

**WHEN QUALITY MATTERS:  
INFORMATION TECHNOLOGY AND  
BUYER-SUPPLIER RELATIONSHIPS**

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CCS TR # 140, Sloan School WP # 3536-93

November, 1992

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Center for Coordination Science Technical Report

Cambridge, Massachusetts

May 1992

Revised November 1992

*Forthcoming in the 1993 Special Issue of the Journal of Organizational Computing*

**Acknowledgments:** We would like to thank Thomas Malone, Eric Clemons, Oliver Hart and participants at the MIT IT workshop and the 4th Workshop on Information Systems and Economics for valuable comments. The National Science Foundation and the Center for Coordination Science at MIT provided generous support for this research.

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## **When Quality Matters: Information Technology and Buyer-Supplier Relationships**

### **ABSTRACT**

As search costs and other coordination costs decline, theory predicts that firms should optimally increase the number of suppliers with which they do business. Despite recent declines in these costs due to information technology, there is little evidence of an increase in the number of suppliers used. On the contrary, in many industries firms are working with fewer suppliers. This suggests that other forces must be accounted for in a more complete model of buyer-supplier relationships.

This paper uses the theory of incomplete contracts to illustrate that incentive considerations can motivate a buyer to limit the number of employed suppliers. In order to induce suppliers to make investments that cannot be specified and enforced in a satisfactory manner via a contractual mechanism, the buyer must commit not to expropriate the *ex post* surplus from such investments. Under reasonable bargaining mechanisms, such a commitment will be more credible if the buyer can choose from fewer alternative suppliers. Thus, it is predicted that when non-contractibles such as "quality" are particularly important, firms will employ fewer suppliers, and that this will be true even when search and transaction costs are very low.

## **1. Introduction**

As firms try to increase their performance, the interface with suppliers has become a major point of emphasis in the quest for additional efficiencies. This topic is enjoying increasing popularity, especially in view of the differences in customer-supplier relationships between Japanese and American firms. For instance, superior supplier relations have been estimated to provide a \$300-\$600 per car cost advantage to Japanese manufacturers (Cole and Yakushiji 1984). These trends are reflected in the information technology (IT) literature as well, which has identified the impact of IT on supplier relationships as an important area for research, and has discussed these relationships in the context of institutional economics (Gurbaxani and Whang 1991, Malone *et al.* 1989) firm size (Brynjolfsson *et al.* 1991) and the form ("governance") of the relationship (Clemons and Reddi 1992).

### **1.1. Transactional considerations predict more suppliers**

Determining the optimal number of suppliers is a natural extension of the "make vs. buy" or "markets vs. hierarchies" decision. Both questions can be analyzed by focusing on coordination costs. Malone, Yates and Benjamin (Malone *et al.* 1987) summarize this argument:

In a pure market, with many buyers and sellers, the buyer can compare many different possible suppliers of the product and select the one that provides the best combination of characteristics (such as design and price), thus presumably minimizing production costs for the desired product... The coordination costs associate with this wide latitude of choice, however are relatively high, because the buyer must gather and analyze information from a variety of possible suppliers....

Hierarchies, on the other hand, restrict the procurer's choice of suppliers to the one supplier hierarchically connected to the procurer, either within a single company or in a closely linked relationship between two companies, [which] reduces coordination costs over those incurred in a market by eliminating the procurer's need to gather and analyze a great deal of information about various suppliers.

Malone, Yates & Benjamin argue further that IT will facilitate a move from single-supplier arrangements ("hierarchies") to multiple supplier arrangement ("markets") because it reduces the costs of coordination with suppliers:

Since the essence of coordination involves communication and processing information, the use of information technology seems likely to decrease these costs (e.g., see (Malone 1985)).

Similarly, in studying the impact of technology on the number of suppliers, IT researchers have focused on transactional considerations, examining tradeoffs such as

those between the increased search costs necessary to locate a large number of suppliers versus the increased probability of finding a better price or locating a superior product offering as a larger number of suppliers is surveyed. According to this logic, technological developments lowering the cost of acquiring information about prices and product characteristics in a given market, should lead to an increase in the number of suppliers considered, especially in markets with differentiated products (Bakos 1991). Since it has been widely argued that information technology in general, and interorganizational systems in particular, tend to lower search costs (Bakos 1987, Clemons and Row 1989, Malone 1985), as these systems are increasingly adopted in several sectors of the economy, they should lead to an increase in the number of suppliers employed by most firms.

## 1.2. Evidence of a move to fewer suppliers

While there is evidence of a shift from single supplier "hierarchies" to multiple supplier "markets" (Brynjolfsson *et al.* 1991, Johnston and Lawrence 1988), we have not observed a wholesale increase in the *number* of suppliers. On the contrary, there is significant recent evidence for an overall *reduction* in the number of suppliers, both as a general trend in certain industries, and as a by-product of information technology adoption in particular. For instance, a study of the automobile industry by Helper (1991a), found that the average number of suppliers decreased 25% between 1983 and 1988. In a survey of Japanese and American firms, Cusumano and Takeishi (1991) found that American firms were increasingly adopting the Japanese model of supplier relations, which involved relationships with about half as many suppliers per part (1.3 vs. 2.8) and resulted in orders of magnitude fewer defects (0 to 0.01% in Japan vs. 0.35 to 2.6% for American suppliers). In some industries the trend has been even more pronounced. Motorola reduced its supplier base from 10,000 to 3,000 in the past few years, prompting one industrial consulting firm to conclude that "A revolution is going on in the relationships between suppliers and customers" (Emshwiller 1991).

The shift to fewer suppliers is often associated with the emergence of "strategic networks," such as the those in the textile industry of central Italy (Antonelli 1988, Piore and Sabel 1984). Although there is a lack of formal empirical studies, anecdotal evidence abounds (Imai *et al.* 1985, Von Hippel 1985, Von Hippel 1986) and a recent review (Jarillo 1988) concluded that networking, especially in the Japanese Keiretsu model, was a theme in "practically all studies of industrial suppliers and industrial markets." In a similar vein, Johnston and Lawrence (1988) review several case studies and argue that "value-adding partnerships" in which each company "cultivates relationships with only a few (from two to six) suppliers for critical items" are supplanting not only vertically-

integrated hierarchies, but also arms-length markets of multiple buyers and suppliers in the economy as a whole.

IT has been linked to these changes in several studies. Johnston and Lawrence specifically attribute the rise of VAPs in part to IT, including minicomputers and PCs, improved software, data standards, networking and CAD/CAM. Helper found a statistically significant correlation between technology use and close supplier relations. Clemons and Reddi (1992) also argue not only that there has been a recent "move to the middle" from both ends of the markets-hierarchies spectrum, but also that IT has been a significant driving force behind this trend.

This move to fewer suppliers in the face of declining coordination costs, including search costs and transaction costs, presents a paradox since it is at odds with the arguments discussed in section 1.1.

### **1.3. Explanations for the move to fewer suppliers**

One possible explanation for the shift to fewer suppliers is that search and coordination costs have actually increased. For example, if there are fixed technological and organizational investments required to connect to a supplier, a firm may wish to limit the number of suppliers it does business with, in order to economize on these fixed costs. Similarly, if investments in electronic integration are specific to a particular supplier and thus are not transferable to new relationships, they may create switching costs limiting the desirable number of suppliers over a period of time. For example, investing in an interorganizational system for the exchange of component blueprints in a CAD format used by a certain supplier, may limit the ability of the firm to explore new potential suppliers.

While arguments like these may explain why investment in interorganizational information systems could reduce the number of suppliers *initially*, it is widely believed that information technology lowers fixed costs and switching costs *in the long run*, principally because information technology standards can decrease the specificity of investment in interorganizational relationships (Clemons and Reddi 1992). For example, once an EDI standard has been adopted in an industry, the cost of basic electronic integration between any supplier and buyer who have implemented this standard will be relatively small. In the long run, the optimal number of suppliers is determined by the *marginal* cost of adding additional suppliers, not the initial cost of establishing or joining a system. Thus any decrease in the number of suppliers resulting from the adoption of information technology is likely to be temporary. The increase in outsourcing throughout the economy suggests that, on balance, there has not been an

increase in transaction costs. Furthermore, direct measures of most basic types of computer-aided transactions show rapid cost declines, ranging as high as 25% per year (Brynjolfsson *et al.* 1991). Overall, the theoretical and empirical evidence appears to weigh heavily on the side of reduced coordination costs in the past decade.

A second possible explanation is that economies of scale have increased so much that it is only worthwhile to deal with a few large suppliers. Although this may be true in a few industries, the weight of the evidence does not support this hypothesis in general. Flexible manufacturing is widely acknowledged to have reduced the average size of production runs and overall set-up costs, enabling smaller plants and firms to compete successfully. For instance, in the automobile industry, lot sizes for both production and delivery were smaller in 1989 than five years earlier (Helper 1991a).<sup>1</sup> Furthermore, trends in information technology strongly favor smaller and cheaper computers and reduced economies of scale in production. Finally, the average size of firms has decreased in the past decade in the US economy as a whole (Brynjolfsson *et al.* 1991).

A third possibility is that flexible manufacturing has enabled each supplier to offer a broader range of products. As a result, the buyer might be able to rely on fewer suppliers in total, but still have the same number for each product.<sup>2</sup> Although theoretically intriguing, this hypothesis could not explain the finding of Helper (1991) that average number competitors producing the same product for a given customer decreased from 2 to 1.5 and the number of rivals producing similar products in the auto industry fell from 2.3 in 1983 to 1.9 in 1988.

If this shift to fewer suppliers is not driven simply by changes in coordination costs, economies of scale or supplier versatility, business leaders suggest an alternative explanation. According to Percy Barnevik, head of the \$29 billion ABB conglomerate, price is less important than benefits like responsiveness and higher quality:

'If you have ten suppliers for porcelain for your transformers ... you can cut those ten down to three.' Because this approach gives each remaining supplier more business, ABB feels it can demand short delivery times and high quality.

'Any idiot can reduce a price by 10% to become more competitive. But if you can off an electric power transmission cable under the Baltic one year earlier than your competitor can, that is of tremendous value to the customer' (Rapoport 1992).

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<sup>1</sup> For example, the percentage of suppliers that deliver in lots that last their customer over eight days fell from 44 to 16 percent.

<sup>2</sup> We thank an anonymous referee for pointing out this possibility.

In fact, several field studies of buyer-supplier relations focus on the advantages that smaller and tighter networks of suppliers have, not only in quality (Cusumano and Takeishi 1991, Helper 1991b, McMillan 1990) and responsiveness (Johnston and Lawrence 1988), but also in innovation and technology adoption (Helper), defect rates (Cusumano), trust (Johnston and Lawrence) and information exchanges (Helper, Cusumano). All of these characteristics involve investments by suppliers that are difficult or impossible to specify in advance in a contract, in other words they are "non-contractible", and they offer benefits which are largely specific to a particular buyer-supplier relationship. Providing incentives for such investments presents special challenges, as discussed in the remainder of this paper; hereafter, we use the term "quality" as a short-hand for desirable characteristics that are "non-contractible" and "specific."

Since investments in quality tend to be non-contractible and specific, suppliers that make such investments must depend on their own *ex post* bargaining power (and/or the goodwill of the buyer) to reap a share of the benefits created by their investments. It has proven difficult to model these considerations in the past, for the same reasons that is difficult to specify them in a contract, and as a result they have largely been ignored in the more formal literature on buyer-supplier relations. Notable exceptions include Clemons and Reddi (1992), Helper (1991a), and Pisano and Chew (1990). Even these alternative approaches, however, do not explicitly address the question of how to provide incentives for investment in quality and, specifically, how the number of suppliers affects the incentives to make such investments. In fact, the idea that limiting the number of suppliers, and thereby increasing their bargaining power, could be a successful competitive strategy, runs counter not only to standard neo-classical economic models, but to the widely-used competitive strategy models as well (Porter 1980). As Alan Blinder put it:

Keiretsu are often portrayed as exclusionary devices that make Japanese companies unduly clannish and insular. How can such apparently restrictive business practices promote efficiency? (Blinder 1991)

This paper builds on the existing literature by adding incentive considerations to the coordination cost considerations, in determining the optimal number of suppliers. In particular, we use the incomplete contracting framework developed by Grossman, Hart and Moore (Grossman and Hart 1986, Hart and Moore 1990) to show that when it is important to provide incentives for suppliers to invest in quality, it can be optimal to limit the number of suppliers with which a buyer contracts. The intuition for this result is that a supplier will be able to garner more of the benefit created by his investment if the buyer does not have too many alternative suppliers. As a result, the supplier will



have greater *ex post* bargaining power and therefore greater *ex ante* incentives to invest in quality.

Studying the role of incomplete contracting considerations in determining the optimal number of suppliers provides an alternative perspective and an additional explanation for the "move to the middle". In addition, while technological progress, such as the development of standards, tends to quickly alleviate technological barriers to increasing the number of suppliers, the incomplete contracting considerations are more resistant to technological solutions, and are thus likely to remain in place for the foreseeable future. We show that even if search and coordination costs were to go to zero, it can still be optimal for a firm to limit the number of suppliers it uses.

#### **1.4. Outline of the paper**

Section 2 of the paper presents a simple model that captures the basic idea of the tradeoff between coordination costs and supplier fit. Considering only these factors leads to the conclusion that the number of suppliers should increase as coordination costs decline. Section 3 introduces the theory of incomplete contracts and models the incentive implications of increasing the number of suppliers, showing that the need to provide incentives for quality can limit the desirable number of suppliers. Section 4 presents an integrated model which includes the impact of coordination costs, fit, and incentives on determining the optimal number of suppliers. Section 5 concludes with implications of the model and some validating examples.

## **2. Coordination costs and the optimal number of suppliers**

A natural approach to determining the optimal number of suppliers is to start from the assumption that a firm would benefit by increasing the number of its suppliers, thereby broadening its choice, but that technological considerations constrain this strategy. In this perspective, the number of suppliers is limited by considerations such as the cost of setting up a relationship, search costs, and transaction costs, which can generally be summarized as coordination costs.

For example, in trying to determine the optimal number of suppliers for a given input, it may be assumed that suppliers' product offerings are substitutes for one another, except that they differ in some desirable feature, such as price, fit or product characteristics. Interacting with each supplier entails a coordination cost. After surveying some number of suppliers, the buyer selects the product offering that provides the best value according to its set of criteria. The optimal number of suppliers is determined by trading off the cost of further searches against the expected benefit from

identifying a better supplier. To illustrate these tradeoffs, in this section we offer a model for the optimal number of suppliers in the neoclassical tradition of Stigler (1951).

### Model 1

Consider a two-period setting with a buyer firm and  $N$  risk-neutral potential suppliers with identical production technology, facing the same marginal cost, assumed to be zero. Supplier offerings differ in a product characteristic, which, without loss of generality, is assumed to be one dimensional, providing to the buyer firm utility  $\varepsilon$  distributed in the interval  $[0,1]$  according to a known density function  $f_\varepsilon$ ;  $\varepsilon$  can be thought of as a "fit" indicator. Suppliers'  $\varepsilon$ 's can be discovered only after a relationship has been established between the buyer firm and the corresponding supplier. The buyer firm faces an irreversible cost  $\kappa$  for each supplier it does business with, which can be thought of as a coordination cost. In the first period, the buyer firm selects  $n$  suppliers from the  $N$  available suppliers ( $n \leq N$ ) as the suppliers it will do business with. In the second period, the buyer discovers the values of the fit parameters  $\varepsilon_i$  for the suppliers, and purchases from the supplier whose offering provides the "best match" (i.e., the highest  $\varepsilon$ ).<sup>3</sup>

To simplify the analysis, assume that competition between the suppliers drives prices to their marginal cost, thus allowing the buyer firm to appropriate the entire surplus<sup>4</sup>. The buyer selects the number of suppliers  $n$ , in order to maximize its expected surplus

$E\left[\max_{i \in \{1,2,\dots,n\}} \varepsilon_i\right] - n\kappa$ . The resulting optimal number of suppliers  $n^*$  is the largest integer satisfying the difference equation  $E\left[\max_{i \in \{1,2,\dots,n+1\}} \varepsilon_i\right] - E\left[\max_{i \in \{1,2,\dots,n\}} \varepsilon_i\right] > \kappa$ . It is easy to see that the expected surplus  $E\left[\max_{i \in \{1,2,\dots,n\}} \varepsilon_i\right] - n\kappa$  is maximized for a finite  $n^*$ , as  $\frac{d}{dn}\left(E\left[\max_{i \in \{1,2,\dots,n\}} \varepsilon_i\right]\right)$  is strictly decreasing and approaches zero as  $n$  approaches infinity, while  $\kappa$  is constant.

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<sup>3</sup> In this model only one supplier (the one with the best fit) is selected to provide the product purchased. Thus when we refer to  $n$  suppliers, the remaining  $n-1$  firms are "suppliers" in the sense that all of them are equally likely, *ex ante*, to be selected. Alternatively, in a multi-period setting, the buyer firm may purchase from different suppliers in each period (assuming the  $\varepsilon$ 's are temporally independent), and thus all  $n$  firms will eventually be used as suppliers, and over time, a variety of suppliers will be seen to deliver goods.

<sup>4</sup> Relaxing this assumption and assuming that prices are determined by *ex-post* bargaining does not qualitatively change the results. See the model in section 4 below, for example. Also, for an alternative interpretation of Model 1, the product can be considered a commodity, and  $1-\varepsilon$  can be the seller price, with a distribution exogenous to the model. In this case the firm buying from the supplier with the highest  $\varepsilon$  is equivalent to buying from the supplier offering the lowest price.

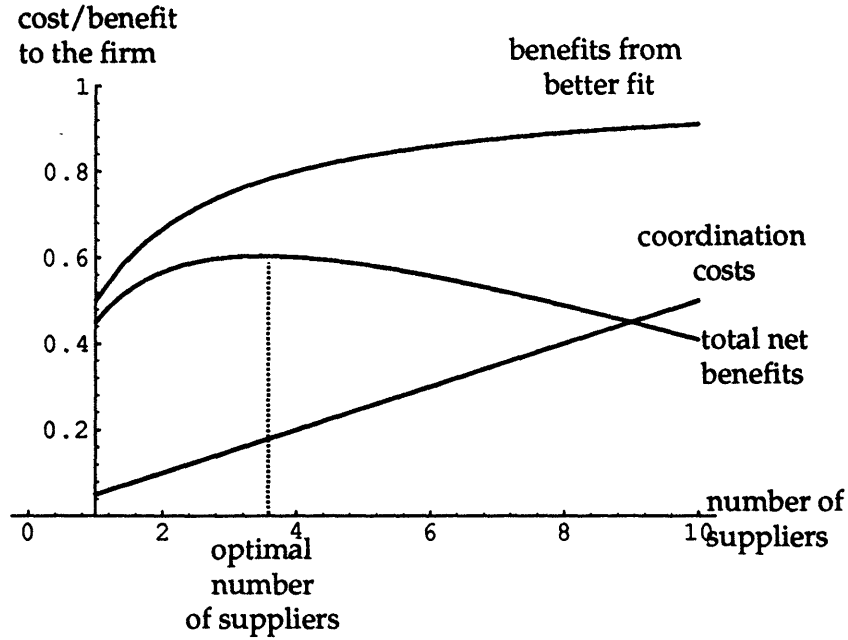


Figure 1: Balancing coordination costs and fit

Figure 1 illustrates the tradeoff between coordination cost and fit as a profit maximization problem, under the assumption that the  $\varepsilon_i$  are independently distributed uniformly in the interval  $[0,1]$ , so that  $E\left[\max_{i \in \{1,2,\dots,n\}} \varepsilon_i\right] = 1 - \frac{1}{n+1}$ , and coordination costs are  $\kappa=0.05$ .

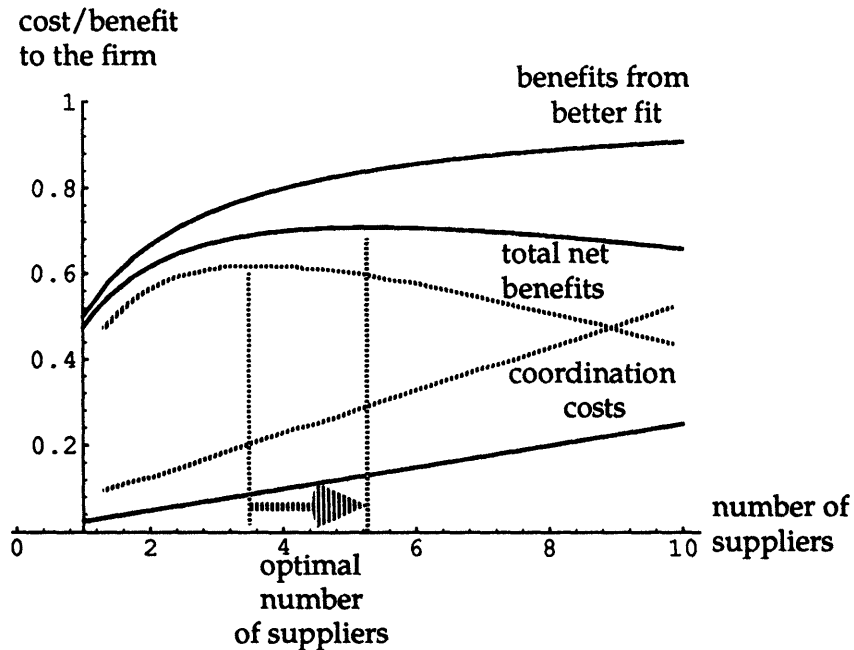


Figure 2: The impact of lower coordination costs

As mentioned earlier, it is widely believed that information technology lowers the costs of inter-firm coordination (Malone *et al.* 1989). Thus, according to these arguments, information technology is likely to favor an increase in the number of suppliers. Figure 2 illustrates this effect in the context of our simplified model by reducing coordination costs from  $\kappa=0.05$  to  $\kappa=0.025$ . Formally, we have:

$$\frac{d}{dn} \left( E \left[ \max_{i \in \{1, 2, \dots, n\}} \varepsilon_i \right] \right) = \kappa, \quad (1)$$

Which becomes:

$$\frac{d}{dn} \left( E \left[ \prod_{i=1}^n F_{\varepsilon_i} \right] \right) = \kappa$$

where  $F_{\varepsilon_i}$  is the arbitrary cumulative distribution for each of the  $\varepsilon_i$ . Since  $F_{\varepsilon_i} < 1$ , we know that the left hand side of (1) is decreasing in  $n$ . Therefore, lower search costs,  $\kappa$ , will be associated with a larger number of suppliers,  $n$ . Figure 3 shows a plot of contour curves for buyer surplus. The darker shading of the lower contours indicates the increase in buyer surplus, and it can be seen how the optimal number of suppliers increases as search costs decline.

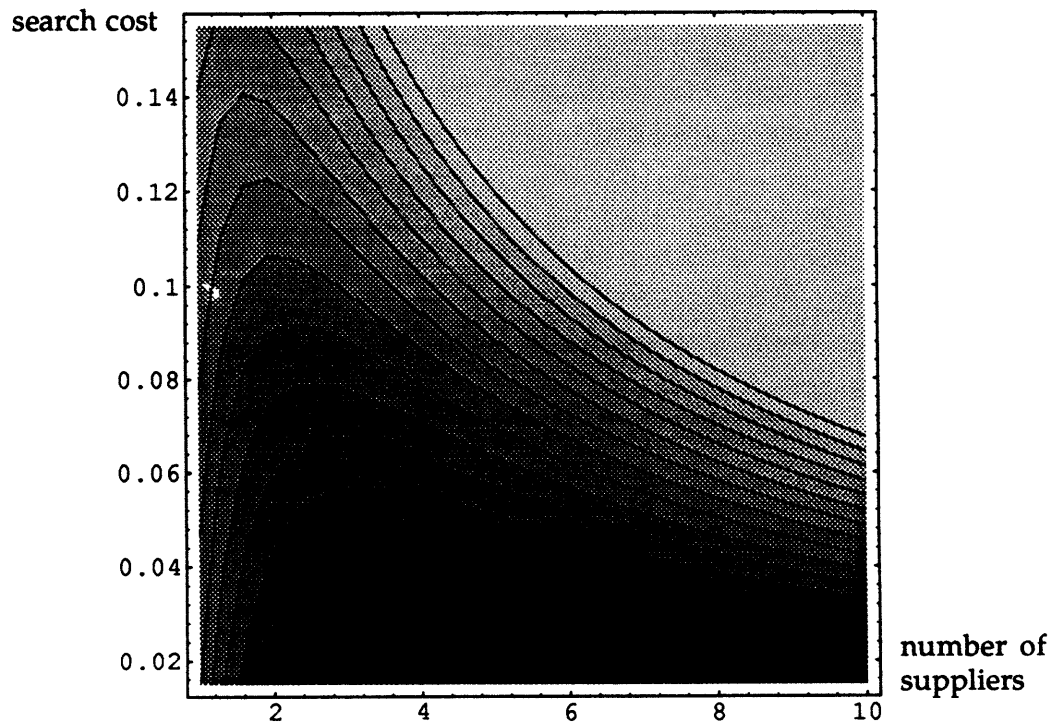


Figure 3: A contour diagram for different coordination costs

### **3. Incomplete contracting and the optimal number of suppliers**

As shown in model 1, *ceteris paribus*, optimizing buyers will never reduce the number of suppliers when coordination costs decrease. This leads us to consider other factors. In particular, we draw on the incomplete contracting literature to model the relationship between a firm and its suppliers focusing on incentive considerations, thereby capturing the incentive effects discussed in section 1.3. As shown below, increasing the number of suppliers will reduce substantially the portion of the marginal returns on investment appropriated by each supplier. This will limit the suppliers' incentive to invest, and if supplier investment is critical, it can result in an outcome that is sub-optimal. The remainder of this section formalizes this argument.

#### **3.1. The incomplete contracts approach**

Williamson (Williamson 1975, Williamson 1985) has argued that complete contracts (in the sense that they never need to be renegotiated or revised) are costly or even infeasible. Grossman and Hart (1986), and Hart and Moore (1990) sharpen Williamson's argument by pointing out that certain variables may not be verifiable by a third party, such as a court or an arbitrator, even though they can be observed by the parties involved in the relationship. In judging the quality of a good delivered, for example, both the firm and the supplier may be able to observe whether the quality is high or low and estimate the resulting value created, but this may not be possible to show that to the satisfaction of a court. Parties cannot enter into a contract based on the outcome of such variables, but instead must divide any resulting value through *ex post* bargaining.<sup>5</sup>

Thus the *ex post* bargaining power of each party will be taken into account before they make investments that create value but are not contractible. Changes in the structure of the relationship that affect each party's bargaining power will therefore have effects on equilibrium output. Based on this principle, we can analyze how changes in the number of suppliers affect their bargaining power, and therefore their incentives to invest in the relationship and ultimately economic output.

#### **3.2. An incomplete contracting model for the optimal number of suppliers**

We now develop a model which considers how the number of suppliers affects the incentives of the buyer firm and its suppliers to invest in their relationship. To this

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<sup>5</sup> Furthermore, in the absence of complete contracting, standard mechanism design arguments, such as those that invoke the revelation principle are infeasible and, as shown by Hart and Moore (Hart and Moore 1990), optimal investment levels generally cannot be sustained.

end, we assume that the buyer firm and its suppliers must invest in some activity which affects the value realized, but is not feasible to describe in a comprehensive contract. These investments produce an outcome which we label "quality", but which could be interpreted more broadly. For example, an interorganizational information system may promote "electronic integration" between the buyer and the suppliers, such as order-entry, just-in-time inventory management, or electronic exchange of product designs. The supplier and the buyers must make investments specific to this relationship, such as identifying and suggesting improvements in product design. These investments will have little value in alternative uses, while their benefits are likely to be observable by the parties involved, but not verifiable by an outside arbitrator or a court of law.

### *Model 2*

Consider a two-period setting with  $N+1$  risk neutral firms indexed by  $i = 0, 1, \dots, N$ , including a buyer firm ( $i = 0$ ) and  $N$  identical suppliers ( $i = 1, \dots, N$ ) connected via an interorganizational system. Before the first period, the buyer determines the number of suppliers  $n$  participating in the system, which are the only suppliers from which it can order goods. We assume that  $n$  cannot be changed until after the second period.<sup>6</sup> All  $N$  suppliers possess identical technology and in the first period, each firm  $i$  makes a private, non-verifiable investment  $x_i$  at cost  $c_0(x_0)$  for  $i=0$ , and  $c_s(x_i)$ , for  $1 \leq i \leq N$ , to which we refer as investments in "quality." In the second period, production takes place, the goods are delivered and payments are made. We assume that once the investments are made, the marginal cost of actually producing the product is zero. A set of firms  $S \subseteq \underline{S}$  can generate value  $v(S, \mathbf{x})$ , where  $\underline{S}$  is the set of firms  $\{0, 1, \dots, N\}$ , and  $\mathbf{x}$  is the vector of investments. The buyer (firm 0) requires access to *at least one* of the suppliers to create any value, while each supplier needs access to the buyer to create value. Suppliers face no capacity constraints and only the total surplus is observable;<sup>7</sup> thus, once investments have been made, there is no loss on expectation from excluding any single supplier, if an alternative supplier exists. In particular, in this case the value of a coalition is given by

$$v(S \setminus \{i\}, \mathbf{x}) = \begin{cases} 0 & \text{if } i = 0 \\ 0 & \text{if } S = \{0, i\} \\ v(S, \mathbf{x}) & \text{otherwise.} \end{cases}$$

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<sup>6</sup> The choice of a finite  $n$  will effectively commit the buyer not to expropriate the entire non-contractible surplus from its relationship with the suppliers.

<sup>7</sup> For example, investments in electronic integration by the firm and its suppliers increase the value generated by the firm and its supplier network, but increases in value cannot be traced to the individual investments responsible for them.

We also make the standard assumption of increasing marginal costs of investment and diminishing marginal returns to investment:

$$\frac{dc_i(x_i)}{dx_i} > 0, \frac{d^2c_i(x_i)}{dx_i^2} > 0, \frac{\partial v}{\partial x_i} > 0 \text{ and } \frac{\partial^2 v}{\partial x_i^2} < 0.$$

We assume that investments in quality and thus the value of the goods delivered are too complex to include in a contract, yet the total value produced is observable by all parties, so that bargaining in the second period takes place under symmetric information; in the terminology of Grossman and Hart, the total surplus generated is observable, but not verifiable (e.g., the buyer and the suppliers can observe quality, but they cannot write a contract contingent on the quality of the goods delivered). Since no contract can be written contingent on firm investments or the value generated by them, the total surplus generated in the second period will be apportioned according to the relative bargaining power of the parties involved.

There are a variety of bargaining models that could be applied to determine the outcome, for definiteness, we follow Hart and Moore (1990) in assuming that Nash bargaining takes place and that consequently each participant will receive a share of the payoffs proportionate to its Shapley value (Shapley 1953). In addition, we assume that all parties know this, and as a result this division of the surplus is mutually acceptable and is reached without any additional bargaining costs. In this setting, the firms' Shapley values are given by:

$$B_i(x) \equiv \sum_{S: i \in S} p(S) [v(S, x) - v(S \setminus \{i\}, x)] \quad (2.1)$$

where 
$$p(S) \equiv \frac{(s-1)!(I-s)!}{I!}$$

$s \equiv$  the number of agents in a given subset  $S$ ,

$I \equiv$  the total number of agents, and

$x = (x_0, x_1, \dots, x_n)$  is the vector of individual investments.

Division of surplus according to the Shapley values amounts to paying each firm an amount equal to its contribution to the value of each potential coalition, multiplied by the probability that that particular coalition will be observed.<sup>8</sup> Under this formulation, firms which are not easily replaced will have more bargaining power and thus will be

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<sup>8</sup> Although the Shapley value is traditionally used to analyze cooperative bargaining, (Gul 1989) provides a detailed non-cooperative bargaining justification for this assumption. It can be useful to think of the Shapley value as the result of generalized Nash bargaining. In any event, the exact rule for division of the surplus will generally have no qualitative effect on the results as long as each agent's share of output is positively correlated with his access to essential assets via coalitions with other parties.

able to garner a larger share of the surplus generated from transacting. In our setting, each of the  $n$  identical suppliers will have some bargaining power and will receive some payments, therefore it is natural to consider *each* of them to be delivering a share of the goods supplied.

We now solve for equilibrium investment and output. The *ex post* bargaining power of the parties will have a considerable effect on the *ex ante* incentives to invest in quality: each firm will invest until the marginal benefit it can expect to receive equals the marginal cost of investment. For example, in a bilateral setting with a single buyer and a single supplier, each firm will invest until the marginal benefit it can expect to receive, as given by its Shapley value, equals the marginal cost of investment, resulting in the following first order conditions for the buyer and supplier firms, where  $v^i(\cdot) \equiv \frac{\partial v(\cdot)}{\partial x_i}$  and

$$c'_i(x_i) = \frac{dc_i(x_i)}{dx_i}:$$

$$\text{Buyer Firm:} \quad \frac{1}{2} v^0(\{0,1\}, (x_0, x_1)) = c'_0(x_0) \quad (2.2a)$$

$$\text{Supplier Firm:} \quad \frac{1}{2} v^1(\{0,1\}, (x_0, x_1)) = c'_1(x_1) \quad (2.2b)$$

Because neither firm can capture 100% of the additional revenue resulting from its investments in quality, each will have a suboptimal incentive to invest. In particular, each firm will invest up to the point at which the marginal cost of investment is equal to just 1/2 of the marginal value created, since this is the proportion it will be able to appropriate under Nash bargaining. This is the familiar "hold-up" problem described by Klein, Crawford and Alchian (1978).

In general, the first order conditions of buyer and supplier firms are given by:

$$\text{Buyer Firm:} \quad \frac{n}{n+1} v^0(\underline{S}, \mathbf{x}) = c'_0(x_0) \quad (2.3a)$$

$$\text{Each Supplier:} \quad \frac{1}{n(n+1)} v^i(\underline{S}, \mathbf{x}) = c'_s(x_i) \quad (2.3b)$$

where  $1 \leq i \leq n$ . The optimal number of suppliers is determined by choosing  $n = n^*$  so that the resulting investments  $\mathbf{x}^*$  maximize the social surplus  $v(\underline{S}, \mathbf{x}^*) - c_0(x_0) - \sum_{k=1}^{n^*} c_s(x_k^*)$ .<sup>9</sup>

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<sup>9</sup>This is the value of  $n$  which maximizes net social surplus. An alternative approach would be to assume that the buyer chooses  $n$  to maximize its private surplus  $B_0(\mathbf{x}^*)v(\underline{S}, \mathbf{x}^*) - c_0(x_0)$ , as in (Bakos and Brynjolfsson 1992). If side payments are allowed, however, then the socially optimal number of  $n$  will also maximize the buyer's individual payoff, since the buyer firm will be compensated via *ex ante* side payments for choosing the socially optimal institutional arrangement.



It is apparent from equations (2.3a) and (2.3b) that as the number as the number of suppliers,  $n$ , increases, underinvestment becomes less severe for the buyer but becomes even worse for the suppliers. For instance, with 2 suppliers, the buyer will invest to the point at which the marginal cost of its investment is equal to 2/3rds of the marginal value created, while each supplier will invest to the point at which its marginal cost of investment is equal to 1/6th of the value created. Figure 4a shows this decline in investment incentives for the suppliers, and figure 4b shows the corresponding increase in buyer incentives, as the number of suppliers increases.

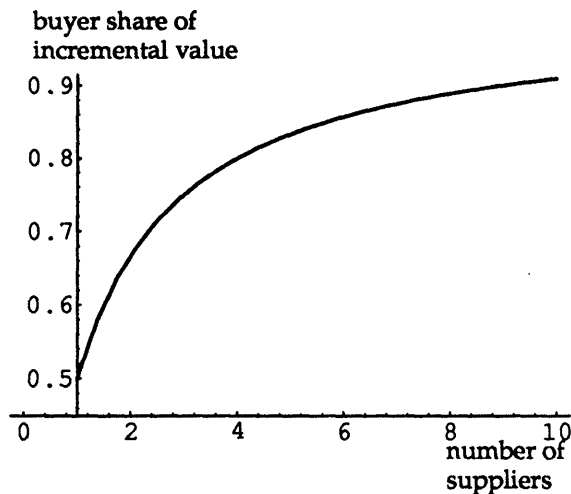


Figure 4a: Buyer incentives to invest

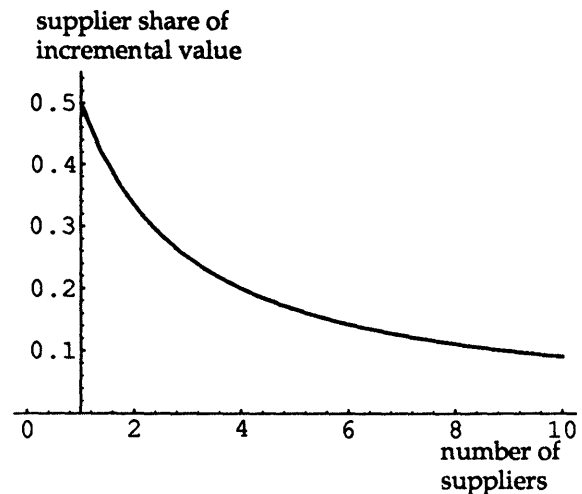


Figure 4b: Supplier incentives to invest

If the buyer's investment in quality is very important relative to the suppliers' investment in quality, then this trade-off may be worth making. For example, if suppliers' investment in quality has no impact on the total value created, the buyer should adopt the maximum feasible number of suppliers, in which case the buyer keeps almost all surplus, but no supplier will make any significant investment in quality. On the other hand, if the buyer wishes to induce significant investments in quality from its suppliers, then it must commit to only buying from a relatively small number of possible suppliers. Although the buyer will be able to keep a smaller fraction of the surplus generated, reducing the number of suppliers will induce each of them to invest in quality, and thus will increase the total surplus to be divided. In other words, as the suppliers' *non-contractible* actions become more important, the optimal number of suppliers decreases. Conversely, as the buyer's non-contractible actions become more important, the optimal number of suppliers increases.

### 3.3. Parametric example

To illustrate the analysis of this section, we can show how production incentives are affected by the number of suppliers, assuming a production function

$$v(\underline{S}, \mathbf{x}) = Ax_0^\alpha + (1-A) \sum_{i=1}^n x_i^\beta, \text{ with declining marginal returns of investment } (0 \leq \alpha, \beta \leq 1).$$

The parameter  $A$  characterizes the relative importance of buyer quality: for example, as  $A$  decreases, buyer quality becomes relatively less important than supplier quality.

Assuming quadratic investment costs  $c_0(x_0) = \frac{1}{2}x_0^2$  and  $c_s(x_i) = \frac{1}{2}x_i^2$ , the marginal return on buyer investment is  $v^0(\underline{S}, \mathbf{x}) = A\alpha x_0^{\alpha-1}$  and the marginal cost is  $c'_0(x_0) = x_0$ . Thus the equilibrium buyer investment  $x_0^*$  satisfies the first order condition:

$$x_0^* = B_0(n)A\alpha(x_0^*)^{\alpha-1} = \frac{n}{n+1}A\alpha(x_0^*)^{\alpha-1} \quad (2.4a)$$

Similarly, the marginal return on supplier  $i$ 's investment is  $v^i(\underline{S}, \mathbf{x}) = (1-A)\beta x_i^{\beta-1}$  and the marginal cost is  $c'_s(x_i) = x_i$ , giving us the corresponding first order condition for the equilibrium supplier investment  $x_i^*$ :

$$x_i^* = B_i(n)(1-A)\beta(x_i^*)^{\beta-1} = \frac{1}{n(n+1)}(1-A)\beta(x_i^*)^{\beta-1} \quad (2.4b)$$

Solving (2.4a) and (2.4b) we get  $x_0^* = \left(\frac{\alpha An}{n+1}\right)^{\frac{1}{2-\alpha}}$  and  $x_i^* = \left(\frac{\beta(1-A)}{n(n+1)}\right)^{\frac{1}{2-\beta}}$ .

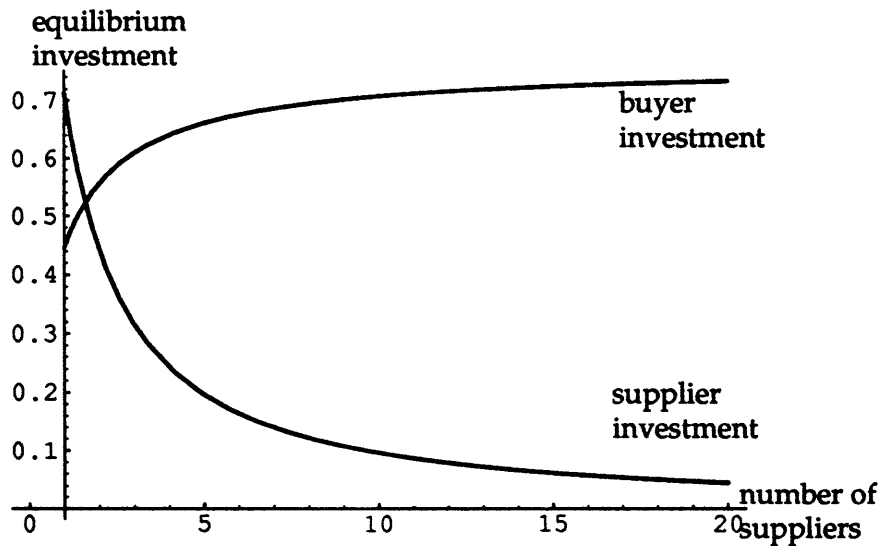


Figure 5

Figure 5 shows that buyer investment increases and supplier investment decreases as the number of suppliers increases.

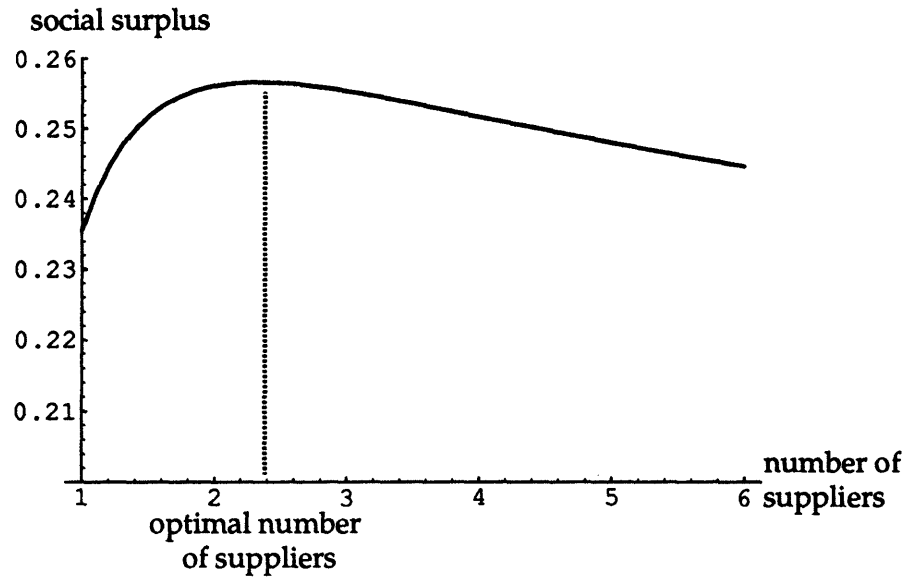


Figure 6

The resulting net social surplus is  $v(\underline{S}, x) - c_b(x_0) - \sum_{i=1}^n c_s(x_i)$ . Figure 6 plots the social surplus generated by the buyer and supplier investments in figure 5, and shows how decreasing the number of suppliers can lead to a more efficient equilibrium, increasing the total social surplus created.<sup>10</sup>

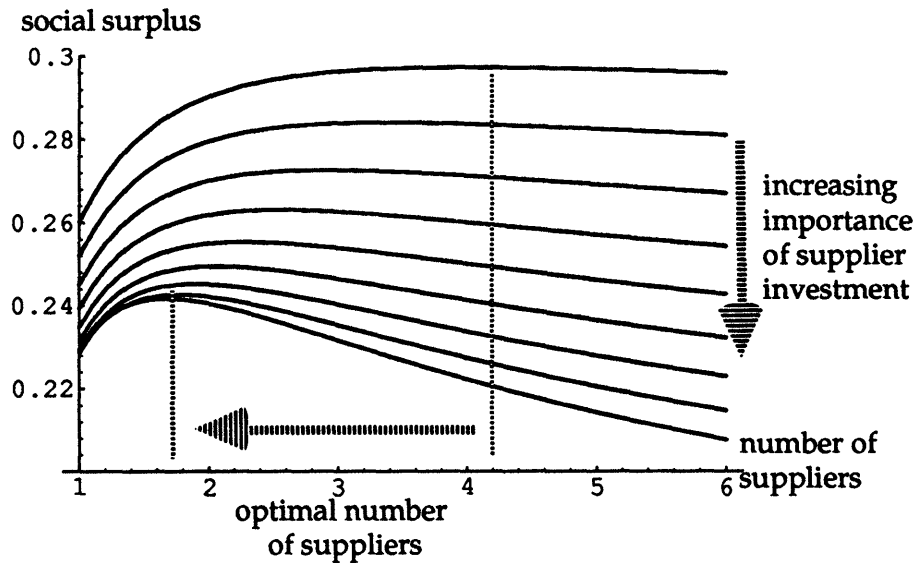


Figure 7

<sup>10</sup>Figures 5, 6 and 7 were derived with  $\alpha=\beta=0.9$  and  $A=0.6$  in Figures 5 and 6 and ranging from 0.475 to 0.715 in Figure 7.

Figure 7 shows how an increase in the importance of supplier incentives (achieved parametrically by decreasing  $A$ ) can lead to a reduction in the optimal number of suppliers.

## 4. Combining incentive considerations with neoclassical considerations

In this section we develop an integrated model which combines incentive considerations with neoclassical considerations to derive the optimum number of suppliers. The setting is similar to Model 2, except that, like Model 1, we incorporate a fixed coordination cost associated with each potential supplier, and we assume that supplier product offerings are heterogeneous in some *contractible* characteristic, thus providing the buyer firm with the incentive to search the supplier market for the product with the best "fit."

### 4.1. The model

#### *Model 3*

Consider a two-period setting with  $N + 1$  risk neutral firms indexed by  $i = 0, 1, \dots, N$ , including a buyer firm ( $i = 0$ ) and  $N$  identical suppliers ( $i = 1, \dots, N$ ). The buyer firm faces an irreversible setup cost  $\kappa$  for each supplier it does business with, which can be thought of as a coordination cost. Before the first period, the buyer selects  $n$  suppliers to do business with. The supplier offerings consist of two parts: a contractible feature ("fit") and a non-contractible feature ("quality").

In the first period, each firm  $i$  makes a private, non-verifiable investment  $x_i$  at cost  $c_0(x_0)$  for  $i=0$ , and  $c_s(x_i)$ , for  $1 \leq i \leq N$ , to which we refer as investments in "quality." All suppliers possess identical technology *ex ante* and there are no binding capacity constraints, so the buyer can make a credible threat to shift the order to any other supplier. As in model 2, the total non-contractible value created is a function of all parties' investments:  $v = v(\underline{x}, \mathbf{x})$ . Once again, we assume increasing marginal costs and diminishing marginal returns to investment, i.e., that  $\frac{dc_i(x_i)}{dx_i} > 0$ ,  $\frac{d^2c_i(x_i)}{dx_i^2} > 0$ ,  $\frac{\partial v}{\partial x_i} > 0$  and  $\frac{\partial^2 v}{\partial x_i^2} < 0$ , which guarantee the existence and uniqueness of an equilibrium with symmetric supplier investments.

In addition to their contributions to quality, supplier offerings differ in "fit." Without loss of generality, fit is assumed to be one dimensional and provide to the buyer utility  $\epsilon$ , distributed in the interval  $[0, \epsilon_{\max}]$  according to a known density function  $f_\epsilon$ . Supplier  $\epsilon$ 's

can be discovered only after a relationship has been established between the buyer firm and the particular supplier, and are *ex post* observable by the buyer firm and all  $n$  suppliers.

In the second period, the non-contractible value,  $v(\underline{S}, \mathbf{x})$ , is realized, the buyer licenses the contractible feature from the most desirable supplier ( $\max \varepsilon$ ) thereby generating total value  $\mu(\underline{S}, \mathbf{x}) = v(\underline{S}, \mathbf{x}) + \max \varepsilon$ , production takes place, the goods are delivered, and payments are made. As in Model 2, each of the  $n$  suppliers provides some portion of total output and gets a share of the surplus based on its bargaining power. Investments are specific to this setting, and the buyer must gain access to at least one supplier (e.g., by purchasing from that supplier) in order to create value. Similar to Model 2, the value of

a coalition  $S$  is given by

$$\mu(S \setminus \{i\}, \mathbf{x}) = \begin{cases} 0 & \text{if } i = 0 \\ 0 & \text{if } S = \{0, i\} \\ \mu(S, \mathbf{x}) + \max_{i \in S \setminus \{0, i\}} \varepsilon_i - \max_{i \in S \setminus \{0\}} \varepsilon_i & \text{otherwise.} \end{cases}$$

Excluding supplier  $i$  from a coalition would reduce total value if, and only if,  $\varepsilon_i$  is larger than the  $\varepsilon$ 's of all other suppliers in the coalition, when the ability to licence  $\varepsilon_i$  is lost to the rest of the coalition. Supplier  $i$  will not reduce the non-contractible portion of a coalition's value as long as there is at least one other supplier in the coalition. On the other hand, if the buyer were to leave a coalition, it would incrementally reduce the value created by the coalition by its entire amount, to zero.

Since no contract can be written contingent on firm investments or the value generated by them, the total surplus generated in the second period will be apportioned according to the relative bargaining power of the parties involved; as before, we assume that this bargaining satisfies the Nash requirements, is costless, and leads to a division of the surplus according to Shapley values.

The Shapley values are given by equation (1), adding the random fit variable  $\varepsilon$

$$B_i(\mathbf{x}) \equiv \sum_{S: i \in S} p(S) [\mu(S, \mathbf{x}) - \mu(S \setminus \{i\}, \mathbf{x})] \quad (3.1)$$

where

$$p(S) \equiv \frac{(s-1)!(I-s)!}{I!}$$

$$\mu(S, \mathbf{x}) = \begin{cases} v(\mathbf{x}) + \max_{i \in S} \varepsilon_i & \text{if } \{0\} \subset S \\ 0 & \text{otherwise} \end{cases}$$

$s \equiv$  the number of agents in a given subset  $S$ ,

$I \equiv$  the total number of agents, and

$\mathbf{x} = (x_0, x_1, \dots, x_n)$  is the vector of individual investments.

We now examine what happens to the quality investments as the number of suppliers changes. While the suppliers are *ex ante* identical, this symmetry is violated in the second period bargaining because of the differences in their products. The result is that if there are multiple suppliers, although all supplier quality investments  $x_i$  ( $i \geq 1$ ) are symmetric, suppliers with favorable product characteristics (large  $\varepsilon$ ) are able to appropriate proportionally more value than the ones with undesirable product characteristics (small  $\varepsilon$ ), since by leaving a coalition they create a bigger reduction in value.

The share of output that each party can expect to receive will determine their incentives to invest. This is reflected in the first order conditions. For the buyer firm, equilibrium investment satisfies:<sup>11</sup>

$$\text{Buyer Firm: } \frac{n}{n+1} v^0(x) + \sum_{k=1}^n \frac{1}{k(k+1)} E[F_{Y_k}(\varepsilon)] = c'_0(x_0) \quad (3.2a)$$

where  $F_{Y_k}(\varepsilon)$  is the distribution function for the  $k$ -th order statistic for random variable  $\varepsilon$ . Because of symmetry, the first order conditions for the suppliers are:

$$\text{Each Supplier: } \frac{1}{n(n+1)} v^i(x) + \frac{1}{n} \left( E[F_{Y_1}(\varepsilon)] - \sum_{k=1}^n \frac{1}{k(k+1)} E[F_{Y_k}(\varepsilon)] \right) = c'_1(x_1) \quad (3.2b)$$

The optimal number of suppliers  $n$  will maximize total surplus, taking into account the connection and coordination costs  $\kappa(n)$  and the benefits from improved fit as the number of suppliers increases, as well as the impact on buyer incentives and seller incentives. More formally,  $n$  will maximize

$$v(x^*) - c(x^*) - \kappa(n) + \max_{i \in \{1, 2, \dots, n\}} \varepsilon_i,$$

where  $x^*$  is given by the first order conditions (3.2a) and (3.3b).

As in model 2, if the buyer wishes to induce significant non-contractible investment from its suppliers, it must commit to only buying from a relatively small number of possible suppliers. From equations (3.2a) and (3.3b), *ceteris paribus*, if the suppliers' non-contractible actions become more important, then the optimal number of suppliers decreases. Conversely, if the buyers non-contractible actions become more important, the optimal number of suppliers increases. The basic effects of fit (improving as  $n$  increases) and coordination costs (increasing with  $n$ ), which were analyzed in model 1, also apply in model 3. The final equilibrium value of  $n$  will balance all of these forces

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<sup>11</sup> See Appendix for an illustrative example when  $n=3$ , and a general proof.

and will lie between the equilibrium of model 1 (which ignored incentives) and that of model 2 (which ignored coordination costs and fit).

#### 4.2. Parametric example

We illustrate the analysis of this section by extending the parametric example developed in section 3.3. We use the same production function  $v(x) = Ax_0^\alpha + (1-A)\sum_{i=1}^n x_i^\beta$  and quadratic investment costs  $\frac{1}{2}x_i^2$ , adding a uniformly distributed fit parameter and a constant coordination cost per supplier. The results of section 3.3 qualitatively persist, except that when coordination costs are high, large numbers of suppliers become less attractive. Figures 8 and 9 correspond to Figures 6 and 7 in section 3.3.<sup>12</sup>

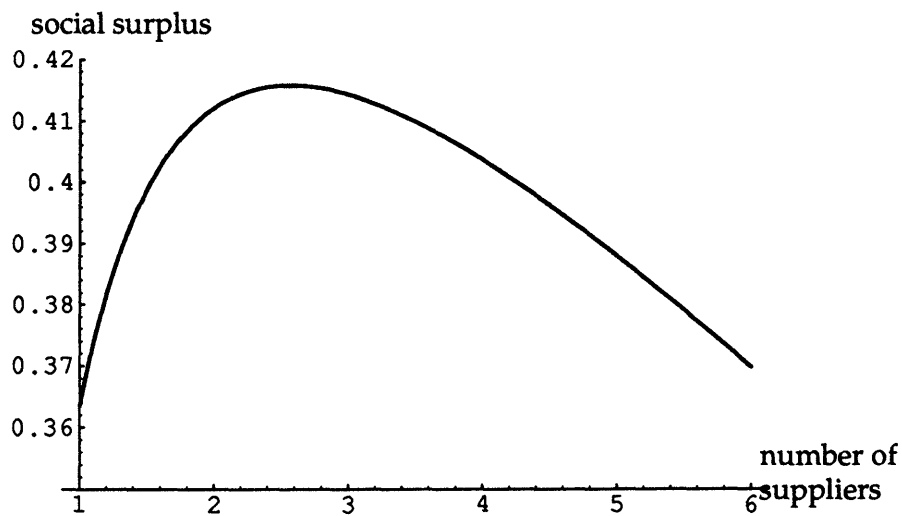


Figure 8: Combining incentives, fit and coordination costs

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<sup>12</sup>Figures 8 and 9 were derived with  $\alpha=\beta=0.9$ ,  $A=0.6$  in Figure 8 and ranging from 0.475 to 0.775 in Figure 9,  $\epsilon_{\max}=0.3$  and  $\kappa=0.02$ .

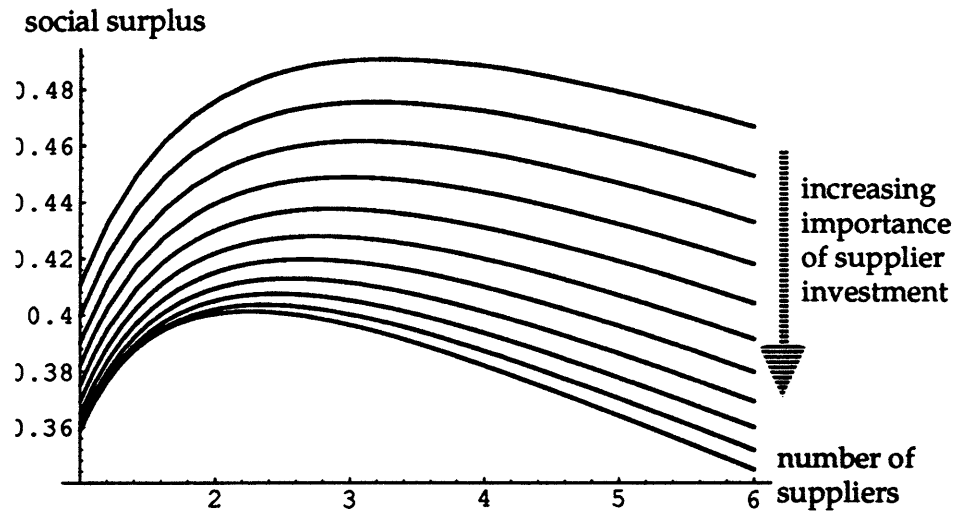


Figure 9: Increasing the importance of supplier incentives

## 5. Conclusion

The last decade has witnessed significant changes in both the technology and the organization of buyer-supplier relations, providing an opportunity to reexamine our theories. The persistence and even proliferation of small networks of suppliers as search and transaction costs have declined suggests that previous theories were incomplete. Drawing on evidence that the principle benefits of reducing the number of suppliers lie in the resulting incentives for quality rather than any reduction in coordination costs, we were able to develop a more comprehensive model.

### 5.1. Implications of the model

Our model leads to some interesting predictions. First, when incentives for supplier quality are important, we find that it may be optimal to work with only a small number of suppliers even if search and transaction costs become negligible. In other words, although technological advances that reduce coordination costs will generally increase efficiency, when they also increase the importance of supplier quality, they do not necessarily lead to an increase in the number of suppliers used by a firm. Thus our model addresses the basic paradox posed in section 1.2.

Second, our model predicts that the number of suppliers will be inversely related to the importance of providing supplier incentives to invest in quality, in the broad sense of the term. This can explain the finding of Cusumano and Takeishi of a strong correlation between the number of suppliers and the importance of certain dimensions of the relationship (see table 1).



**Table 1: Reported differences in supplier management**

Dimension	U.S.	Japanese
1. Number of suppliers	Many	Fewer
2. Selection criteria	Price	Quality, price, etc.
3. Role in development	Smaller	Larger
4. Pricing practices	Competitive bids	Target Prices
5. Price changes	Upward	Downward
6. Defect rates	Higher	Lower
7. Quality improvement	Lower	Higher
8. Information exchanges	Lower	Higher
9. Suggestions to Suppliers	Few	Many

*Source: Cusumano & Takeishi (Cusumano and Takeishi 1991).*

In our interpretation, each of the dimensions 2 through 8 above is indicative of an important, non-contractible investment on the part of the supplier, and a correspondingly smaller reliance on explicit contracts to govern the relationship. According to our model, the role of quality and other factors in supplier selection, and the suppliers' continuing effort to improve these characteristics even after selection, go hand-in-hand with the reliance on fewer suppliers.

This sort of empirical correlation is not unique to Cusumano and Takeishi. The advantages of close buyer-supplier relations, such as quality, trust, innovation, information-sharing and responsiveness that are highlighted by other authors (Antonelli 1988, Helper 1991a, Helper 1991b, Johnston and Lawrence 1988, McMillan 1990, Piore 1989), are also exactly those dimensions which are most difficult to contract for explicitly. In particular, our model provides a way of formalizing and explaining the contrasting observations that

General Motors Corp.'s suppliers enjoy less security [than the Japanese] and hence have less reason to invest in the relationship (Blinder 1991)

and that

[S]ince an implicit/explicit arrangement of profit sharing is the normal practice in [the Japanese supplier] relationship, under investment in transaction-specific assets may be avoided to both parties' mutual advantage (Aoki 1986).

The effectiveness of the strategy of reducing the number of suppliers to improve incentives for quality is supported by the experiences of companies like Xerox, which has reduced its supplier base from 5000 to about 500, and has seen its reject rates on parts go down by a factor of 13 (Emshwiller 1991).

It is worth noting, however, that our model predicts that reducing the number of suppliers will not always be beneficial. If the importance of specific, non-contractible investments by suppliers is relatively low, then it is optimal to increase the number of suppliers searched until the marginal cost of search equals the expected marginal benefit from improved fit. For example, incentive considerations effectively can be ignored for easily specified products such as commodities. For these products, continued reductions in coordination costs should lead to an increase in the number of suppliers considered.

There is a second situation under which reducing the number of suppliers may be unwise. According to our model, reducing the number of suppliers will reduce the incentives of the *buyer* to invest in quality, because the buyer's bargaining power is weakened. Thus, when it is relatively more important for the buyer to make investments in quality, we should expect the buyer to keep his options open with a larger number of suppliers. The decisions by IBM and other computer manufacturers to second- and third-source some of their vital components, such as IC's, is consistent with a desire to prevent any one supplier from having too much bargaining power. In this way, they can hang on to more of the surplus resulting from their investments in quality and similar non-contractibles.

Finally, it should be noted that the number of suppliers that strikes the optimal balance between buyer and supplier incentives (as analyzed in model 2), in general will not happen to be the same as the number that strikes the optimal balance between coordination costs and fit (as analyzed in model 1). The number that balances all four forces (as analyzed in model 3) will be a weighted average of the previous two optima, and its value will depend on the relative importance of incentives vs. coordination costs. Thus if the importance of buyer and supplier incentives increases, the optimal number of suppliers employed will likely be reduced, *even if the importance of both buyer and supplier incentives increases proportionately*. For example, suppose the number of suppliers that provides the best net incentives for both the buyer and the suppliers to invest in quality is 2, and, because of low coordination costs, the optimum balance between fit and coordination costs is reached with 100 suppliers. The overall optimum will then require between 2 and 100 suppliers. If it becomes more important to provide incentives for quality, then the overall optimum will decrease so that it is closer to 2. This will happen even if the need for buyer incentives increases just as much as the need for supplier incentives.

## 5.2. Why has the number of suppliers generally declined?

We have seen that the general trend toward fewer suppliers can be explained by the increasing emphasis placed by American firms on supplier attributes such as quality, epitomized by the "Total Quality Management" theme popular in management circles. Furthermore, many of the other characteristics listed in Table 1 are getting increasing attention as well. It is possible to treat this new emphasis on quality as an exogenous trend, perhaps due simply to a belated realization that quality ultimately affects profits, or perhaps due to an increasingly fierce competitive environment. This trend is likely to counteract any increase in the number of suppliers caused by declining coordination costs.

Nevertheless, we are tempted to go further and suggest that underlying technological considerations play a role enabling the "move to the middle". Our model indicates that the mechanism behind this move is that IT combines reduced coordination costs with an increased need to emphasize quality in order to remain competitive. Although the impact of lowering coordination costs has been discussed elsewhere (Bakos 1987, Malone *et al.* 1988), there are a number of reasons why IT will also affect the importance of quality. For instance, just-in-time (JIT) inventory systems imply a very low tolerance for defects (O'Neal 1989). Milgrom and Roberts (1990) provide a formal model of "modern manufacturing" in which they demonstrate that an emphasis on "quality" is a necessary complement for the successful use of "technologically advanced equipment".

Furthermore, exploiting IT to rapidly respond to changing market conditions may preclude detailed contracts or work rules. For instance, Brynjolfsson (1990a, 1990b) has argued that information technology tends to automate the more routine tasks, which are typically those which are easiest to detail in a contract, leaving behind a residue of tasks that are neither automatable, nor contractible. He also suggests that cheap information can be a complement for knowledge-intensive tasks, and shows how this can lead to a decentralization of authority and incentives. Both of these effects would increase the need to rely on institutional mechanisms, such as reducing the number of suppliers, to provide appropriate supplier incentives.

More generally, we suggest that IT has contributed to the increased expectations for speed, flexibility and responsiveness throughout the economic environment. Any comprehensive contract between a buyer and a supplier would have to consider and provide for an increasing number of future scenarios. Thus it has become relatively more cost-effective for both parties to share the benefits of their relationship relying on trust and *ex post* bargaining. In such an environment, a good partner is one who does not adhere merely to the "letter of the contract," but one who does whatever reasonably needs to be done. This requires an increased reliance on the institutional incentives

available to deal with incomplete contracts, such as "partnering," leading to reduced numbers of suppliers and long-term relationships. In effect, IT has led to a situation where the technology of production has outrun our ability to write contracts that keep pace.<sup>13</sup>

In a related stream of thought, Huber (1990) has pointed out the distinction between knowledge-intensive and product-intensive relationships and activities. Knowledge-intensive activities are not as easily contractible, because of the difficulty of writing complete contracts that define them precisely in a way that allows legal description of the contingencies. As the widespread adoption of information technology increases the share of knowledge-related activities in the relationship between a firm and its suppliers, our analysis predicts that the significance of incomplete contracting considerations will increase.

Recent empirical evidence has highlighted the need to extend the theory of buyer-supplier relationships to account for the importance of incentive considerations. Ultimately, while technological developments are likely to continue to reduce the magnitude of coordination costs, the need to provide incentives for non-contractible investments is likely to remain an important factor in limiting the optimal number of suppliers.

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<sup>13</sup> Indeed, if the growing number of lawyers employed is any indication, we are far from automating the writing and enforcement of comprehensive contracts. Despite all the effort, gaps still remain in most contracts.

## Appendix

Pay-offs in Model 3 for the Buyer (B) and each Supplier (1, 2, and 3) for the case when  $n=3$  and  $\varepsilon_1 > \varepsilon_2 > \varepsilon_3$ .

Ordering	B	1	2	3
B123		$\varepsilon_1$		
B132		$\varepsilon_1$		
B213		$\varepsilon_1 - \varepsilon_2$	$\varepsilon_2$	
B231		$\varepsilon_1 - \varepsilon_2$	$\varepsilon_2$	
B312		$\varepsilon_1 - \varepsilon_3$		$\varepsilon_3$
B321		$\varepsilon_1 - \varepsilon_2$	$\varepsilon_2 - \varepsilon_3$	$\varepsilon_3$
1B23	$\varepsilon_1$			
1B32	$\varepsilon_1$			
12B3	$\varepsilon_1$			
123B	$\varepsilon_1$			
13B2	$\varepsilon_1$			
132B	$\varepsilon_1$			
2B13	$\varepsilon_2$	$\varepsilon_1 - \varepsilon_2$		
2B31	$\varepsilon_2$	$\varepsilon_1 - \varepsilon_2$		
21B3	$\varepsilon_1$			
213B	$\varepsilon_1$			
23B1	$\varepsilon_2$	$\varepsilon_1 - \varepsilon_2$		
231B	$\varepsilon_1$			
3B12	$\varepsilon_3$	$\varepsilon_1 - \varepsilon_3$		
3B21	$\varepsilon_3$	$\varepsilon_1 - \varepsilon_2$	$\varepsilon_2 - \varepsilon_3$	
31B2	$\varepsilon_1$			
312B	$\varepsilon_1$			
32B1	$\varepsilon_2$	$\varepsilon_1 - \varepsilon_2$		
321B	$\varepsilon_1$			
Share of total payoff:	$\frac{1}{24}(12\varepsilon_1 + 4\varepsilon_2 + 2\varepsilon_3)$	$\frac{1}{24}(12\varepsilon_1 - 8\varepsilon_2 - 2\varepsilon_3)$	$\frac{1}{24}(4\varepsilon_2 - 2\varepsilon_3)$	$\frac{1}{24}(2\varepsilon_3)$

Each of the 24 ways (orderings) possible in forming the grand coalition is considered, and the pay-offs are calculated on the assumption that the each party gets its incremental contribution to the coalition. Blanks denote zero payoffs. For example, in the first

ordering, B123, the payoff to the buyer B is zero, since B adds no value to the coalition  $\{B\} \setminus \{B\} = \emptyset$ . Formally,  $\mu(\{B\}, x) - \mu(\{B\} \setminus \{B\}, x) = 0$ . The payoff to supplier 1 is its incremental contribution  $\varepsilon_1$ , since the coalition  $\{B, 1\}$  creates value  $\varepsilon_1$ . The pay-off to supplier 2 is zero since the value of coalition  $\{B, 1, 2\}$  is no greater than the value of coalition  $\{B, 1\}$ . Similarly, the payoff to supplier 3 is zero since the value of coalition  $\{B, 1, 2, 3\}$  is no greater than the value of coalition  $\{B, 1, 2\}$ . The payoffs in each of the other possible orderings are similarly calculated. Each party's Shapley value is then computed by summing the individual payoffs, with equal weight for each possible ordering, and thus deriving the final set of payoffs. Since each supplier is equally likely *ex ante* to realize any given value of  $\varepsilon$ , the risk neutral suppliers make their investment decisions based on the average of the three possible supplier payoffs. The resulting first order conditions for arbitrary  $n$  are given by equations 3.2a (for the buyer) and 3.2b (for the  $n$  suppliers). An inductive proof for the buyer's share in equation 3a is given below, while the suppliers' shares in equation 3b follow from the *ex ante* symmetry.

### *Proof*

Assume, without loss of generality, that suppliers are ordered by  $\varepsilon_k$ , i.e.,  $\varepsilon_1 > \varepsilon_2 > \dots > \varepsilon_n$ . If there is only one supplier, then the buyer retains its Shapley payoff of one half of  $\varepsilon_1$  as its share of the "fit" surplus, i.e. the buyer's share is given by  $\sum_{k=1}^n \frac{1}{k(k+1)}$  when  $n=1$ .

Assume the formula is true for all  $n \leq j$ . If  $n=j+1$ , then for each of the  $(j+1)!$  orderings of the  $j+1$  firms  $0, 1, \dots, j$ , there are  $j+2$  corresponding orderings of the firms  $0, 1, \dots, j+1$ , each derived by adding firm  $j+1$ . Since  $\varepsilon_{j+1}$  is the smallest  $\varepsilon_i$ , the buyer's payoffs in the new orderings change only when the buyer received nothing (by being first) in the original ordering. There are  $j!$  orderings of firms  $0, 1, \dots, j$  in which the buyer (firm 0) is first, and for each of these there is one of the corresponding  $j+2$  orderings of firms  $0, 1, \dots, j+1$  in which supplier  $j+1$  comes before firm 0; in that case the buyer receives  $\varepsilon_{j+1}$  as its payoff. Thus the buyer receives  $\varepsilon_{j+1}$  in  $j!$  out of the  $(j+2)!$  possible orderings of firms  $0, 1, \dots, j+1$ , for a ratio of  $1/j(j+2)$ . Hence the buyer's share is still given by  $\sum_{k=1}^n \frac{1}{k(k+1)}$  when  $n=j+1$ , and by induction the formula is true for all  $n$ .

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