input or pay the penalty $\theta_i k$. If M buys all inputs, M produces widgets and generates

[6]If liability was not limited, the problem of coordinating suppliers could be solved by offering contracts where suppliers receive a penalty for failing to produce if and only if all other suppliers sign a contract.

revenue R. Otherwise, M produces no widgets and generates zero revenue.

Notice that if M contracted with suppliers after they produce inputs—rather than before—suppliers would receive zero for their inputs since M has all of the bargaining power. Suppliers would, consequently, choose not to produce in the first place. M solves this hold-up problem by contracting with suppliers ex ante rather than ex post, as we have assumed.

2.1 Analysis

For ease of exposition, we will assume that suppliers accept M's offer when otherwise indifferent, and both M and the suppliers produce when otherwise indifferent.

We can analyze the game by backward induction. At time 3, there are two possibilities: either all suppliers produced inputs, in which case M can produce widgets, or M is unable to produce widgets. In the former case, we can assume that M will pay p_i to each supplier and produce widgets (if not, M would have offered different contracts at time 1). M's payoff is $R - \sum_i p_i$ and S_i's payoff is $p_i - c_i$. In the event that M cannot produce widgets, M obtains zero revenue and pays each supplier i that produced either p_i or $\theta_i k$ (whichever is smaller). Notice that the penalty $\theta_i k$ is only used if $\theta_i k \leq p_i$. Thus, it makes sense to choose θ_i initially so that $\theta_i k \leq p_i$. Hence, we can assume that M pays the penalty rather than p_i.

Now, consider time 2. Suppliers are weakly better off if they accept M's offer since, if they accept, they can always choose not to produce (there is no penalty for failing to do so). Thus, suppliers will always accept M's offer. Let a_i denote S_i's decision whether to produce. Based on our analysis of time 3, we conclude that S_i's payoff is:

$$\pi_{S_i}(a_1, ...a_n) = \begin{cases} 0, & \text{if } a_i = 0 \\ p_i - c_i, & \text{if } a_1 = a_2 = ... = a_n = 1 \\ \theta_i k - c_i & \text{otherwise} \end{cases}$$

In order to get the suppliers to produce, M must set $p_i \geq c_i$ for all i, so let us focus on this case. If $k \geq \sum_i c_i$, M can set $\theta_i = \frac{c_i}{k}$ for all i; this makes $a_i = 1$ a weakly dominant strategy and ensures that all suppliers produce. In this case, moreover, M can set $p_i = c_i$, which gives M all of the surplus ($R - \sum_i c_i$).

If instead $k < \sum_i c_i$, it is not possible to make $a_i = 1$ a weakly dominant strategy for all suppliers: $\theta_i k - c_i < 0$ for some i. In this case, the suppliers face a coordination game with multiple Nash equilibria: there is a Nash equilibrium in which all suppliers produce ($a_1 = a_2 = ... = a_n = 1$) and a Nash equilibrium in which no supplier produces ($a_1 = a_2 = ... = a_n = 0$).

In order to refine the set of time-2 equilibria, we will apply an equilibrium concept developed by Kets and Sandroni (2021) called introspective equilibrium. Introspective equilibrium is based upon level-k thinking (see Crawford et al. (2013) for a review). Each player has an exogenously-given "impulse" which determines how they react at level 0; at level $k > 0$, players react according to the belief that other players are acting at level $k-1$. Introspective equilibrium is defined as the limit of this process as $k \to \infty$.

As we will see, the introspective equilibrium depends critically upon players' impulses, or level-0 thinking. We make the following assumption regarding suppliers' impulses.

Assumption 1. *Let $x_i^0 \in \{0, 1\}$ denote the impulse of supplier i: $x_i^0 = 1$ means that supplier i's impulse is to produce and $x_i^0 = 0$ means that supplier i's impulse is to not produce. We assume that $x_i^0 = 1$ with probability γ_i. The x_i^0's are mutually independent. x_i^0 is private information of supplier i.*

The parameter γ_i captures supplier i's perceived willingness to produce. We formally define introspective equilibrium in our context as follows.

Definition 1 (Introspective Equilibrium for Supply Chains)**.** *An introspective equilibrium $(a_1^*, a_2^*, ..., a_n^*)$ is constructed as follows:*

1. *Supplier i's choice at level $k > 0$, denoted x_i^k, is obtained by letting each supplier*

best respond to the belief that other suppliers are at level $k-1$:

$$x_i^k = \begin{cases} 1, & \textit{if} \quad \mathbb{E}_i[(\Pi_{j\neq i} x_j^{k-1})(p_i - c_i) + (1 - \Pi_{j\neq i} x_j^{k-1})(\theta_i k - c_i)] \geq 0 \\ 0, & \textit{otherwise.} \end{cases}$$

2. *An introspective equilibrium is the limit as $k \to \infty$:*

$$a_i^* = \lim_{k\to\infty} x_i^k.$$

The following lemma characterizes the introspective equilibria of the game.

Lemma 1. *The introspective equilibrium is unique and:*

1. *All suppliers produce in equilibrium if condition 1 holds for all i:*

$$p_i \Gamma_{-i} + \theta_i k(1 - \Gamma_{-i}) \geq c_i, \tag{1}$$

where $\Gamma_{-i} = \prod_{j\neq i} \gamma_j$.

2. *No supplier produces in equilibrium otherwise, except in the following special case where no equilibrium exist: (i) there are exactly two suppliers and (ii) condition 1 holds for one supplier and is violated for the other.*

Proof. First, consider supplier i's leve1-1 choice (x_i^1). At level 1, supplier i assumes that other suppliers are at level 0. The expected return to supplier i from producing is $p_i\Gamma_{-i} + \theta_i k(1 - \Gamma_{-i})$ (since Γ_{-i} is the probability that all of the other suppliers produce). Hence, supplier i produces at level 1 ($x_i^1 = 1$) if and only if equation 1 holds. Now, consider supplier i's level-2 choice (x_i^2). Supplier i knows that other suppliers produce at level 1 if and only if equation 1 holds for all $j \neq i$. Hence, supplier i produces at level 2 if and only if equation 1 holds for all $j \neq i$.

Let us split our analysis of level 3 into two cases: (i) more than two suppliers and (ii) two suppliers. In case (i), supplier i produces at level 3 if and only if equation 1 holds for all suppliers (including i). To see this, take any two suppliers besides i. These two suppliers both produce at level 2 if and only if equation 1 holds for all suppliers. From level 3, it is easy to iterate up. It is clear that, at any level $k \geq 3$, supplier i produces if and only if equation 1 holds for all suppliers. This establishes the lemma for case (i).

Now consider case (ii). In the case where there are two suppliers only, supplier i produces at level 3 if and only if equation 1 holds for supplier i. The reason is that supplier j produces at level 2 if and only if equation 1 holds for supplier i. More generally, at odd levels, supplier i produces if and only if equation 1 holds for supplier i and, at even levels, supplier i produces if and only if equation 1 holds for supplier j. Hence, for all levels $k \geq 1$, both suppliers produce (neither supplier produces) if and only if equation 1 holds (is violated) for both suppliers. If equation 1 holds for one supplier and is violated for the other, there is cycling and no convergence, so no equilibrium exists. This establishes the lemma for case (ii). □

Suppose the manufacturer wishes to produce widgets rather than not. The manufacturer's problem is to minimize costs ($\sum_i p_i$) subject to the incentive compatibility condition for of the suppliers (equation 1) and the incentive compatibility constraint of the manufacturer ($\theta_i k \leq p_i$). It clearly makes sense to choose p_i such that the suppliers' incentive compatibility constraints bind, which implies that $p_i = \frac{c_i - \theta_i k(1-\Gamma_{-i})}{\Gamma_{-i}}$. Substituting for p_i, we can rewrite the incentive compatibility constraint for the manufacturer as $\theta_i k \leq c_i$. We can thus rewrite the manufacturer's problem as:

$$\min_{\theta_i} \sum_i \frac{c_i - \theta_i k(1 - \Gamma_{-i})}{\Gamma_{-i}}$$

$$\text{subject to: } \theta_i k \leq c_i \text{ for all } i$$

Without loss of generality, assume that $\Gamma_{-1} \leq \Gamma_{-2} \leq ... \leq \Gamma_{-n}$. This means that it is hardest to convince supplier 1 to produce and easiest to convince supplier n. Note that, with this indexing, supplier 1 also has the greatest impulse to produce: $\gamma_1 \geq \gamma_2 \geq ... \geq \gamma_n$. Intuitively, despite supplier 1's high impulse, it is hard to convince supplier 1 because of the low impulse of other suppliers.

Additionally, let us define m to be the number of suppliers who can be paid off using capital k. More precisely, let m be the integer such that $\sum_{i=1}^{m} c_i \leq k < \sum_{i=1}^{m+1} c_i$ (or, in the event that $\sum_{i=1}^{n} c_i \leq k$, let $m = n$). Note that there might be some capital remaining after paying off the first k suppliers that could be used to partially pay off the $m+1$-st supplier. For the sake of simplifying exposition, we will assume that there is zero capital remaining after paying off the first m suppliers.

Assumption 2. *There is no capital remaining after paying off the first m suppliers: $\sum_{i=1}^{m} c_i = k$.*

Proposition 1. *If M produces widgets:*

1. *M fully insures the first m suppliers and does not insure other suppliers:*
   - $\theta_i = \frac{c_i}{k}$ *for* $i \leq m$.
   - $\theta_i = 0$ *for* $i > m$.
2. *M pays the first m suppliers marginal cost and pays a markup to other suppliers:*
   - $p_i = c_i$ *for* $i \leq m$.
   - $p_i = \frac{c_i}{\Gamma_{-i}} = c_i + \underbrace{c_i \cdot \frac{1 - \Gamma_{-i}}{\Gamma_{-i}}}_{\text{markup paid to i}}$ *for* $i > m$.

M produces widgets if the total markup does not exceed the surplus:

$$\underbrace{\sum_{i>m} c_i \cdot \frac{1 - \Gamma_{-i}}{\Gamma_{-i}}}_{\text{total markup}} \leq S$$

Otherwise, M does not produce widgets and offers suppliers nothing for their inputs ($p_i = 0$ for all i).

3 Make or Buy

We now extend the model to consider whether it makes sense for M to make input i in-house or buy the input from another firm. Our approach to the make-or-buy problem is based on Aghion and Tirole (1997). As in Aghion and Tirole (1997), M and S_i decide ex ante on an allocation of formal authority. If M has formal authority, we will say that M and S_i are integrated; otherwise, we will say that they are separate firms. The party with formal authority has the right to make two decisions: (1) whether input i is produced and (2) which production methods are used. The timing is similar to the baseline model:

1. M makes take-it-or-leave-it offers to each supplier of the form (p_i, θ_i, A_i), where $A_i \in \{M, S_i\}$ is an allocation of formal authority.

2. Suppliers decide whether to accept the offers.

3. Suppliers exert effort at generating cost-cutting production methods. The party with authority then chooses among the production methods.

4. The parties with authority simultaneously decide whether to produce inputs.

5. For each input i that is produced, M decides whether to use the input and pay p_i to S_i, or pay a penalty $\theta_i k$ to S_i. If M uses all of the inputs, M produces widgets and generates revenue R. Otherwise, M produces no widgets and generates zero revenue.

In Section 3.1, we will carefully spell out what happens at time 3. As a preview, the main finding is that M-authority raises the cost of producing input i to $(1 + \beta_i)c_i$. In Section 3.2, we will show that, while M-authority increases *production costs*, it also lowers the *costs of coordination*. This is the main tradeoff governing the make-or-buy decision.

3.1 Cost cutting

Let us consider how production methods are chosen at time 3. We will focus on input i and we will drop i subscripts to reduce notation.

There are P aspects of the production process and a production method for each aspect. Let m_p denote the production method used for aspect p and let $\frac{c(m_p)}{P}$ denote the associated cost. The overall cost of production is $\frac{1}{P}\sum_{p=1}^{P} c(m_p)$.

For each aspect of production, there is a default method with a cost c_H and two cheaper methods (m1 and m2) that might be uncovered. One of the cheaper methods has an associated cost $c_L < c_H$ and the other method has an associated cost $c_L - \Delta < c_L$. The cost of production is borne by the supplier, so the supplier prefers the cheapest possible method. The manager receives a private benefit of negligible size from one of the two cheaper methods. The manager prefers whichever of the cheaper methods generates this negligible private benefit. The supplier's preferred method is the same as the manager's preferred method with probability α. Parameter α captures the degree of preference congruence of M and the supplier.

The supplier uncovers the cheaper methods for process p with probability $\eta_S > 0$ and the manufacturer uncovers the cheaper methods with probability $\eta_M > 0$. The chance of uncovering cheaper methods is independent across players and processes. After methods have been uncovered, the party with formal authority chooses among the production methods they know or, alternatively, delegates the choice to the other party.

Analysis

Let us now examine how the allocation of authority affects the cost of production.

M-authority. If the manager has formal authority, they choose the method themselves whenever they uncover the cheap methods and they delegate the choice to the supplier otherwise. The expected cost to the supplier of producing the input is:

$$C^{M-auth} = c_H - \underbrace{\eta_M(c_H - c_L + \alpha \cdot \Delta)}_{\text{M uncovers the cheap methods}} - \underbrace{(1-\eta_M)\eta_S(c_H - c_L + \Delta)}_{\text{M delegates and S uncovers the cheap methods}} .$$

$$= c_H - (\eta_M + \eta_S + \eta_M\eta_S)(c_H - c_L) - (\eta_S + \eta_M(\alpha - \eta_S))\Delta$$

Supplier-authority. If the supplier has formal authority, they choose the method themselves whenever they uncover the cheap methods and they delegate to the manager otherwise. The expected cost to the supplier of producing the input is:

$$C^{S-auth} = c_H - \underbrace{\eta_S(c_H - c_L + \Delta)}_{\text{S uncovers the cheap methods}} - \underbrace{(1-\eta_S)\eta_M(c_H - c_L + \alpha \cdot \Delta)}_{\text{S delegates and M uncovers the cheap methods}} .$$

$$= c_H - (\eta_M + \eta_S + \eta_M\eta_S)(c_H - c_L) - (\eta_S + \eta_M(1-\eta_S)\alpha)\Delta$$

Notice that $C^{S-auth} < C^{M-auth}$ when $\alpha < 1$. Intuitively, $\alpha < 1$ means that the manufacturer is not sufficiently concerned with cost-cutting and allocating formal authority to them leads to inflated costs.

Because it is probabilistic whether the manufacturer and the supplier uncover the cheaper methods, the cost may differ from the expected cost. However, as the number of aspects of production P becomes large, the cost converges to the expected cost (due to the law of large numbers). Since it simplifies the exposition to deal with a fixed cost rather than a random cost, we will focus on the case where $P \to \infty$. Moreover, we will let $c_i \equiv C^{S-auth}$ and $\beta_i \equiv \frac{C^{M-auth} - c_i}{c_i}$, so that $(1+\beta_i)c_i = C^{M-auth}$. Parameter β_i, which is increasing in preference incongruence, captures the extent to which costs increase under M-authority.

3.2 Authority allocation

Let us now examine how authority will be allocated at time 1. To aid intuition, let us begin by considering a simple case where there are just two suppliers and the manager has zero capital ($k = 0$). We will then examine the general case.

3.2.1 Two suppliers and $k = 0$

If neither supplier is integrated, the problem is the same as in Section 2. In order to produce widgets, the manager must pay a markup of:

$$\Phi^{NI} = c_1 \cdot \frac{1-\gamma_2}{\gamma_2} + c_2 \cdot \frac{1-\gamma_1}{\gamma_1}$$

Now suppose that both suppliers are integrated. At time 4, there is no longer a coordination problem since M has the authority to produce both types of inputs. Hence, there is no need to pay a markup because of the coordination problem. However, there is a markup in this case arising from the added production costs of M authority. At time 1, M must offer supplier i a contract where $p_i = (1 + \beta_i)c_i$. Consequently, there is a markup of $\beta_i \cdot c_i$ on input i, and the total markup is:

$$\Phi^{12} = c_1 \cdot \beta_1 + c_2 \cdot \beta_2$$

Finally, consider the case where only supplier i is integrated. At time 4, the parties deciding whether to producing inputs are M and supplier j. The coordination game is played, in other words, between M and j rather than i and j. To analyze this case, we will assume that M has an impulse just as suppliers do.

Assumption 3. *The manufacturer has an impulse to produce, denoted $x_M^0 \in \{0, 1\}$, just like suppliers. We assume that $x_M^0 = 1$ with probability γ_M. x_M^0 is private information of the manufacturer.*

In order to get supplier j to produce at time 4, the supplier must pay a markup of $c_j \cdot \frac{1-\gamma_M}{\gamma_M}$. Because M is the second party in the game, the only party that must be paid a markup is supplier j; however, there is an *incentive compatibility constraint* that must be satisfied in order for M to choose to produce input i. The incentive compatibility constraint for M follows immediately from Lemma 1:

$$\underbrace{S - (\text{total markup})}_{\text{payment to M for producing input i} \equiv p_M} = S - \Phi^i \geq \frac{1}{\gamma_j} c_i (1 + \beta_i) \tag{2}$$

While supplier i is not part of the time-4 game, and thus does not need to be paid a coordination markup, the allocation of authority to M increases the cost of producing input i by $c_i \cdot \beta_i$.

Thus, the total markup that is paid in this case is:

$$\Phi^i = c_i \cdot \beta_i + c_j \cdot \frac{1 - \gamma_M}{\gamma_M}$$

To summarize, the manufacturer will choose an authority structure based upon which minimizes the markup; however, the authority structure where supplier i is integrated but not j is only available if the IC constraint for the manufacturer (Condition 2) is satisfied. The following proposition immediately follows.

Proposition 2. *Suppose there are two suppliers.*

1. *Integrating supplier i is preferred to no integration ($\Phi^i \leq \Phi^{NI}$) if and only if:*

$$c_j \cdot \left(\frac{\gamma_M - \gamma_i}{\gamma_M \cdot \gamma_i} \right) \geq c_i \left(\beta_i - \frac{1 - \gamma_j}{\gamma_j} \right) \tag{3}$$

2. *Integrating both suppliers is preferred to integrating i only ($\Phi^{12} \leq \Phi^i$) if and only if:*

$$\frac{1 - \gamma_M}{\gamma_M} \geq \beta_j \tag{4}$$

Equation 3 shows what makes it is preferable to integrate supplier i rather than have no integration. Whether it is preferable depends in part upon is how the markup on input i changes when supplier i's authority is taken away ($\beta_i - \frac{1-\gamma_j}{\gamma_j}$). Additionally, it depends upon whether supplier i has a low impulse to produce compared to the manufacturer ($\gamma_M - \gamma_i$). Equation 4 shows what makes it is preferable to integrate both suppliers rather than supplier i only. What matters in this case is how the markup on input j changes when supplier j's authority is taken away ($\beta_j - \frac{1-\gamma_M}{\gamma_M}$).

Notice that in the special case where $\gamma_1 = \gamma_2 = \gamma_M = \gamma$ and $\beta_1 = \beta_2 = \beta$, full integration is preferred when $\frac{1-\gamma}{\gamma} \geq \beta$ and non-integration is preferred otherwise. In other words, integration occurs when the cost of giving authority to M (β) is low relative to the costs of coordinating suppliers (γ).

3.2.2 The General Case

Let us turn now to the general case where there are n suppliers and the manufacturer has capital k. The following lemma gives a formula for the markup.

Lemma 2. *Suppose the manufacturer integrates a set of suppliers I and their capital is used to fully ensure a set of suppliers K (i.e. $\theta_i = 1$ for $i \in K$ and $\theta_i = 0$ for $i \notin K$). When at least one supplier is integrated,*

1. *The total markup is:*

$$\Phi^I(K) = \underbrace{\sum_{i \in I} c_i \cdot \beta_i}_{\text{non-congruence costs}} + \underbrace{\sum_{i \notin I \cup K} c_i \cdot \frac{1 - \Gamma_{-i-I} \cdot \gamma_M}{\Gamma_{-i-I} \cdot \gamma_M}}_{\text{coordination costs}},$$

   where $\Gamma_{-i-I} = \prod_{j \notin \{i\} \cup I} \gamma_j$.

2. *The incentive compatibility constraint for the manufacturer is:*

$$\underbrace{S - \Phi^I(K)}_{\text{payment to M for producing inputs } I \equiv p_M} \geq \frac{1}{\Gamma_{-I}} \sum_{i \in I} c_i(1 + \beta_i),$$

   where $\Phi_I(K)$ denotes the total markup and $\Gamma_{-I} = \prod_{j \notin I} \gamma_j$.

The first term of the markup formula is the added cost of producing inputs when suppliers are integrated. This cost is lower when the integrated suppliers' preferences are more congruent with those of M. The second term of the markup formula is the cost of coordinating the non-integrated suppliers. The difference relative to the formula in Lemma 1 is that manufacturer M takes the place of the integrated suppliers. As in the two-supplier case, there is an incentive compatibility constraint for the manufacturer since the manufacturer must be properly incentivized to produce at time 4. This incentive compatibility constraint can be derived from Lemma 1.

The following corollary is a consequence of Lemma 2.

Corollary 1.

1. *The manufacturer does not insure suppliers who are integrated ($\theta_i = 0$ for $i \in I$).*

2. *Among the non-integrated suppliers, the manufacturer insures those who are most reluctant to produce (i.e. those of lowest index).*

Point 1 of the corollary can be seen from the markup formula. The reason to insure a supplier is to reduce the coordination markup; but there is zero coordination markup for integrated suppliers, and hence no reason to insure them. Point 2 can also be seen from the markup formula and the logic is akin to that in Proposition 1. The low-index suppliers are the most reluctant to invest. Insuring these suppliers has the greatest bang for the buck in terms of reducing the total markup.

The next proposition examines when a given supplier is more or less likely to be integrated. The proof is given in the Appendix.

Proposition 3. *Lowering β_i or γ_i makes it more likely supplier i will be integrated. More precisely, let $I^*(\beta_i, \gamma_i)$ denote the firms that are integrated as a function of β_i and γ_i. If $i \in I^*(\beta, \gamma, c)$:*

1. *$i \in I^*(\beta', \gamma, c)$ for all $\beta' < \beta$.*

2. *$i \in I^*(\beta, \gamma', c)$ for all $\gamma' < \gamma$.*

Intuitively, lowering β_i reduces the cost of integrating supplier i, and hence raises the chance that supplier i will be integrated. When γ_i is low and supplier i is not integrated, it is hard to coordinate the other suppliers. Thus, lowering γ_i raises the benefit of integrating supplier i, and hence raises the chance that supplier i will be integrated.

Proposition 4 gives some additional results (the proof is given in the Appendix).

Proposition 4.

1. *If $\beta_i = 0$ for all suppliers, all suppliers are integrated.*

2. *If suppliers differ only in their β's ($c_i = c$ and $\gamma_i = \gamma$ for all i), the suppliers who are integrated are those for whom β_i is lowest.*

3. *If suppliers differ only in their γ's ($c_i = c$ and $\beta_i = \beta$ for all i), the suppliers who are integrated are those for whom γ_i is lowest.*

4. *If suppliers are homogeneous ($c_i = c$, $\beta_i = \beta$, and $\gamma_i = \gamma$ for all i), it is possible that some suppliers are integrated and some are not.*

Point 1 follows from the observation that there is no cost to integration—only benefit—when $beta_i = 0$ for all i. Point 2 follows from the observation that the cost of integration for the most congruent suppliers (i.e. the suppliers with the lowest $beta_i$'s). Point 3 follows from the observation that the coordination benefits of integration are greatest for the suppliers with the lowest impulses (i.e. the suppliers with the lowest γ_i's).

Point 4 considers the case where all suppliers are homogeneous. In this case, cost of integrating an additional firm is β. The marginal benefit of integration is decreasing, by contrast. Consequently, the point where the marginal cost of integration equates with the marginal benefit may be interior. Point 4 has the interesting implication that initially identical suppliers may be treated differently by the manufacturer; moreover, their ultimate costs of production may be different (c vs. $(1 + \beta)c$). This result speaks to the growing literature on persistent performance differences between firms (see, for instance, Gibbons and Henderson (2012), Chassang (2010), Ellison and Holden (2014)).

4 Applications

Supplier Investments

Suppose the inputs the manufacturer needs to produce a widget are generic and have a low marginal cost of production. In such a case, the manufacturer is likely have sufficient capital to purchase all of the inputs ($k \geq \sum_i c_i$), in which case no coordination problem arises.

There are two circumstances where coordination problems are more likely to arise: (i) the inputs are generic but have a high marginal cost of production, or (ii) the inputs are non-generic. In both cases, a coordination problem is likely because the cost of producing inputs (c_i) is high. In the latter case, the cost of producing inputs is high because suppliers need to make investments to produce them. This was a key reason for ASML's coordination problem: its main suppliers (e.g. Cymer, Trumpf, and Zeiss) needed to make expensive, years-long investments.

The idea that coordination problems arise when suppliers make expensive investments suggests an interesting extension to the model. Consider a dynamic version of the model where there are several potential manufacturers of widgets. At time 1, it is hard to produce widgets because input suppliers have not made the requisite investments. If suppliers make investments at time 1, the coordination problem disappears at time 2. Such a model suggests that a given manufacturer M might *prime the pump* at time 1. If M solves the coordination problem at time 1, they create a supply chain that other manufacturers can exploit at time 2.

One consideration that arises here is akin to the classic dilemma in the patent literature, where manufacturer M might be disincentivized from creating the supply chain at time 1 if they lose market power at time 2. Hence, preserving market power at time 2 becomes an important consideration for manufacturer M. This desire to preserve market power is arguably another important reason why we might see integration. By integrating suppliers at time 1, M obtains market power in the input market at time 2.

Movers and Shakers

Our model considers three tools that the manufacturer can use to achieve coordination: (i) insuring suppliers, (ii) paying markups, and (iii) integrating suppliers. Potentially, additional tools might be available to the manufacturer besides these three. Akerlof and Holden (2016) consider the role that "movers and shakers" play in coordinating parties. They consider, for instance, the role that financial institutions or real estate developers play in creating expectations that a project will succeed. Movers and shakers, according to this view, create a virtuous cycle where each party's confidence raises the confidence of the other parties.

In terms of the present model, we might view movers and shakers as changing the impulses of suppliers (γ_i). They might raise a supplier's γ_i by working to sell them on the project. Since raising γ_i reduces the overall markup that the manufacturer needs to pay, we might also expect movers and shakers to command large rents for the role that they play.

Movers and shakers might also serve as a substitute for integration. We might, more generally, think of movers and shakers as generating a sense of trust between parties. In cases where trust between firms is strong, integration might be lower. This may explain, for instance, the types of company relationships we see in Japan and Korea (i.e. *keiretsu* and *chaebol*).

International Trade

Suppose manufacturer M decides to obtain an input from overseas rather than domestically. How might this affect the integration decision? One possibility is trust between the parties declines. We might think of this as a reduction in γ_i. At the same time, the congruence of preferences between M and the supplier might decline as well. We might think of this as an increase in β_i. According to Proposition 3, a decline in γ_i pushes the manufacturer toward integrating the supplier while an increases in β_i pushes the manufacturer against integrating the supplier. Hence, there are competing considerations. The model suggests that whether integration increases or decreases when production moves abroad depends upon which of these considerations dominates.

Industrial Policy

A number of rationales used to justify industrial policy in advanced economies in the 1960s and 1970s have been thoroughly debunked. For instance, industrial policy was sometimes justified on the grounds of job creation, exchange-rate or balance-of-payments management, or sectoral externalities. These arguments did not stand up to scrutiny (see, inter alia, Scitovsky (1954), Bhagwati et al. (1978)).

Our theory offers a different rationale for the potential efficacy of industrial policy. If there are projects with positive surplus that are not occuring, a government can play a coordinating role. This could happen through the moving-and-shaking channel we discussed above, or it could happen by the government providing capital. By providing a manufacturer with additional capital, a government could facilitate coordination where it otherwise would not occur, or help it be achieved at lower cost by reducing the need to pay markups.

Complex issues such as the green-energy transition exhibit obvious coordination problems, suggesting a potentially important role for "coordination-based" industrial policy.

5 Concluding Remarks

We have provided a model of supply chains that emphasizes the importance of coordination and speaks to relationships between a single manufacturer and multiple suppliers—or "spiders" as they have become known. Our model not only provides stark predictions that are consistent with existing empirical evidence, but is tractable enough to facilitate the analysis of a number of applications. These include important issues in International Trade and Industry Policy.

At the heart of our approach in this paper is a novel theory of the firm based on the importance of coordination. Coase (1937) first raised the deep question of why firms exist if markets are an efficient means of allocating resources. The

Transaction Costs theory of the firm that Coase suggested and Williamson developed (Williamson (1971), Williamson (1975)) was the first alternative to the rather unsatisfying *Neoclassical* theory of the firm.

Grossman and Hart (1986) and Hart and Moore (1990) pioneered the *Property Rights Theory* of the firm. PRT emphasizes the importance of assets ownership in alleviating hold-up problems and hence encouraging ex ante relationship-specific investments.

There is also an earlier *Principal-Agent Approach* which emphasizes the importance of agency problems for hiring employees our outsourcing production to independent contractors. See for instance (Alchian and Demsetz (1972) and Holmstrom (1982)).

A fourth major approach to theory of the firm is the *Incentives Approach* of Holmstrom and Milgrom (1994). Those authors view the make-or-buy decisions as two alternative systems for managing incentives. Gibbons (2005) provides an excellent overview of these theories.

We offer a distinct approach—a *Coordination-Based* theory of the firm.[7] This approach emphasizes the role that a firm (the manufacturer in our model) plays in coordinating the provision of inputs from a number of disparate suppliers. The firm can encourage provision of an input either through contract—by providing insurance to a supplier in the event that they supply the input but other suppliers do not—or via control of decision rights, whereby they can compel provision of the input from a given supplier. Our coordination-based theory provides sharp predictions about when exchange is mediated by contract, and when integration is preferable. We have showed that the coordination-based theory can provide starkly different predictions than PRT.

Our view is that all five of these rationales for the existence of firms are important. But to date the coordinating role that firms play has received little formal attention. We hope that our contribution has partially remedied this oversight.

[7] Alonso et al. (2008) emphasize the role of coordination in a different way to us. They focus on the need to adapt decisions to local conditions but also coordinate those decisions in a multi-divisional firm. As such they focus on the internal structure of an organization whereas we focus on how the boundaries of firms are determined–i.e. the make-or-buy decision.

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6 Appendix

Proof of Proposition 3. Suppose that a set of suppliers I are integrated. Let us consider how adding supplier i to set changes the total markup. Let $\Delta(I)$ denote the change in the total markup from integrating i:

$$\Delta(I) \equiv \Phi^{I\cup\{i\}}(K') - \Phi^{I}(K),$$

where K is the optimal insurance choice when suppliers I are integrated and K' is the optimal choice when suppliers $I \cup \{i\}$ are integrated. To prove the result, it is sufficient to show that $\Delta(I)$ is weakly increasing in β_i and γ_i. There are four cases we need to consider:

1. I is nonempty and $i \notin K$.
2. I is nonempty and $i \in K$.
3. I is empty and $i \notin K$.
4. I is empty and $i \in K$.

In case 1, corollary 1 implies that $K' = K$. We find that:

$$\Delta(I) = c_i \cdot [\beta_i - \frac{1-\Gamma_{-i-I}\cdot\gamma_M}{\Gamma_{-i-I}\cdot\gamma_M}] - \sum_{j\notin I\cup\{i\}\cup K} c_j \cdot [\frac{1-\Gamma_{-j-I}\cdot\gamma_M}{\Gamma_{-j-I}\cdot\gamma_M} - \frac{1-\Gamma_{-i-j-I}\cdot\gamma_M}{\Gamma_{-i-j-I}\cdot\gamma_M}]$$

It is clear that $\Delta(I)$ is increasing in β_i. γ_i appears in the second term of the above expression: a higher γ_i increases Γ_{-j-I}, which increases $\Delta(I)$.

In case 2, integrating i frees up some capital to insure other suppliers. We have $K' = [K - \{i\}] \cup A$, where A denotes the additional insured suppliers. We find that:

$$\Delta(I) = c_i \cdot \beta_i - \sum_{j\notin I\cup K} c_j \cdot [\frac{1-\Gamma_{-j-I}\cdot\gamma_M}{\Gamma_{-j-I}\cdot\gamma_M} - \frac{1-\Gamma_{-i-j-I}\cdot\gamma_M}{\Gamma_{-i-j-I}\cdot\gamma_M}] - \sum_{j\in A} c_j \cdot [\frac{1-\Gamma_{-i-j-I}\cdot\gamma_M}{\Gamma_{-i-j-I}\cdot\gamma_M}]$$

It is clear that $\Delta(I)$ is increasing in β_i. γ_i appears in the second term of the above expression: a higher γ_i increases Γ_{-j-I}, which increases $\Delta(I)$.

In case 3, corollary 1 implies that $K' = K$. We find that:

$$\Delta(I) = c_i \cdot [\beta_i - \frac{1-\Gamma_{-i}}{\Gamma_{-i}}] - \sum_{j \notin \{i\} \cup K} c_j \cdot [\frac{1-\Gamma_{-j}}{\Gamma_{-j}} - \frac{1-\Gamma_{-j-i} \cdot \gamma_M}{\Gamma_{-j-i} \cdot \gamma_M}]$$

It is clear that $\Delta(I)$ is increasing in β_i. γ_i appears in the second term of the above expression: a higher γ_i increases Γ_{-j}, which increases $\Delta(I)$.

In case 4, integrating i frees up some capital to insure other suppliers. We have $K' = [K - \{i\}] \cup A$, where A denotes the additional insured suppliers. We find that:

$$\Delta(I) = \Delta(I) = c_i \cdot \beta_i - \sum_{j \notin K} c_j \cdot [\frac{1-\Gamma_{-j}}{\Gamma_{-j}} - \frac{1-\Gamma_{-j-i} \cdot \gamma_M}{\Gamma_{-j-i} \cdot \gamma_M}] - \sum_{j \in A} c_j \cdot [\frac{1-\Gamma_{-j-i} \cdot \gamma_M}{\Gamma_{-j-i} \cdot \gamma_M}]$$

It is clear that $\Delta(I)$ is increasing in β_i. γ_i appears in the second term of the above expression: a higher γ_i increases Γ_{-j}, which increases $\Delta(I)$.

This completes the proof. □

Proof of Proposition 4.

The reasoning behind Points 1-3 is straightforward and given in the text. To establish Point 4, let us focus on the case where there is no supplier heterogeneity, $k = 0$, and $\gamma_M = \gamma$. In this case, the markup when g firms are integrated is:

$$\Phi(g) = g \cdot \beta + (n-g)c(\gamma^{g-n} - 1)$$

Differentiating with respect to g:

$$\Phi'(g) = \beta + c + c \cdot \gamma^{g-n}[(n-g)\log\gamma - 1]$$

Observe that $\Phi'(n) = \beta$ and $\Phi'(0) = \beta + c + c \cdot \gamma^{-n}[n \log\gamma - 1]$. If $\beta > 0$, $\gamma < 1$, $c > 0$, and n is large, $\Phi'(n) > 0$ and $\Phi'(0) < 0$. Hence, the value of g for which the markup is lowest is interior ($0 < g^* < n$). This establishes the result. $\square$