Vertical Integration and Technology: Theory and Evidence*

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Abstract

This paper investigates the determinants of vertical integration using data from the UK manufacturing sector. We find that the relationship between a downstream (producer) industry and an upstream (supplier) industry is more likely to be vertically integrated when the producing industry is more technology intensive and the supplying industry is less technology intensive. Moreover, both of these effects are stronger when the supplying industry accounts for a large fraction of the producer's costs. These results are generally robust and hold with a variety of alternative measures of technology intensity, with alternative estimation strategies, and with or without controlling for a number of firm and industry-level characteristics. They are consistent with the incomplete contract theories of the firm that emphasize both the potential costs and benefits of vertical integration in terms of investment incentives.

JEL: L22, L23, L24, L60.

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1. Introduction

Many experts believe that recent technological developments and globalization are transforming the internal organization of the firm. First, it is argued, new technologies, especially information technology, are creating a shift from the old integrated firms towards more delayered organizations and outsourcing.[1] Second, globalization often creates a tendency to transfer certain labor-intensive parts of the production process to countries with lower wages.[2] Third, it is often maintained that the greater competitive pressures created by both globalization and advances in information technology favor smaller firms and more flexible organizations that are more conducive to innovation.[3] Summarizing many of these views, the Business Week wrote: "Globalization and the arrival of the information economy have rapidly demolished all the old precepts. The management of global companies, which must innovate simultaneously and speed information through horizontal globe-spanning networks, has become a daunting challenge. Old, rigid hierarchies are out ....".[4]

Despite the importance of these issues in public debate and a large literature on vertical integration,[5] the economics profession is still far from a consensus on the empirical determinants of vertical integration in general and about the relationship between technological change and vertical integration in particular. This paper provides detailed empirical evidence on the determinants of vertical integration and confronts a number of theoretical predictions with data.

The two leading theories of vertical integration are the "Transaction Cost Economics" (TCE) approach of Williamson (1975, 1985) and the "Property Right Theory" (PRT) approach of Grossman and Hart (1986) and Hart and Moore (1990).[6] Both approaches emphasize the importance of incomplete contracts and ex post opportunistic behavior (hold up) on ex ante relationship-specific investments. The TCE approach views ver-

[1] Breshanan et al. (1999) find that IT use is associated with more decentralized decision-making within firms. Helper (1991) document the increase in outsourcing in the U.S. automobile industry.

[2] See, for instance, Feenstra and Hanson (1996), Feenstra (1998), Grossman and Helpman (2003), and Antras (2003).

[3] See, for instance, Milgrom and Roberts (1990), Athey and Schmutzler (1995) and Marin and Verdier (2002, 2003).

[4] Business Week "The 21st Century Corporation", cover story August 21-28, 2000.

[5] We discuss the empirical literature below. On the theory side, see, among others, Klein, Crawford and Alchian (1978), Williamson (1975, 1985), Grossman and Hart (1986), Hart and Moore (1990), Bolton and Whinston (1992), Aghion and Tirole (1994a,b and 1997) and Legros and Newman (2003), and the survey in Holmstrom and Tirole (1989). See also the models of vertical integration in the context of industry or trade equilibria, such as McLaren (2000), Grossman and Helpman (2002, 2003) and Antras (2003).

[6] See Whinston (2001) and Joskow (2003) for recent discussions.

tical integration as a way of circumventing the potential holdup problems, and thus predicts that vertical integration should be more common when there is greater specificity, increasing the costs of holdup. The PRT approach, on the other hand, focuses on the role of ownership of assets as a way of allocating residual rights of control, and emphasizes both the costs and the benefits of vertical integration in terms of ex ante investment incentives. To illustrate the central insight of the PRT, consider a relationship between a supplier (upstream firm) and a (downstream) producer. Also suppose that only two organizational forms are possible: (backward) vertical integration, where the downstream producer buys up the upstream supplier and has residual rights of control, and non-integration (outsourcing), where the producer and supplier are separate firms. Vertical integration in this world does not automatically improve efficiency. Instead, by allocating the residual rights of control to the producer, who has ownership and thus control of the assets if there is a breakup of the relationship, vertical integration increases the bargaining power of the producer, and encourages its investment. However, by the same mechanism, it also reduces the ex post bargaining power and the investment incentives of the supplier. Non-integration, on the other hand, gives greater investment incentives to the supplier. Consequently, vertical integration has both costs and benefits in terms of ex ante investments, and its net benefits depend on whether the producer's or the supplier's investments are more important for the output and success of the joint venture.

While the key predictions of the TCE approach could be tested by investigating relationship between measures of specificity and vertical integration, as also emphasized by Whinston (2001), the PRT approach is much harder to test because it makes no predictions between the overall level of specificity and vertical integration.

In this paper, we develop a simple methodology to study the forces emphasized by the PRT approach. First, we shift the focus from relationship-specific investments to technology intensity. The presumption is that parties making investments of any kind, especially in technology, are subject to holdup, and this will lead to the type of problems highlighted by the TCE and PRT approaches.[7] Second, we look at the relationship between pairs of suppliers and producers, and focus on the prediction that vertical integration should affect the investment incentives of suppliers and producers in

[7] This could be for a variety of reasons. First, associated with any technological investment, parties also make specific investments. Second, market imperfections, for example search frictions, typically turn technologically general investments into specific investments (e.g., Acemoglu, 1996, Acemoglu and Pischke, 1999). Third, many of these investments might loosely be refered to as "entrepreneurship", which is generally subject to holdup.

opposite directions.

We first develop these points using a simple theoretical framework and derive a number of predictions that are testable with the data we have available. The framework highlights that backward vertical integration gives greater investment incentives to the producer, while forward vertical integration encourages supplier investment. Non-integration provides intermediate incentives to both parties. Consequently, we show that:

1. The importance of technology intensity by the producer and supplier have opposite effects on the likelihood of vertical integration.

2. Vertical integration is more responsive to technology intensities of both the supplier and the producer when the supplier accounts for a larger fraction of the input costs of the producer.

3. If the relevant margin is backward integration, vertical integration is less likely when the supplier is more technology intensive, and more likely when the producer is more technology intensive. The opposite results apply when the relevant margin is forward integration.

4. Backward integration is more likely (and forward integration less likely) when the supplier accounts for a larger fraction of the input costs of the producer, because, in this case, there is greater scope for holdup by the supplier, and backward integration protects the producer against this holdup.

We investigate these predictions and other determinants of vertical integration using a detailed microdata set on all British manufacturing plants, the UK Census of Production (ARD) between 1992 and 2001. In order to identify the effects of both supplier and producer technology we look across all manufacturing industries. Using this dataset and the UK Input-Output table, we calculate two measures of vertical integration, defined at the level of firm-industry-pair (more precisely, for firm i producing product j with input from industry k). The first measure is a dummy variable indicating whether the firm owns a plant producing input k necessary for product j. The second measure calculates how much of the inputs from industry k, necessary for the production of j, the firm can produce in-house. Clearly, these measures do not distinguish between backward or forward integration, since we do not observe who has residual rights of control.

We proxy technology intensity with a number of different measures: R&D to value added ratio, investment to value added ratio, the rate of labor productivity growth and the rate of total factor productivity growth. All of these variables are defined at the industry level and are calculated over a sample predating our vertical integration measures (between 1992 and 1995, while the vertical integration measures refer to 1996-2001).

We find that:

- Consistent with prediction 1 above, technology intensities of the producing (downstream) and supplying (upstream) industries have opposite-signed effects on the likelihood of vertical integration.

- Consistent with prediction 2 above, the effect of the technology intensities of both the producing and supplying industries are substantially larger when the share of costs of the supplying industry in the total costs of the producing industry (for short, "share of costs") is high.

- In addition, the effect of the technology intensity of the producing industry on vertical integration is positive and that of the supplying industry is negative. Prediction 3 above suggests that, provided that our approach is a good approximation to reality, the marginal form of vertical integration in the data is likely to be backward integration.

- Greater share of costs is also associated with more vertical integration, which, combined with prediction 4, also suggests that the marginal form of vertical integration in the data is backward integration.

These results, especially the main effects, are generally robust, and hold with all four measures of technology intensity, with or without a variety of industry and firm-level controls, and with various different estimation strategies. Moreover, they are robust to the addition of fixed effects for producing or supplying industries, which enable us to investigate whether a given producing industry is more vertically integrated with suppliers that are more or less technology intensive (and vice versa). The only check that significantly weakens our results is the addition of a full set of firm fixed effects, which forces us to focus on firms that are in more than one industry, losing a large part of the variation in the data. In this case, the effect of the technology intensity of producing industry is no longer significant, though the effect of the technology intensity of the supplying industry and the interaction between the share of cost and both the producing and the supplying industries' R&D intensity remain robust.

It has to be emphasized at this point that what we uncover are correlations, not necessarily causal relations. In our regressions, a measure of vertical integration is on the left-hand side, and industry and firm characteristics are on the right. However, in theory, and most likely in practice, vertical integration also affects technology choices. Moreover, other factors omitted in the regression could influence both vertical integration and technology intensity. As an imperfect attempt to deal with these endogeneity problems, we also report results where the technology intensity of each industry is instrumented with the technology intensity of the same industry in the U.S.. This instrumentation strategy generally yields results similar to the ordinary least squares strategy.

Finally, we also briefly investigate the empirical relationship between competition and vertical integration, and find that the patterns in the data are broadly consistent with the simple theory we outline in the next section, and interestingly, not easily reconcilable with the popular claims that greater competition is leading to the demise of large vertically-integrated firms.

Although our empirical investigation is motivated by a specific theoretical approach, the PRT, the empirical patterns we document should be of more general interest and may be consistent with various alternative theories. Nevertheless, the current versions of the most popular alternative approaches seem to be unable to account for all the findings. For example, the emphasis of Williamson's TCE approach that vertical integration circumvents holdup problems would be consistent with the positive association between vertical integration and producer technology intensity, but not with the negative effect of supplier technology intensity. Theories based on supply assurance (e.g., Green (1986), or Bolton and Whinston (1992)) could also account for part of the results if more technology-intensive firms require more assurance. But these theories do not provide an explanation for why greater technology intensity of suppliers is associated with less vertical integration. Theories based on securing intellectual property rights (e.g., Aghion and Tirole (1994b)) could account for both main effects of producer and supplier technology intensity, for example because creating a vertically-integrated structure may provide better protection of intellectual property rights. Nevertheless, these theories would not explain why these effects become stronger when the share of costs is high.

In addition to the theoretical studies mentioned above, this paper is related to a large empirical literature on vertical integration. In contrast to our approach, most empirical studies of vertical integration are motivated by that TCE approach and focus on a single industry. These include Joskow's (1987) seminal paper on ownership arrangements in electricity generating plants, Stuckey's (1983) study of integration between aluminium refineries and bauxite mines, Monteverde and Teece's (1982) investigation of integration in the automobile industry, Masten's (1984) work on the aerospace industry, Ohanian's (1994) work on the pulp and paper industry, and Klein's (1998) work on Fisher Body and General Motors relationship. More recently, important papers by Baker and Hubbard (2000, 2002) study the trucking industry, Lerner and Merges (1998) look at the biotech sector, Woodruff (2002) studies integration in the Mexican footwear industry, and Chipty (2001) investigates vertical integration and market foreclosure in the cable television industry. The only cross-industry evidence relevant to our investigation that we are aware of comes from Caves and Bradburd (1988), who document a positive cross-industry correlation between measures of specificity and vertical integration, and from Antras (2003), who looks at the share of intra-firm imports over total imports for 23 U.S. industries and relates this to capital intensity. We are not aware of any other papers investigating the prediction that technology intensity of suppliers and producers should have opposite effects on vertical integration decisions.

The paper is organized as follows. Section 2 presents the theoretical framework and derives the main testable implications. Section 3 details the construction of our measure of vertical integration, and also discusses data sources and the construction of the other key variables. Section 4 presents the results and robustness checks. Section 5 concludes.

2. Theory and Empirical Predictions

The basic model is an extension of Grossman and Hart (1986), henceforth GH. We consider a one period relationship between a producer and a supplier, which are both risk-neutral. Both parties can undertake technological investments to increase the productivity of the relationship. We presume that these technology decisions have a specific component in that greater technology intensity leads to a greater possibility of holdup. Decision rights over these investments cannot be transferred between the two parties, for example, because the investments require tacit knowledge or human capital. This implies that the producer cannot make the supplier's investments or vice versa.

As is standard in this literature, we assume that the investments and the output of the relationship are non-verifiable. Consequently, neither contracts conditional on investments nor contracts specifying rules for ex post revenue-sharing are possible. However, before investments and production take place, the parties can choose an organizational form and transfers. We denote the amount of ex ante transfer to party i conditional on the organizational form z by $T_i(z)$, where P and S denote respectively the producer and the supplier. The organizational form can be either backward vertical integration (VIB), where the supplier is employed by the producer, or forward vertical integration (VIF), where the producer is employed by the supplier, or non-integration/outsourcing (NI), where the two parties remain independent.

The timing of events in this relationship are as follows:

1. The producer offers an organizational form (ownership structure) $z \in \{VIB, NI, VIF\}$ and associated transfers, $T_P(z)$ and $T_S(z)$, such that $T_P(z) + T_S(z) = 0$.[8] There are no credit constraints, so $T_i(z)$ can be negative.

2. The supplier decides whether or not to accept the offer. If the offer is not accepted, the game ends with payoffs $\{O_P^{NI}, O_S^{NI}\}$ defined below.[9] Otherwise, the producer and the supplier simultaneously choose their investments, e_P and e_S.

3. The supplier and the producer bargain over the division of the revenue, according to the Nash bargaining solution given the organizational form z.[10] Output is realized and shared.

The production technology of the relationship is:

$$F(x_S, e_P, e_S) = \phi x_S(pe_P + se_S + 1) + (1 - \phi)(pe_P + 1). \tag{2.1}$$

The first term in (2.1) is the output generated by the producer and the supplier conditional on the supplier providing a customized (relationship-specific) input, denoted $x_S = 1$. If $x_S = 0$ and this input is not supplied, these activities generate no revenue. The value of the relationship can be increased further by the producer's and the supplier's investments, e_P and e_S. The parameters p and s designate the relative importance of investments by the producer and the supplier, and $\phi \in (0, 1)$ corresponds to the share of the producer's inputs accounted for by the supplier.[11] Note that ϕ also determines

[8] The feature that the producer makes the organizational form offer is without loss of any generality.

[9] The assumption that the parties receive their non-integration outside options is not important for the results, and any other combination of reservation payoffs that sum to less than the output of the relationship would give identical results.

[10] Following other papers in this literature, we are using the Nash bargaining solution. See Binmore, Rubinstein and Wolinsky (1986) for a potential justification for Nash bargaining and a discussion of alternative bargaining rules. Our qualitative results do not depend on Nash bargaining.

[11] With competitive spot market transactions and without any specific investments, i.e., $e_P = e_S = 0$, ϕ would exactly correspond to the share of costs of the producer accounted for the supplier in question. Although with positive investments and ex post bargaining there will be a wedge between the two, we refer to ϕ as the "share of costs" to simplify the terminology.

the importance of the supplier's investment, e_S.[12] This production function has also normalized the level of output in the absence of any investments to 1, which is without any loss of generality. The feature that there are no complementarities between the investments of the supplier and the producer is for simplicity, and highlights that for the results that we want to emphasize, such complementarities are not essential.

To simplify the expressions, we assume the supplier can provide the basic input x_S at no cost, and also that the costs of investment for both parties are quadratic:

$$\Gamma_P(e_P) = \frac{1}{2}e_P^2 \text{ and } \Gamma_S(e_S) = \frac{1}{2}\phi e_S^2. \tag{2.2}$$

Notice that the investment costs of the supplier are multiplied by ϕ. This ensures that costs are proportional to the scale of operation and that the socially optimal levels of both e_P and e_S are independent of ϕ.[13]

In the event of disagreement, the two parties receive their outside options, which depend on the organizational form. We denote the outside option of party i under organizational form z by O_i^z.

With *backward vertical integration* (VIB), the producer owns all the assets, and in the event of ex post breakup, the supplier simply walks away from the firm, and receives nothing. The producer, who has residual control rights, keeps all the assets and the customized input, but lack of cooperation from the supplier causes the loss of a fraction λ of the supplier's investment, so the "effective investment" of the supplier is reduced to $(1-\lambda)e_S$ where $\lambda \in [0,1)$.[14] Therefore, the outside options of the supplier and the producer in this case are:

$$O_S^{VIB}(e_P, e_S) = 0 \text{ and } O_P^{VIB}(e_P, e_S) = F(x_S = 1, e_P, (1-\lambda)e_S).$$

With *non-integration* (NI), the supplier and the producer own their separate firms and assets. In case of disagreement, the producer does not receive the customized input from the supplier ($x_S = 0$), and consequently, generates no output from the part of the

[12] Symmetrically, we could introduce another parameter, say η, to capture the importance of the producer for the supplier. Comparative statics with respect to η are very similar to those with respect to ϕ. We omit this generalization to reduce notation and also because empirical results on the effect of a measure related to η do not show a consistent pattern (see below).

[13] The socially optimal levels of investment are $e_P = p$ and $e_S = s$. Modifying the supplier's cost function to $\Gamma_S(e_S) = e_S^2/2$ introduces an implicit "scale economies", and an increase in ϕ makes the supplier's investment more profitable (the socially optimal level of investment for the supplier becomes $e_S = s\phi$). Consequently, the comparative static results with respect to ϕ become ambiguous.

[14] Alternatively, λ can be interpreted as the fraction of investment which is incurred at the end of the period by the supplier to fine-tune the quality of the input. The supplier would not undertake this investment in the event of disagreement.

operations that relies on those inputs. The supplier can sell her input in the market, but with some revenue loss because of the specificity of the input to this producer. Therefore, the outside options under non-integration are:

$$O_S^{NI}(e_P, e_S) = \theta\phi(se_S + 1) \text{ and } O_P^{NI}(e_P, e_S) = F(x_S = 0, e_P, e_S) = (1-\phi)(pe_P + 1),$$

where $\theta \in [0, 1)$ is an inverse measure of how much the supplier looses if she sells the input outside of the specific relationship.[15] The general equilibrium determination of θ is beyond the scope of our paper. Here we treat it as exogenous and in the empirical section we proxy it by the relative number of producers to suppliers (with more producers, it might be easier for the supplier to find a suitable buyer to her input in the secondary market).

The third organizational form is *forward vertical integration* (VIF), where the supplier owns all the assets. In this case, with a similar reasoning to before, the outside options are:

$$O_S^{VIF}(e_P, e_S) = F(x_S = 1, (1-\lambda')e_P, e_S) \text{ and } O_P^{VIF}(e_P, e_S) = 0,$$

where $\lambda' \in [0, 1)$ is the fraction of the producer's investment that the supplier loses in case of disagreement.

Let y_i^z denote the output accruing to party i under organizational form z. Symmetric Nash bargaining implies that:

$$y_i^z(e_P, e_S) = O_i^z(e_P, e_S) + \frac{1}{2}\left[F(x_S = 1, e_P, e_S) - O_P^z(e_P, e_S) - O_S^z(e_P, e_S)\right], \quad (2.6)$$

where the term in square brackets is the relationship-specific surplus over which bargaining takes place and is positive for all $z \in \{VIB, NI, VIF\}$. The important feature is that each party's share of revenue will be increasing in his or her own outside option, and decreasing in that of the other party. This feature creates a link between outside options and investment incentives, and via this channel, between organizational forms and investment incentives.

Finally, the utility of party $i \in \{P, S\}$ can be expressed as:

$$U_i^z(y_i(e_P, e_S), e_i) = y_i^z(e_P, e_S) - \Gamma_i(e_i) + T_i(z). \quad (2.7)$$

[15] It is possible to also allow a secondary market in which the producer can purchase a less suitable input, in which case his outside option would be:

$$O_P^{NI}(e_P, e_S) = (1-\phi)(pe_P + 1) + \rho\phi(pe_P + 1),$$

where $\rho + \theta < 1$. This modification does not affect the results.

We can now characterize the unique equilibrium of the game specified in the previous subsection. Unless specified otherwise, we refer to an equilibrium by the on-the-equilibrium-path actions and revenues, $(z^*, T_P^*, T_S^*, e_P^*, e_S^*, y_P^*, y_S^*)$.

It is useful to define the "total surplus" of the relationship as:

$$S^z = U_S^z \left(y_S^z \left(e_P^* \left(z \right), e_S^* \left(z \right) \right), e_S^* \left(z \right) \right) + U_P^z \left(y_P^z \left(e_P^* \left(z \right), e_S^* \left(z \right) \right), e_P^* \left(z \right) \right),$$

where $e_i^* \left(z \right)$ denotes party i's optimal investment under the ownership structure z. Using equations (2.6) and (2.7), and the fact that $T_S \left(z \right) + T_P \left(z \right) = 0$ gives the total surplus of the relationship as:

$$S^z = F(x_S = 1, e_P^* \left(z \right), e_S^* \left(z \right)) - \Gamma_P(e_P^* \left(z \right)) - \Gamma_S(e_S^* \left(z \right)). \tag{2.8}$$

Since both parties have access to perfect credit markets and ex ante transfers, the subgame perfect equilibrium will always pick the organizational form that maximizes the surplus, S.[16] In other words, $S^{z^*} \geq S^z$ for all $z \in \{VIB, NI, VIF\}$.[17]

We now characterize the equilibrium by calculating the levels of social surplus under backward integration (S^{VIB}), non-integration (S^{NI}), and forward integration (S^{VIF}). The equilibrium organizational form is then given by $z^* = \arg\max_{z \in \{VIB,NI,VIF\}} S^z$.

Equilibrium investments are determined as the Nash equilibrium of a game where each party chooses its investment so as to maximize utility, given the other party's investment and the ownership structure. More formally, the equilibrium conditional on the ownership structure z is given by the pair $\{e_S^* \left(z \right), e_P^* \left(z \right)\}$ such that:

$$e_P^* \left(z \right) = \max_{e_P} \{ y_P^z(e_P, e_S^* \left(z \right)) - \Gamma_P(e_P) \} \text{ and } e_S^* \left(z \right) = \max_{e_S} \{ y_S^z \left(e_P^* \left(z \right), e_S \right) - \Gamma_S(e_S) \},$$

where the expressions for $y_i^z \left(. \right)$ are given in (2.6), and those for $\Gamma_i(.)$'s are given in (2.2). The Nash equilibrium investment levels under each of the three ownership structures can be calculated as:

[16] With credit constraints, the party that is less constrained may become the owner even when this structure does not maximize the ex ante social surplus, because the other party does not have the cash to compensate the first party for giving up ownership (see, for example, Aghion and Tirole (1994a), or Legros and Newman (2003)).

[17] Suppose not, and that the equilibrium involves z^*, but $S^{z^*} < S^{z'}$. Then the producer, which has the bargaining power in the first stage of the game, can propose z' together with a compensating transfer to the supplier, and increase its payoff. Namely, he can offer

$$T_S \left(z' \right) = T_S \left(z^* \right) + y_S^{z^*} - y_S^{z'} - \Gamma_S(e_S^* \left(z^* \right)) + \Gamma_S(e_S^* \left(z' \right)) + \varepsilon$$

with $\varepsilon > 0$, which would be at least as attractive for the supplier, and for $\varepsilon < S^{z'} - S^{z^*}$ also profitable for the producer.

$$e_P^*(VIB) = p \text{ and } e_S^*(VIB) = \frac{\lambda}{2}s \tag{2.9}$$

$$e_P^*(NI) = \left(1 - \frac{\phi}{2}\right)p \text{ and } e_S^*(NI) = \frac{1+\theta}{2}s \tag{2.10}$$

$$e_P^*(VIF) = \frac{\lambda'}{2}p \text{ and } e_S^*(VIF) = s. \tag{2.11}$$

These expressions highlight the effect of the different ownership structures on investment incentives. The investment of the producer is highest under backward vertical integration (i.e., $e_P^*(VIB) > e_P^*(NI) > e_P^*(VIF)$), while the investment of the supplier is highest under forward vertical integration (i.e., $e_S^*(VIF) > e_S^*(NI) > e_S^*(VIB)$). Furthermore, most relevant for our empirical analysis, backward vertical integration leads to greater producer investment and lower supplier investment relative to non-integration. This is a fundamental result in this class of models: (backward) vertical integration reduces the outside option of the supplier, and increases the share of the surplus accruing to the producer. It therefore discourages supplier investment and encourages producer investment. Another important feature is that with non-integration, the investment level of the producer is decreasing in ϕ, because a greater share of costs increases the scope for holdup by the supplier. Also with non-integration, the investment of the supplier is increasing in θ because a greater θ provides her with a better outside market (the outside market is irrelevant for the other organizational forms, since one of the parties has residual rights of control over the input and the assets).

Finally, substituting for $e_S^*(z)$ and $e_P^*(z)$ in (2.8), we obtain the total surplus under the three ownership structures, S^{VIB}, S^{NI}, and S^{VIF}, and the comparison of the surpluses gives the following proposition (the relevant expressions and the proof are in Appendix A):

Proposition 1. *There exist $\underline{r}$, $\overline{r}$, and $\widehat{r}$ such that the unique subgame perfect equilibrium ownership structure, z^*, is given as follows:*

- *If $\underline{r} < \overline{r}$, then $z^* = VIB$ for $p/s > \overline{r}$, $z^* = NI$ for $p/s \in (\underline{r}, \overline{r})$, and $z^* = VIF$ for $p/s < \underline{r}$. Moreover,*

$$\frac{\partial \overline{r}}{\partial \phi} < 0,\ \frac{\partial \underline{r}}{\partial \phi} > 0,\ \frac{\partial \overline{r}}{\partial \theta} > 0 \text{ and } \frac{\partial \underline{r}}{\partial \theta} < 0.$$

- *If $\underline{r} \geq \overline{r}$, then $z^* = VIB$ for $p/s > \widehat{r}$, and $z^* = VIF$ for $p/s < \widehat{r}$. Moreover,*

$$\frac{\partial \widehat{r}}{\partial \phi} > 0 \text{ and } \frac{\partial \widehat{r}}{\partial \theta} = 0.$$

This proposition gives the most important comparative static results that will be empirically investigated in the second part of the paper. First, the proposition shows that given the other parameters, the choice of organizational form depends on the ratio of p to s. When this ratio is high, backward integration is the equilibrium organizational form; for intermediate values, non-integration may emerge; and when this ratio is small, forward integration results in equilibrium. Intuitively, backward integration becomes more likely when p is large because, in this case, the tasks in which the producer specializes are highly "technology intensive" (i.e., the investment of the producer is more important), so increasing the producer's investment is the first priority. Backward vertical integration achieves this by increasing the producer's outside option and reducing the supplier's. In contrast, when s is large, backward integration becomes less likely, because now the supplier's investment is more important, and backward integration, by reducing the outside option of the supplier, discourages her investment. The opposite comparative static results apply for forward integration.

Second, as long as we are in the first case with $\underline{r} < \overline{r}$, non-integration is a possibility, which is clearly the empirically relevant case. In this case, an increase in ϕ makes backward integration relative to non-integration more likely and non-integration relative to forward integration also more likely. A greater share of costs (of the supplier's inputs in the producer's total costs) increases the degree to which the producer will be held up by the supplier. Backward vertical integration becomes more preferable because it avoids this problem. In addition, this result also implies that there are important interaction effects: the effect of p/s on vertical integration is amplified by ϕ. To see this differently, let us focus of the comparison between non-integration and backward integration, and denote the difference in surplus between these two organizational forms by $\Delta^B S \equiv S^{VIB} - S^{NI}$. Then we have that:

$$\frac{\partial^2 \Delta^B S}{\partial \phi \partial p} > 0 \text{ and } \frac{\partial^2 \Delta^B S}{\partial \phi \partial s} < 0.$$

This prediction is also quite intuitive. It suggests that when the relationship between the producer and the supplier is less important, their respective technology intensities should have less effect on integration decisions.

Finally, a greater θ makes non-integration more likely relative to backward integration; with a greater θ, the supplier invests more under non-integration because she has a better outside option, and this makes non-integration a more desirable organizational form. If we interpret θ as the degree of competition in the market, this result would imply that, consistent with some of the claims made in the popular press, greater competition encourages non-integration. However, a more appropriate interpretation might be that θ is a function of the ratio of producers to suppliers in the market, since, with more producers, after a breakup the supplier is more likely to find a suitable match in the secondary market.

In summary, the most important empirical prediction of this framework is that the technology intensity of the producer and the supplier should have opposite effects on the likelihood of vertical integration. In addition, there should be interaction effects between the producers' and suppliers' technology intensity on the one hand and the share of costs on the other, such that a greater share of costs should increase the magnitude of both effects. The rest of the predictions depend on whether the relevant margin in the data is backward or forward integration. In the case of backward integration, the results suggest that greater technology intensity of the producers should be associated with greater vertical integration, greater technology intensity of the suppliers should be associated with less vertical integration, and a greater share of costs should encourage vertical integration. Finally, we may also expect the number of producing firms relative to supplying firms to encourage non-integration.

3. Data and Measurement

3.1. Vertical Integration

Central to our empirical strategy is a measure of vertical integration, which we define at the sub-firm level. Namely, for each firm $i = 1, 2, .., N$, our first measure is a dummy for whether, for each product (industry) $j = 1, 2, .., J$ it is producing, the firm owns a plant in the supplying industry $k = 1, 2, .., K$:

$$vi_{ijk} = \begin{cases} 0 & \text{if firm does not own a plant in industry } k \text{ supplying industry } j \\ 1 & \text{if firm owns at least one plant in industry } k \text{ supplying industry } j \end{cases} . \tag{3.1}$$

This measure provides a direct answer to the question of whether the firm can supply some of its own input k necessary for the production of product j. It does not, however, use any information on how much of its required inputs the firm does (or can) supply from its own plants.

We also construct an alternative measure which uses this information. Let c_{ij} denote the total cost (including intermediate, capital and labor costs) of firm i in producing j and w_{jk} denote the proportion of total costs of producing j that are made up of input k, which is obtained from the UK Input-Output table. We can think of $c_{ij}w_{jk}$ as the firm's demand for input k for product j (to get the firm's total demand for k we sum over j). Let y_{ik} denote the amount of k that firm i produces. The alternative measure of the degree of vertical integration of firm i in the industry pair jk is calculated as:

$$\overline{vi}_{ijk} = \min\left\{\frac{y_{ik}}{c_{ij}w_{jk}}, 1\right\}. \tag{3.2}$$

When a firm produces several different products that demand input k, and where the total demand is greater than the firm itself can supply, we assume it allocates the input across plants proportionately to their demand, so the measure becomes

$$\overline{vi}_{ijk} = \min\left\{\frac{y_{ik}}{\sum_j c_{ij}w_{jk}}, 1\right\}. \tag{3.3}$$

In practice, there is little difference between vi_{ijk} and $\overline{vi}_{ijk}$, because when a firm owns a plant in a supplying industry, this is typically sufficient to cover all of its input requirements from that industry.[18]

Our main source of data is the annual UK Census of Production (called the ARD or ABI).[19] This is collected by the UK Office of National Statistics (ONS) and it is a legal obligation for firms to reply. These data provide us with information on input costs and output for all production plants located in the UK at the 4-digit industry level and on the ownership structure of these plants.[20] These data do not, however, tell us directly whether a plant purchases inputs from a related plant in the same firm. Data on the demand for intermediate inputs is available at the 2/3-digit industry level from the Input-Output Domestic Use Table for 1995. The Input-Output table contains information on domestic input flows between 77 manufacturing industries, giving 5,929 pairs of producing-supplying industries, of which 3,840 have positive flows. Appendix Table A.1 lists all 77 (supplying) industries together with their largest purchaser and other information.

Because of the level of aggregation of the Input-Output table, one difficulty arises when we look at industry pairs where the input and the output are in the same 2/3-digit industry. In this case, we consider a firm to be vertically integrated only if it has plants in more than one of the 4-digit industries within that 2/3-digit industry. As a

[18] Davies and Morris (1995) construct a related index with more aggregate data, while Fan and Lang (2000) measure corporate relatedness using a similar measure.

[19] See Griffith (1999) and Barnes and Martin (2002) for a description of these data.

[20] Data on employment is available for all plants. Data on other inputs and output is available for all plants with over 100 employees, data from smaller plants are collected from a random stratified sample and values for non-sampled plants are imputed.

robustness check we also report results which exclude all industry pairs in the same 2/3-digit industry.

Further details on the construction of these measures are provided in Appendix B. Overall, the vertical integration measures are constructed using data on 46,392 manufacturing firms over the period 1996-2001.[21]

3.2. Technology intensity and the share of costs

We construct a number of measures of technology intensity at the industry level. Our main measure is R&D intensity, i.e., R&D expenditure divided by total value added, which most closely corresponds to the notion of investment in new technologies. This measure, like all of our technology intensity measures, is calculated on a sample predating the vertical integration sample, in this case 1994-1995 (we do not have R&D information before this date). The total value added in the denominator includes all firms in the industry (both those that perform R&D and those that do not).

R&D intensity is our prefered measure because it is a direct measure of investment in new technologies. A possible concern is that the distribution of R&D across industries is rather skewed. Another concern might be that R&D could be spuriously correlated with vertical integration, for example, because it is better reported in larger firms and larger firms are more likely to be vertically integrated (though, in many specifications, we also control for firm size). We consider alternative indicators of industry technology including physical investment intensity, growth in labour productivity and growth in total factor productivity.

Our first alternative measure is investment intensity, which we expect to be correlated with technology intensity and the extent of relationship-specific investments. This measure is calculated also from the ARD as the average ratio of investment to value added for each industry over the years 1992-1995.

Because some types of technology investments may not be reflected in R&D or physical investment spending, we also use the growth in labour productivity and growth in total factor productivity as additional measures. These are also constructed from the ARD and are averages for the years 1992-1995. Growth in labour productivity is measured as:

$$g_{jt}^{LP} = \ln\left(\frac{VA_t}{VA_{t-1}}\right) - \ln\left(\frac{E_t}{E_{t-1}}\right), \tag{3.4}$$

where j indexes industry, VA is real value-added and E is numbers employed, and

[21] We exclude single plant firms with fewer than 20 employees.

growth in total factor productivity is measured using a superlative index (Caves et al. 1982a,b):

$$g_{jt}^{TFP} = \ln\left(\frac{VA_t}{VA_{t-1}}\right) - \widetilde{s}_{t-1,t}^{l} \ln\left(\frac{E_t}{E_{t-1}}\right) - \left(1 - \widetilde{s}_{t-1,t}^{l}\right) \ln\left(\frac{K_t}{K_{t-1}}\right), \tag{3.5}$$

where $\widetilde{s}_{t-1,t}^{l} = \left(s_t^l + s_{t-1}^l\right)/2$ and s^l is the wage bill over value-added and K is a perpetual inventory measure of capital stock. In our main specifications, when we investigate the effect of TFP growth and labor productivity growth, we limit the sample to industries with non-negative growth (see Appendix B). The results are similar when we set negative growth rates to zero or use the full sample (details available upon request).

Finally, the share of costs between each industry pair jk, sc_{jk}, is calculated from the Input-Output table as the share of inputs from industry k in the total cost of industry j (£ of input k necessary to produce £1 of product j).

3.3. Descriptive Statistics

Table 1 gives descriptive statistics for the whole sample, and also for subsamples separated according to whether the producer (supplier) has high or low R&D intensity, and whether the share of costs (of the producer made up by the inputs from the supplying industry) are high or low. There are 4,352,810 firm-industry-pair observations in 5,929 industry-pairs. Of these 3,840 industries pairs have positive flows with 2,973,008 observations. Since pairs without positive flows cannot be vertically integrated, we focus on the 3,840 pairs that have positive flows throughout the analysis.

The first row gives the mean and standard deviation of the continuous measure of verticle integration, $\overline{vi}_{ijk}$. The mean is 0.008 with a standard deviation of 0.087, which shows that there is substantial variation across firms and at the subfirm level. In fact, there is also substantial variation even within industry pairs. To illustrate this, we have also calculated the average within-industry-pair standard deviation of $\overline{vi}_{ijk}$, which is 0.086 (not shown in the table). This indicates that even within a relatively narrow industry-pair there is as much variation in the extent of vertical integration as in the whole sample.

The low mean of this variable is driven by the large number of zeros. The mean of $\overline{vi}_{ijk}$ conditional on $\overline{vi}_{ijk} > 0$ (not shown) is 0.93. This shows that if a firm can produce some of its inputs k in-house, it can typically produce *all* of that input (k) necessary for production.[22] This motivates our focus on the simpler dummy variable

[22] Naturally this does not imply that if a firm is vertically integrated for one of its inputs, it is also

vi_{ijk}, which indicates whether the firm owns a plant producing input k which it needs in the production of the product j (see equation (3.1)). Not surprisingly, the second row shows that the mean of this variable, 0.009, is very similar to that of $\overline{vi}_{ijk}$.

The other columns illustrate the differences in the extent of vertical integration when we separate firm-industry pairs into low and high producer R&D intensity, supply R&D intensity and low and high producer investment intensity, supplier investment intensity. These differences, which will be investigated in greater detail in the regression analysis below, indicate that vertical integration is higher when the R&D intensity of the producing industry is high. Interestingly, the descriptive statistics do not show a difference between vertical integration when we cut the sample by whether the R&D intensity of the supplying industry is high or low, but do when we cut on investment intensity. The regression analysis below will show a relatively robust effect of supplier R&D and more generally technology intensity on vertical integration, but because of nonlinearities in this relationship (see also Appendix Table A.4), the high-low cut does not show this result.

The table also gives descriptive statistics for the various technology measures. Another noteworthy feature here is that, as also documented in Appendix Table A.2, the correlation between the R&D intensity and the other technology intensity measures is quite low. Appendix Table A.2 shows that this is also true for investment intensity, but growth in labor productivity and TFP are somewhat more highly correlated. The relatively weak correlation between these measures means that each of these measures is a highly imperfect proxy for the overall technology intensity of the sector, and consequently, there might be some attenuation bias in our estimates of the relationship between technology intensity and vertical integration. It also suggests that these measures capture different dimensions of technology and investment intensity, so it is useful to look at the relationship between each of them and vertical integration separately.

The table also shows the means and standard deviations of the other main covariates.

vertically integrated for its other inputs. In fact, the mean of $\sum_k w_{jk}\overline{vi}_{ijk}$ conditional on $\overline{vi}_{ijk'} > 0$ for some k' is 0.053, so on average, across firms that are vertically integrated in any one input, firms are vertically integrated in around 5% of their total inputs demanded.

4. Results

4.1. Main results

Table 2 reports the main results using the R&D intensity measure. It reports estimates from the following linear probability model:[23]

$$vi_{ijk} = \alpha sc_{jk} + \beta_P RD_j^P + \beta_S RD_k^S + X'_{ijk}\eta + \varepsilon_{ijk} \tag{4.1}$$

where sc_{jk} is share of costs, RD_j^P is R&D intensity in producing industry j, RD_k^S is R&D intensity in supplying industry k, X_{ijk} is a vector including the constant term and firm and producing or supplying industry characteristics (firm size and age, average firm size and age in producing and supplying industries). The main coefficients of interest are α, β_P and β_S. The regressions are at the firm industry-pair level, while some of the main regressors are at the (producing or supplying) industry level. For this reason, throughout all standard errors are corrected for clustering at the industry pair level.[24]

The first two columns of Table 2 look at the bivariate relationship between R&D intensity in the producing and supplying industries and vertical integration. Column 1 shows a positive and highly statistically significant relationship between R&D intensity in the producing industry and vertical integration. The estimate of β_P is 0.038 with a standard error of 0.006. Column 2 shows a negative and highly statistically significant relationship between R&D intensity in the supplying industry and vertical integration; the estimate of β_S is -0.010 (standard error of 0.002). These relationships are robust to the inclusion of other covariates in the rest of the table.

The third column includes both R&D intensity variables and the share of costs. The R&D intensity variables continue to be highly statistically significant, with coefficients quite close to those in columns 1 and 2 (0.040 and -0.007), while the share of costs is positive and also statistically significant. The pattern of opposite signs on R&D intensity of producing and supplying industries is consistent with the theoretical prediction

[23] In Appendix Table A.3, we also show estimates from a probit model, with very similar results to the linear probability model.

[24] There is also a potential correlation between observations for the same firm in different industry pairs. Unfortunately, because of the size of the dataset, we were unable to estimate a variance-covariance matrix with multiple random effects, or multiple levels of clustering.

Nevertheless, we believe that the downward bias in the standard errors should be small in our case. Kloek (1981), for example, calculates that in the case with only a single correlated error component, the bias in the standard errors of approximately $\sqrt{1+\rho_i(m_i-1)}$, where ρ_i is the inter-class correlation coefficient and m_i is the number of observations in the class. In our data set, the maximum this could be (if ρ_i's were all equal to 1) is 1.187. In practice, since ρ_i's would be substantially less than 1, we expect the actual number to be much less. Even multiplying all the standard errors by a factor of 1.187 does not change any of our conclusions.

derived above. In addition, the directions of the effects of R&D intensities and the share of costs are consistent with the theory, as long as the relevant margin in the data is backward integration. Since we find the same pattern in practically all of our specifications, from now on we take the relevant comparison to be the one between backward vertical integration and non-integration, which is also consistent with the greater prevalence of backward integration in the manufacturing sector documented in previous studies (see, for example, Joskow (1987), Stuckey (1983)).

Note also that the magnitude of the effect of R&D intensity in the producing and supplying industries are quite different, with the effect of the producing industry more than four times the size of the effect of R&D intensity in the supplying industry. We do not have a good explanation for this pattern. However, we will see that with other measures of technology intensity, the effect of R&D intensity in the supplying industry is sometimes larger than the effect of R&D intensity in the producing industry. Therefore, the differences in the relative magnitudes of these coefficients may be due to the fact that each of the intensity measures is capturing a different part of the variation in the sample, combined with potentially heterogeneous effects of technology intensity on vertical integration,[25] though it is also possible that these differences reflect different degrees of attenuation bias due to measurement error.

The theoretical model above also suggests the possibility of interaction effects between the share of costs and R&D intensity. To investigate this issue, we modify our estimating equation to

$$vi_{ijk} = \alpha sc_{jk} + (\beta_P + \gamma_P sc_{jk})\, RD_j^P + (\beta_S + \gamma_S sc_{jk})\, RD_k^S + X'_{ijk}\eta + \varepsilon_{ijk}, \qquad (4.2)$$

with γ_P and γ_S as the additional coefficients of interest. Theory suggests that γ_P should have the same sign as β_P, and γ_S should have the same sign as β_P, so that the effects of R&D intensity in producing and supplying industries are amplified when there is a greater share of costs. Throughout, when we include interaction terms, we report the main effects evaluated at the sample mean, so that these estimates are comparable to those in the models without interaction effects.

The estimates in column 4 are consistent with the theoretical predictions. The main effects are close to those in the previous columns, and the interaction effects are large and statistically significant: γ_P is positive (1.112 with a standard error of 0.402), while γ_S is negative (-0.909 with a standard error of 0.353).

[25] See, for example, Angrist and Krueger (2000) on the weighting function of the OLS with heterogeneous coefficients.

Columns 5 and 6 add a number of firm and industry-level characteristics, namely firm size and age, and average firm size and average firm age in producing and supplying industries. All five coefficients of interest are robust, and remain close to their baseline values (the only minor exception is β_P, which declines from 0.040 in column 3 to 0.030 in column 6). The effects of these controls are also interesting. They indicate, for example, that larger and older firms are more likely to be vertically integrated, which is plausible. Furthermore, greater average firm size in the producing industry makes vertical integration more likely, while average firm size in the supplying industry appears to reduce the probability of integration. This opposite pattern of coefficients, with firm size in the producing industry having a positive effect, is also consistent with our conjecture that the relevant margin in the data is backward integration.

Column 7 reports estimates including a full set of firm fixed effects. The sample is limited to 578,560 observations where firms produce in more than one industry. In this case, the direct effect of the technology intensity of producing industry is no longer significant, though the effect of the supplier technology intensity, and the interaction between the share of cost and both the producing and supplying industry R&D intensity remain robust. We suspect that the main effect of the producing industry is no longer significant because estimation with firm fixed effects uses a small part of the variation in the data. The estimates in column 8, which are for the entire sample and include a full set of random firm effects, are broadly similar to our main results. The only exception is the coefficient on producer technology intensity, which is now substantially smaller, though still statistically significant.

Overall, the results in Table 2 show an interesting pattern of opposite effects from technology intensity in producing and supplying industries. They also show that these effects are magnified when the share of costs that the supplying industry accounts in the total costs of the producing industry is large. These results are consistent with the predictions of the PRT approach discussed above, and the direction of the effects are also consistent with the theory as long as the relevant margin in the data is backward integration. The rest of the paper shows that these results also hold with alternative measures of technology intensity and are robust to a variety of alternative controls and estimation strategies.

Before investigating robustness, it is useful to discuss the economic magnitudes of the estimates in Tables 2. We calculate the effect of the one standard deviation increase in R&D intensity on vertical integration at different points of the distribution of share of costs. In interpreting this exercise, it is important to recall that the mean of the vertical integration variable is 0.009, while its standard deviation is 0.091.

The magnitude of the main effect is generally small relative to the standard deviation of vertical integration. For example, one standard deviation increase in producer R&D intensity raises the probability of vertical integration by one sixteenth of a percentage point (i.e., 0.0016), which is a very small effect compared both to the mean and the standard deviation of the vertical integration measure. This effect is evaluated at the mean share of producer costs, which is 1%. However, the impact is considerably larger when we consider industry pairs where the share of producer costs is larger. If we look at the observations in the top decile of the share of costs distribution (where the average share of costs is above 3%), the economic impact is sizable; one standard deviation increase in producer are indeed increases the probability of vertical integration by over a half a percentage points (0.0054). For the 10 industry pairs with the largest share of costs, the impact is to increase the probability of vertical integration by 2.2 percentage points. Similarly, a one percentage point increase in supplier R&D intensity decreases the probability of vertical integration by around 0.7 percentage points for pairs in the top decile of share of costs and by approximately 3.3 percentage points for the 10 industry pairs with a large share of costs. That the average magnitude of the effect of technology intensity on vertical integration is small is not surprising, since most industry pairs do not trade much, so they are less likely to be vertically integrated, and changes in their technological characteristics are less likely to have an effect on vertical integration. However, our estimates imply that the quantitative effect of technological characteristics for industry pairs that are engaged in subsection trade could be sizable.

4.2. Results with alternative measures of technology intensity

Table 3 reports estimates from equations (4.1) and (4.2), with alternative measures of technology intensity replacing the RD_j^P and RD_k^S variables. For each of the three alternative measures, investment intensity, growth in labor productivity, and growth in TFP, we report the equivalent of specifications 3 and 6 from Table 2.

The results are generally consistent with those in Table 2. Technology intensity in the producing industry is positively associated with vertical integration, while technology intensity in the supplying industry is negatively associated with integration. For example, column 1 uses investment to value added ratio as the measure of technology, and shows a coefficient (standard error) of 0.030 (0.006) on producer technology intensity, while the coefficient (standard error) on supplier technology intensity is -0.046 (0.004). The only exception to this pattern is for producer technology intensity with investment and the full set of additional covariates (column 2). In this case, although supplier technology intensity continues to be highly significant, producer technology intensity is no longer statistically significant. However, note that there is a positive effect of producer investment intensity when these additional covariates are not included (see column 1), and in column 2, the interaction term between share of costs and producer investment intensity is positive and significant.

There is also a positive effect of share of costs in all six columns, and the magnitude of this effect is very similar to those in Table 2. In addition, the interaction terms between the share of costs and technology intensity in the producing and supplying industries also show the same pattern as in Table 2, and are typically significant; the only exceptions are those for the interaction terms between the share of costs and technology intensity in the producing industry in columns 4 and 6 (i.e., for labor productivity and TFP growth).

The effects of the other covariates (not shown) in all columns are also similar to those in Table 2. Notice also that, contrary to Table 2, with investment intensity as the technology measures, the magnitude of the effect of technology intensity in the supplying industry is greater than that for the producing industry. Finally, not reported in Table 3, we also repeated the estimates with firm fixed effects and random effects. The results were similar to those in Table 2, and the effect of technology intensity of the producing industry is insignificant with firm fixed effects, while the random effects estimates were similar to the baseline results.

4.3. Within-industry variation

A more demanding test of the relationship between technology in intensity and vertical integration is to investigate whether a particular producing industry is more vertically integrated with supplying industries that are less technology intensive relative to its mean propensity to be vertically integrated. Similarly, for a supplying industry, whether it is more vertically integrated with producing industries that are more technology intensive relative to its mean. We cannot investigate both of these questions simultaneously, since equations (4.1) and (4.2) would not be identified with a full set of producing and supplying and industry dummies. However, we can include one set of dummies at a time. In other words, we can separately estimate

$$vi_{ijk} = \alpha sc_{jk} + \delta_j^P + \beta_S RD_k^S + X_{ijk}'\eta + \varepsilon_{ijk}$$

and

$$vi_{ijk} = \alpha sc_{jk} + \beta_P RD_j^P + \delta_k^S + X_{ijk}'\eta + \varepsilon_{ijk},$$

where δ_j^P denotes a full set of producing industry dummies and δ_j^S denotes a full set of supplying industry dummies. Estimates from these equations and from similar ones with interaction terms are reported in Tables 4 and 5. Here the standard errors are clustered at the industry level (in Table 4 they are clustered at the supplier industry level and Table 5 at the producer industry level).

The estimates of the main effects are generally similar to those in Tables 2 and 3, and show a positive effect of producer technology intensity and negative effect of supplier technology intensity. For example, in Table 4 the effect of R&D intensity in the producing industry is 0.025 (standard error=0.008) both with and without the additional covariates. However, the effect of R&D intensity in the supplying industry in Table 5 is no longer significant, though the effect of the other three measures of technology intensity are (except for growth in TFP with all the covariates).

The interaction effects are generally estimated less precisely. The interactions between the share of costs and producer technology intensity in Table 4 are never significant, and sometimes of the wrong sign, while the interaction between the share of costs and supplier technology intensity in Table 4 are always negative, and significant in columns 6 and 8.

4.4. An instrumental variable strategy

The results so far show statistically significant associations between vertical integration and the technology intensity in the producing and supplying industries. However, these associations do not necessarily correspond to the causal effects of the technology intensity variables on vertical integration decisions. First, as highlighted by the theory above, vertical integration also affects investment, so there is room for reverse causality. Second, and potentially more important, there may be other variables that are omitted from the regressions, which causally affect both technology intensity and vertical integration. This will mean the error term is correlated with the regressors and will lead to biased estimates of the coefficients of interest. To the extent that the omitted variables are at the industry level and relatively constant over time, the within-industry estimates discussed in the previous section go some way to controlling for this.

A more satisfactory approach would be to use an instrumental variable strategy, with instruments that affect technology intensity, but have no other effect on vertical integration (i.e., they should be orthogonal to the error term, ε_{ijk}, in equations (4.1) and (4.2)). Although we do not have such perfect instruments, measures of technology intensity in the same industry in the U.S. are potential candidates. These instruments are useful in avoiding the potential reverse causality problems and in removing the effect of UK-specific omitted variables, though this procedure would not help with omitted industry-specific variables that are common across the U.S. and the UK. Therefore, these results should be interpreted not as causal estimates but as investigating a different source of variation in the data.

The first-stage equations for the model in (4.1) are:

$$
\begin{aligned}
RD_j^P &= \alpha^{US,P} sc_{jk} + \beta_P^{US,P} RD_j^{P,US} + \beta_S^{US,P} RD_k^{S,US} + (X_{ijk})' \eta^P + u_{ijk}^P \\
RD_k^S &= \alpha^{US.S} sc_{jk} + \beta_P^{US,S} RD_j^{P,US} + \beta_S^{US,S} RD_k^{S,US} + (X_{ijk})' \eta^S + u_{ijk}^S,
\end{aligned}
$$

where $RD_j^{P,US}$ is technology intensity in the producing industry j in the U.S. and $RD_k^{S,US}$ is technology intensity in the supplying industry k in the U.S..[26]

For the model in (4.2), there are four first-stage equations, since the interaction terms between technology intensity and the share of costs also have to be instrumented, and we create two additional instruments by interacting US technology intensity measures with the UK share of costs.

While we have corresponding measures of investment intensity, growth in labor productivity, and growth in TFP at the 2/3-digit industry level in the U.S., we do not have R&D data in the U.S. at this level of disaggregation. For this reason, in the regressions with R&D intensity, we use the alternative measures of technology intensity in the U.S. as instruments. The IV results for the specifications in columns 3 and 6 of Table 2 and all columns of Table 3 are reported in Table 6. The specifications in the even-numbered columns include the additional firm and industry-level covariates (these covariates are not reported to save space). The bottom panels of the table report some of the main first-stage coefficients and the p-value of the F-statistics for the significance of the instruments in the first-stage regressions and the R^2. All of the first-stage relationships are highly significant and show an intuitive pattern: producer technology intensity in the U.S. is strongly correlated with producer technology intensity in the UK, and no correlation with the supply of technology intensity in the UK, while this pattern is reversed for supplier technology intensity in the U.S..

The results are generally consistent with those in Tables 2 and 3. The weakest results are for R&D intensity, which is not surprising given the absence of an appropriate instrument for R&D. Recall that R&D intensity is only weakly correlated with the other

[26] As in the OLS estimates, the producing and supplying industry R&D intensities are assigned to all corresponding firm-industry pairs, so that both the first and the second stages are estimated at the firm-industry pair level.

measures of technology intensity even when we use only UK data (see Appendix Table A.2). Consequently, the first stages for the R&D intensity variables are relatively weak when we use other measures of technology intensity from the U.S. as instruments. Nevertheless, even in this case, the main effects of R&D intensity in producing and supplying industries are of the right sign and significant without the additional covariates. But with the additional covariates, only the R&D intensity in the supplying industry is significant.[27]

The results using investment intensity, growth in labor productivity, and growth in TFP are stronger and more precisely estimated than those for R&D intensity. In all cases, the main effects have the same pattern as the OLS estimates, and are highly significant. The interaction terms, on the other hand, are typically imprecise and insignificant. This is not surprising, given the difficulty of simultaneously instrumenting for four regressors, some of which are highly correlated. It is remarkable, however, that even with the interaction terms instrumented, the main effects of technology intensity in the producing and supplying industries are reasonably precisely estimated and similar to the OLS results.

Another noteworthy feature is that the IV estimates of the main effects of the technology intensity variables are typically larger than the corresponding OLS values in Table 2 and 3. This might be because the IV procedure reduces the attenuation bias resulting from classical measurement error or from the fact that our measures are only imperfect proxies of the importance of relationship-specific technology investments. Another possibility is that, consistent with the significant interactions between technology intensity and the share of costs which show heterogeneous effects conditional on observables, there are also heterogeneous effects conditional on unobservables. In that case, because OLS and IV have different weighting functions, it is natural that they will lead to different estimates (see Angrist and Imbens (1995)).

Overall, the IV estimates using the U.S. values yield results that are similar to the OLS estimates, and make us more confident that the OLS estimates are informative about the relationship between technology intensity and vertical integration decisions.

[27] If we use the U.S. values of each of the three other measures separately as instruments for R&D intensity in the producing and supplying industries, the results are similar to those reported in columns 1 and 2 with growth in labor productivity and investment intensity, but weaker with growth in TFP. Details are available upon request.

4.5. Robustness

Appendix Table A.3 reports a number of robustness checks. In all cases, we only report the specification corresponding to column 6 in Table 2 (though we do not report the covariates to save space). First, in the top panel we report estimates from a probit model rather than the linear probity model, with similar results.

Second, the second panel reports results using our alternate (continuous) measure $\overline{vi}_{ijk}$ rather than the dummy variable vi_{ijk}. Not surprisingly given the close correspondence between the two measures, the results are very similar to those in Tables 2 and 3.

Third, the next three panels show the robustness of our results in different subsamples of the data. One of these panels excludes pairs where the supplying and producing industries are the same, and shows that this has little effect on the coefficients of interest. The next two panels exclude the top and the bottom quartiles of firms by size, again with little effect on the results.

Appendix Table A.4 looks into potential nonlinearities. It reports results with dummies for a producing (or supplying) industry being at the second, third or fourth quartile of the corresponding distribution (with the first quartile as the omitted group). The share of costs is also parameterized with dummies for medium and high (with low as the omitted group). The results show that there is generally a monotonic pattern, consistent with the linear regressions reported in previous tables, with the exception of the effect of R&D intensity in the supplying industry. Here the second quartile has the largest negative effect, while the third quartile has a small, and sometimes insignificant, sometimes positive effect. This nonlinear pattern, for which we do not have a good explanation, is the reason why the difference in vertical integration by the R&D intensity of the suppliers was not visible in the descriptive statistics in Table 1. In regressions using other technology measures (not reported), we find that the coefficients broadly follow the patterns described above.

In addition, we investigated the stability of the basic relationship over years, and the results are highly stable across years (details available upon request). We also estimated specifications controlling for the share of the output of the supplying industry going to the producing industry in question. When entered by itself, this variable is significant with the expected sign, but when entered together with the share of cost, it is no longer significant and typically has the opposite signed relative to that predicted by our model (see footnote 12).

4.6. Outside options and competition

Finally, we consider the effect of competition and the number of firms. Our model also points out potential links between competition and vertical integration. In Table 7, we briefly investigate this relationship using the number of firms in producing and supplying industries as our main indicator of competition (see, for example, Bresnahan and Reiss (1991)). Table 7 shows that a greater number of firms in the producing industry is associated with lower vertical integration, while a greater number of firms in the supplying industry leads to lower vertical integration.

The coefficient on the number of firms in the supplying industry is about four times the magnitude of the coefficient for the number of firms in the producing industry. Ignoring this difference in magnitude, for which we do not have a good explanation, these results are consistent with the theory. There we showed that, as long as the relevant margin is backward integration, a greater θ, which increases the outside option of the supplier, should make vertical integration less likely. A greater number of firms in the producing industry is likely to increase the outside option of the supplier, while more firms in the supplying industry should reduce it. This is the pattern we find data.[28]

Interestingly, if we think of an increase in overall competition as corresponding to a proportional increase in the number of producing and supplying firms, since the coefficient on the number of supplying firms is larger, our estimates suggest that there should be an increase in vertical integration. Although this result is not our main focus, it sheds some doubt on the popular claims that greater competition is necessarily leading to less integrated firms.

5. Summary and Conclusions

Despite a number of well-established theories and a prominent public debate on the effect of technology and technical change on the internal organization of the firm, there is little evidence on the determinants of vertical integration. This paper confronts some of the predictions of one of the leading approaches to the theory of the firm, the PRT of Grossman and Hart (1986) and Hart and Moore (1990), with data from the entire population of UK manufacturing plants, and documents a number of empirical regularities in the relationship between technology intensity and vertical integration.

[28] We also experimented with Hirfindahl indices for producing and supplying industries. Although the Hirfindahl indices were sometimes significant, the results were not robust. The addition of the Hirfindahl indices did not change the effects of the number of firms in the producing and supplying industries on vertical integration, however.

Our results show that vertical integration in a pair of industries (products) is less likely when the supplying industry is more technology intensive and the producing industry is less technology intensive. Moreover, both of these effects are larger when inputs from the supplying industry form a large fraction of the total costs of the producing industry. This pattern of opposite effects of technology intensity of producing and supplying industries is consistent with the PRT approach. In addition, the direction of these effects, for example, that vertical integration is more likely when the producing industry is more technology intensive, and the other patterns we find, are consistent with the theory provided that the relevant margin in the data is the choice between backward vertical integration and non-integration.

We show that these results are generally robust to the choice of technology intensity measure and to a battery of robustness checks. We report similar results instrumenting UK technology intensity measures with U.S. measures. We also find that vertical integration is more likely when the average number of producing firms is greater relative to the average number of supplying firms, which is also consistent with the theoretical predictions we derived from a simple incomplete contracts model (and not entirely consistent with the claims made in the popular press about the effect of competition on the structure of firms).

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6. Appendix A: Proof of Proposition 1

Substituting the optimal investments given by (2.9), (2.10) and (2.11) into (2.8), social surplus under the three organizational forms is obtained as:

$$\begin{aligned} S^{VIB} &= 1+\frac{1}{2}p^2+\frac{\phi}{2}\lambda\left(1-\frac{\lambda}{4}\right)s^2, \\ S^{NI} &= 1+\left(1-\frac{2-\phi}{4}\right)\left(1-\frac{\phi}{2}\right)p^2+\frac{\phi}{2}\left(1+\theta\right)\left(1-\frac{1+\theta}{4}\right)s^2, \\ S^{VIF} &= 1+\frac{1}{2}\lambda'\left(1-\frac{\lambda'}{4}\right)p^2+\frac{\phi}{2}s^2. \end{aligned} \tag{A1}$$

Let

$$\Delta^{VIB,NI} \equiv S^{VIB}-S^{NI} = \phi^2p^2/8-\left(3-\theta-\lambda\right)\left(1+\theta-\lambda\right)\phi s^2/8.$$

It is straightforward to verify that $\Delta^{VIB,NI}$ is increasing in p, decreasing in s, and $\Delta^{VIB,NI}=0$ if and only if

$$\frac{p}{s}=\sqrt{\left(3-\theta-\lambda\right)\left(1+\theta-\lambda\right)/\phi}\equiv\overline{r}>0.$$

When $p/s>\overline{r}$, backward integration is preferred to non-integration. When $p/s<\overline{r}$, it is dominated by non-integration. Differentiation establishes that $\frac{\partial\overline{r}}{\partial\phi}<0$ and $\frac{\partial\overline{r}}{\partial\theta}>0$.

Similarly, let

$$\Delta^{VIF,NI}\equiv S^{VIF}-S^{NI}=-\left(\left(2-\lambda'\right)^2-\phi^2\right)p^2/8+\phi\left(1-\theta\right)^2s^2/8.$$

$\Delta^{VIF,NI}$ is decreasing in p and increasing in s. $\Delta^{VIF,NI}=0$ if and only if

$$\frac{p}{s}=\sqrt{\frac{\phi\left(1-\theta\right)^2}{\left(2-\lambda'\right)^2-\phi^2}}\equiv\underline{r}>0.$$

When $p/s<\underline{r}$ ($p/s>\underline{r}$), forward integration is preferred to (dominated by) non-integration. Again, differentiation establishes that $\frac{\partial\underline{r}}{\partial\phi}>0$ and $\frac{\partial\underline{r}}{\partial\theta}<0$.

Suppose, first, that $\underline{r}<\overline{r}$. Then, the analysis so far establishes that the equilibrium organizational form is given by

$$z^*=\left\{\begin{array}{cc} VIB & \text{if } \frac{p}{s}\geq\overline{r} \\ NI & \text{if } \frac{p}{s}\in\left(\underline{r},\overline{r}\right) \\ VIF & \text{if } \frac{p}{s}\leq\underline{r} \end{array}\right\}.$$

The set of parameters such that $\underline{r}<\overline{r}$ is non-empty. For instance, as $\theta\rightarrow1$ we have that $\underline{r}\rightarrow0$, whereas $\overline{r}\rightarrow\left(2-\lambda\right)/\sqrt{\phi}>0$.

Suppose, next, that $\underline{r}\geq\overline{r}$. Then NI is always dominated by either VIF and VIB. Let

$$\Delta^{VIB,VIF}\equiv S^{VIB}-S^{VIF}=\left(2-\lambda'\right)^2p^2/8-\phi\left(2-\lambda\right)^2s^2/8.$$

$\Delta^{VIB,VIF}$ is increasing in p and decreasing in s, and also $\Delta^{VIB,VIF}=0$ if and only if

$$\frac{p}{s}>\frac{2-\lambda}{2-\lambda'}\sqrt{\phi}\equiv\widehat{r}.$$

When $p/s>\widehat{r}$ ($p/s<\widehat{r}$), backward integration is preferred to (dominated by) forward integration. Differentiation establishes that $\frac{\partial\widehat{r}}{\partial\phi}>0$ and$\frac{\partial\widehat{r}}{\partial\theta}=0$. This completes the proof of the proposition.

7. Appendix B: Data Sources and Construction

Our main source of data is the plant level production data underlying the UK Census of Production (ARD). This is collected by the UK Office of National Statistics (ONS) and it is a legal obligation for firms to reply. We use the data on all manufacturing plants from 1996-2001, along with information from the Input-Output Domestic Use Table for 1995, to measure vertical integration and other firm characteristics. We use data from the ARD from 1992-1995 to measure a number of other industry characteristics and data from the annual Business Enterprise Researcher and Development (BERD) survey from 1994-1995 to measure R&D expenditure at the industry level. US variables are measured using the US Census data at the 4-digit level (available on the NBER web site). The UK and US data are matched based on a mapping of UK SIC92 to US SIC87 and then aggregated up to input-output industry level.

7.1. The plant level production data

The ARD contains information on all production activity located in the UK. The basic unit for which information on inputs and output is reported is a reporting unit. A reporting unit can be a single plant or a group of plants owned by the same firm operating in the same 4-digit industry. Information is also available on all plants (called local units) within each reporting unit, their location and number of employees are also reported. There are over 150,000 reporting units with non-zero employment in the ARD each year 1996-2000. Detailed data is collected from a random stratified sample.[29] Data on value-added and costs for non-sampled reporting units are imputed.

Table 1 shows the total number of reporting units and the number of reporting units in multi and single plant firms by year. Single plant firms are identified as those reporting units which represent only one plant and which have no sibling, parent or child plants. Single plants with fewer than 20 employees are dropped from the analysis, resulting in between 100,000 - 130,000 reporting units being dropped per year. In addition 1,000 - 2,000 reporting units per year which are owned by foreign firms are dropped, as we do not observe their foreign activities.

Plants in the ARD in these years are classified by their major product accroding to the 1992 revision of the 4-digit standard industrial classification (SIC code). Input-output (IO) tables are reported at the 2/3-digit level. Where more than one reporting unit exists within an IO industry these are aggregated so that there is only one observation per firm in each IO industry. The total number of firms used (after dropping the small and single and foreign owned firms and averaging over years) is 46,392. [how many in more than on producing industry?] We measure firm age in each producing industry as the number of years since the first plant in that industry was established. We measure firm size in each industry by the number of employees it has in that industry. The average number of firms in an industry is measured from the ARD. Table 3 (in the main text) shows means for these variables.

[29] The sampling probabilities vary over time, with industry and with reporting unit size. Reporting units with 100 or more employees are always sampled. Below that the sampling probabilities range from 1 in 5 to 1 in 2.

7.2. The Input-Output Table

The Input-Output table contains information on 77 manufacturing industries (supplying and producing). There are 5,929 pairs of producing-supplying industries, for which 3,840 the input-output table indicates positive trade flows. For each industry pair we calculate the proportion of total costs (including intermediate, labour and capital) of producing j that are made up of input k, denoted w_{jk}. In 2,766, or just under half of industry pairs, at least one firm is vertically integrated to some extent. Table A.3 contains descriptive statistics on the share of output from each supplying industry that is sold for intermediate consumption, to all industries and to manufacturing industries, and shows the largest purchasing industry along with the share of sales this purchaser represents (which ranges from a half of a percent to over fifty percent and average 3.7 percent) and the share of the purchaser's total costs this input represents (which ranges from zero to 37 percent and averages 2.7 percent).

7.3. Technology indicators

Our measures of technology intensity are all at the industry level. R&D intensity is measured using the micro data underlying the annual Business Enterprise Research and Development (BERD) matched to the ARD. The micro data is aggregated to the industry level using the industry of the R&D reporting unit for the years 1994-1995. This is scaled by total value-added in firms producing in the industry (including both R&D and non-R&D doing firms). The ratio of physical investment (capital expenditure on machinery, buildings, land and vehicles) to value-added is constructed in a similar manner from the ARD data at the industry level and averaged over the years 1992-1995. Growth in labour productivity and growth in total factor productivity are measured at the industry level and average over the years 1992-1995 using the ARD data. The correlation between the four measures is given in Table A.4.

Table 1: Descriptive statistics

Variable	Mean (s.d.)	Producer R&D		Supplier R&D		Producer investment		Supplier investment	
		low	high	low	high	low	high	low	high
Mean $\overline{vi}_{ijk}$	0.008	0.007	0.010	0.008	0.009	0.008	0.009	0.011	0.006
	(0.087)	(0.078)	(0.096)	(0.084)	(0.089)	(0.084)	(0.092)	(0.101)	(0.073)
Mean of vi_{ijk}	0.009	0.009	0.013	0.010	0.011	0.010	0.012	0.015	0.007
	(0.091)	(0.093)	(0.114)	(0.101)	(0.104)	(0.100)	(0.108)	(0.120)	(0.085)
Firm age	10	10	10	10	10	10	10	10	10
	(7)	(7)	(7)	(7)	(7)	(7)	(7)	(7)	(7)
Firm employment	111	99	125	109	112	95	143	109	112
	(455)	(346)	(559)	(444)	(465)	(456)	(453)	(447)	(463)
Share of producer costs on this intermediate input	0.010	0.010	0.010	0.012	0.009	0.011	0.10	0.014	0.007
(jk)	(0.034)	(0.038)	(0.029)	(0.040)	(0.028)	(0.036)	(0.030)	(0.041)	(0.026)
Producing industry									
R&D over value-added	0.027	0.004	0.055	0.026	0.028	0.024	0.033	0.027	0.027
	(0.055)	(0.002)	(0.072)	(0.055)	(0.055)	(0.047)	(0.067)	(0.055)	(0.055)
Investment over value-added	0.101	0.095	0.109	0.102	0.101	0.079	0.147	0.101	0.102
	(0.041)	(0.031)	(0.049)	(0.040)	(0.041)	(0.017)	(0.038)	(0.041)	(0.041)
Growth in labour productivity	0.059	0.048	0.071	0.058	0.059	0.052	0.072	0.059	0.058
	(0.036)	(0.028)	(0.040)	(0.035)	(0.036)	(0.030)	(0.042)	(0.035)	(0.036)
Growth in TFP	0.046	0.036	0.052	0.043	0.044	0.042	0.047	0.044	0.043
	(0.034)	(0.030)	(0.041)	(0.035)	(0.037)	(0.030)	(0.046)	(0.036)	(0.036)
Mean number of firms in industry	5757	8267	2763	5755	5759	7476	2231	5571	5914
	(6585)	(7978)	(1635)	(6525)	(6636)	(7348)	(1748)	(6331)	(6789)
Supplying industry									
R&D over value-added	0.046	0.044	0.050	0.005	0.082	0.047	0.045	0.031	0.059
	(0.107)	(0.103)	(0.113)	(0.003)	(0.137)	0.109)	(0.104)	(0.078)	(0.126)
Investment over value-added	0.122	0.123	0.122	0.106	0.136	0.122	0.123	0.079	0.159
	(0.057)	(0.057)	(0.057)	(0.038)	(0.067)	0.057)	(0.057)	(0.016)	(0.054)
Growth in labour productivity	0.074	0.073	0.074	0.061	0.086	0.075	0.072	0.063	0.083
	(0.052)	(0.052)	(0.051)	(0.039)	(0.059)	(0.053)	(0.050)	(0.044)	(0.056)
Growth in TFP	0.057	0.050	0.052	0.040	0.061	0.051	0.049	0.050	0.052
	(0.048)	(0.051)	(0.051)	(0.039)	(0.058)	0.052)	(0.050)	(0.045)	(0.056)
Mean number of firms in industry	2316	2320	2309	3347	1433	2296	2355	3730	1120
	(3730)	(3727)	(3733)	(5065)	(1471)	(3715)	(3759)	(4960)	(1324)

Source: Authors' calculations using the United Kingdom Office of National Statistics data. All statistical results remain Crown Copyright.

Notes: $\overline{vi}_{ijk}$ is a continuous measure of the share of the producers demand can be met by its own supply. vi_{ijk} is a dummy for whether a firm owns plants in both producing and supplying industries. Share of producer costs on this intermediate input is the share of producers total costs (including labour and capital) that goes on this input (from the Input-Output Table). Sample means reported for all variables except growth in labour productivity and growth in total factor productivity. Sample contains 2,973,008 observations on 46,392 firms. Numbers reported are means (standard deviations).

Table 2: Main results – R&D intensity

dependent variable: vi_{ijk}	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Share of costs (jk)			0.204 (0.029)	0.187 (0.028)	0.187 (0.028)	0.182 (0.027)	0.560 (0.068)	0.182 (0.005)
R&D intensity, producing (j)	0.038 (0.006)		0.040 (0.005)	0.044 (0.005)	0.037 (0.005)	0.030 (0.005)	0.022 (0.021)	0.030 (0.004)
x Share of costs				1.112 (0.402)	1.104 (0.397)	1.067 (0.374)	3.292 (1.021)	1.067 (0.122)
R&D intensity, supplying (k)		-0.010 (0.002)	-0.007 (0.001)	-0.013 (0.003)	-0.013 (0.003)	-0.007 (0.003)	-0.028 (0.010)	-0.007 (0.001)
x Share of costs				-0.909 (0.353)	-0.914 (0.351)	-0.871 (0.324)	-2.756 (0.963)	-0.871 (0.100)
ln Firm size (ij)					0.0053 (0.0002)	0.0052 (0.0002)	0.0025 (0.0005)	0.0052 (0.0004)
ln Firm age (ij)					0.0010 (0.0001)	0.0009 (0.0001)	0.0006 (0.0006)	0.0009 (0.0002)
ln Average firm size, producing (j)						0.0011 (0.0005)	0.003 (0.003)	0.0011 (0.0003)
ln Average firm size, supplying (k)						-0.0036 (0.0004)	-0.017 (0.002)	-0.0036 (0.0002)
ln Average firm age, producing (j)						0.012 (0.003)	-0.004 (0.012)	0.0123 (0.0014)
ln Average firm age, supplying (k)						0.004 (0.002)	0.022 (0.007)	0.0036 (0.0011)
Observations	2,973,008	2,973,008	2,973,008	2,973,008	2,973,008	2,973,008	578,560	2,973,008
Clustering	3,840 industry pairs	3,840 industry pairs	3,840 industry pairs	3,840 industry pairs	3,840 industry pairs	3,840 industry pairs	3,840 industry pairs	4,485 firms
Fixed effects							4,485 firms	

Source: Authors' calculations using the United Kingdom Office of National Statistics data. All statistical results remain Crown Copyright.
Notes: The dependent variable is a dummy for whether a firm is vertically integrated in that industry pair at any time over the years 1996-2001. Standard errors in parentheses are clustered at the level indicated. The RHS variables firm size and firm age are measured at the firm-industry pair level in 1996 (age is equal to 1 if the firm enters that industry pair after 1996). R&D intensity is R&D carried out in the UK divided by value-added produced in the UK, taken from plant level R&D data, aggregated to the 2/3-digit industry level and average over the years 1994-1995, share of costs is from the 1995 input-output table and is at the industry pair level. Average firm size and age are calculated from the firm-industry pair data and average over the years 1996-2001. In regression with interactions, all main effects evaluated at sample means.

Table 3: Alternative measures of technology

	(1)	(2)	(3)	(4)	(5)	(6)
dependent variable: vi_{ijk}						
technology variable:	Investment Intensity		growth labour productivity		growth TFP	
Share of costs (jk)	0.203	0.187	0.205	0.214	0.207	0.222
	(0.028)	(0.024)	(0.028)	(0.027)	(0.030)	(0.030)
technology intensity,	0.030	-0.002	0.065	0.036	0.057	0.030
producing (j)	(0.006)	(0.008)	(0.009)	(0.009)	(0.010)	(0.010)
x Share of costs		1.402		0.520		-0.126
		(0.453)		(0.338)		(0.325)
technology intensity,	-0.046	-0.041	-0.035	-0.015	-0.036	-0.014
supplying (k)	(0.004)	(0.005)	(0.005)	(0.004)	(0.006)	(0.005)
x Share of costs		-1.562		-1.278		-1.046
		(0.489)		(0.299)		(0.267)
Covariates		yes		yes		yes
Observations	2,973,008	2,973,008	2,839,954	2,839,954	2,509,849	2,509,849
Clustering	3,840 industry pairs	3,840 industry pairs	3,840 industry pairs	3,840 industry pairs	3,840 industry pairs	3,840 industry pairs

Source: Authors' calculations using the United Kingdom Office of National Statistics data. All statistical results remain Crown Copyright.
Notes: The dependent variable is a dummy for whether a firm is vertically integrated in that industry pair at any time over the years 1996-2001. Standard errors in parentheses are clustered at the level indicated. The RHS variables firm size and firm age are measured at the firm-industry pair level in 1996 (age is equal to 1 if the firm enters that industry pair after 1996). Investment intensity is capital expenditure carried out in the UK divided by value-added produced in the UK, growth in labour productivity is annual change in value-added produced in the UK divided by numbers employed in the UK, growth in total factor productivity is measured using a superlative index (see section 3.2). All technology measures use plant level data aggregated to the 2/3-digit industry level and average over the years 1992-1995. Industries where growth in labour productivity or growth in total factor productivity were negative have been dropped. Share of costs is from the 1995 input-output table and is at the industry pair level. Average firm size and age are calculated from the firm-industry pair data and average over the years 1996-2001. In regression with interactions, all main effects evaluated at sample means. Covariates included where indicated are: producing firm size, age, mean firm size and mean firm age in producing and supplying industries.

Table 4: Within industry variation: producer technology

dependent variable: vi_{ijk}	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Technology indicator	R&D		Investment		growth labour productivity		growth TFP	
Share of costs (jk)	0.167 (0.033)	0.170 (0.033)	0.166 (0.033)	0.168 (0.034)	0.165 (0.034)	0.166 (0.033)	0.165 (0.036)	0.167 (0.035)
technology, producing (j)	0.039 (0.010)	0.025 (0.008)	0.030 (0.012)	-0.008 (0.016)	0.063 (0.019)	0.035 (0.020)	0.056 (0.020)	0.031 (0.021)
x Share of costs		0.117 (0.242)		0.250 (0.293)		-0.185 (0.415)		-0.735 (0.414)
Observations	2,973,008	2,973,008	2,973,008	2,973,008	2,839,954	2,839,954	2,509,849	2,509,849
Clustering	77 producing industries	77 producing industries	77 producing industries	77 producing industries	77 producing industries	77 producing industries	77 producing industries	77 producing industries
Fixed effects	77 supplying industries	77 supplying industries	77 supplying industries	77 supplying industries	77 supplying industries	77 supplying industries	77 supplying industries	77 supplying industries
Covariates		yes		yes		yes		yes

Source: Authors' calculations using the United Kingdom Office of National Statistics data. All statistical results remain Crown Copyright.

Notes: The dependent variable is a dummy for whether a firm is vertically integrated in that industry pair at any time over the years 1996-2001. Standard errors in parentheses are clustered at the level indicated. The RHS variables firm size and firm age are measured at the firm-industry pair level in 1996 (age is equal to 1 if the firm enters that industry pair after 1996). R&D intensity is R&D carried out in the UK divided by value-added produced in the UK, taken from plant level R&D data, aggregated to the 2/3-digit industry level and average over the years 1994-1995, share of costs is from the 1995 input-output table and is at the industry pair level. Average firm size and age are calculated from the firm-industry pair data and average over the years 1996-2001. In regression with interactions, all main effects evaluated at sample means. Covariates included where indicated are: producing firm size, age, mean firm size and mean firm age in producing and supplying industries.

Table 5: Within industry variation: supplier technology

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
dependent variable: vi_{ijk}								
Technology indicator	R&D		Investment		growth labour productivity		growth TFP	
Share of costs (jk)	0.205	0.189	0.204	0.192	0.207	0.213	0.208	0.225
	(0.039)	(0.032)	(0.039)	(0.033)	(0.037)	(0.032)	(0.039)	(0.036)
technology, supplying (j)	-0.007	-0.003	-0.047	-0.035	-0.036	-0.016	-0.038	-0.015
	(0.004)	(0.006)	(0.012)	(0.015)	(0.013)	(0.013)	(0.015)	(0.014)
x Share of costs		-0.295		-0.708		-1.265		-1.160
		(0.274)		(0.560)		(0.365)		(0.334)
Observations	2,973,008	2,973,008	2,973,008	2,973,008	2,839,954	2,839,954	2,509,849	2,509,849
Clustering	77 supplying industries	77 supplying industries	77 supplying industries	77 supplying industries	77 supplying industries	77 supplying industries	77 supplying industries	77 supplying industries
Fixed effects	77 producing industries	77 producing industries	77 producing industries	77 producing industries	77 producing industries	77 producing industries	77 producing industries	77 producing industries
Covariates		yes		yes		yes		yes

Source: Authors' calculations using the United Kingdom Office of National Statistics data. All statistical results remain Crown Copyright.
Notes: The dependent variable is a dummy for whether a firm is vertically integrated in that industry pair at any time over the years 1996-2001. Standard errors in parentheses are clustered at the level indicated. The RHS variables firm size and firm age are measured at the firm-industry pair level in 1996 (age is equal to 1 if the firm enters that industry pair after 1996). R&D intensity is R&D carried out in the UK divided by value-added produced in the UK, taken from plant level R&D data, aggregated to the 2/3-digit industry level and average over the years 1994-1995, share of costs is from the 1995 input-output table and is at the industry pair level. Average firm size and age are calculated from the firm-industry pair data and average over the years 1996-2001. In regression with interactions, all main effects evaluated at sample means. Covariates included where indicated are: producing firm size, age, mean firm size and mean firm age in producing and supplying industries.

Table 6: Instrumental variables

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
dependent variable: vi_{ijk}								
technology variable:	R&D		Investment		growth labour productivity		growth TFP	
Share of costs (jk)	0.192 (0.029)	0.207 (0.052)	0.203 (0.028)	0.180 (0.023)	0.209 (0.027)	0.223 (0.030)	0.207 (0.031)	0.243 (0.038)
technology intensity, producing (j)	0.071 (0.011)	-0.037 (0.017)	0.083 (0.010)	0.054 (0.013)	0.134 (0.018)	0.113 (0.031)	0.173 (0.027)	0.181 (0.059)
x Share of costs		0.938 (1.111)		-0.072 (0.944)		0.095 (0.805)		-0.220 (1.340)
technology intensity, supplying (k)	-0.072 (0.012)	-0.047 (0.016)	-0.051 (0006)	-0.041 (0.008)	-0.115 (0.017)	-0.148 (0.048)	-0.034 (0.034)	-0.254 (0.101)
x Share of costs		0.329 (1.319)		-2.142 (1.023)		-0.899 (0.624)		-0.617 (0.957)
Covariates		yes		yes		yes		yes
First stage, producing industry technology								
US producing industry technology	-	-	1.070 (0.025)	0.998 (0.024)	0.685 (0.015)	0.544 (0.017)	0.456 (0.021)	0.371 (0.021)
US supplying industry technology	-	-	-0.005 (0.016)	-0.011 (0.016)	0.013 (0.019)	0.010 (0.016)	0.006 (0.017)	0.003 (0.015)
F-stat P-value	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
R^2	0.189	0.263	0.469	0.520	0.218	0.314	0.133	0.227
First stage, supplying industry technology								
US producing industry technology	-	-	-0.003 (0.031)	0.011 (0.033)	-0.0003 (0.0377)	-0.025 (0.030)	0.012 (0.045)	-0.018 (0.036)
US supplying industry technology	-	-	1.006 (0.020)	0.967 (0.022)	0.528 (0.033)	0.492 (0.029)	0.292 (0.043)	0.438 (0.033)
F-stat (P-value)	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
R^2	0.097	0.102	0.538	0.544	0.1148	0.381	0.049	0.279
Observations	2,973,008				2,839,954		2,509,849	
Clustered	3,840 industry pairs				3,840 industry pairs		3,840 industry pairs	

Source: Authors' calculations using the United Kingdom Office of National Statistics data. All statistical results remain Crown Copyright.

Notes: The dependent variable is a dummy for whether a firm is vertically integrated in that industry pair at any time over the years 1996-2001. Standard errors in parentheses are clustered at the level indicated. The RHS variables firm size and firm age are measured at the firm-industry pair level in 1996 (age is equal to 1 if the firm enters that industry pair after 1996). R&D intensity is R&D carried out in the UK divided by value-added produced in the UK, taken from plant level R&D data, aggregated to the 2/3-digit industry level and average over the years 1994-1995, share of costs is from the 1995 input-output table and is at the industry pair level. Average firm size and age are calculated from the firm-industry pair data and average over the years 1996-2001. In regression with interactions, all main effects evaluated at sample means. Covariates included where indicated are: producing firm size, age, mean firm size and mean firm age in producing and supplying industries.

Table 7: Outside option

dependent variable: vi_{ijk}	(1) R&D	(3) Investment	(5) growth labour productivity	(7) growth TFP
Share of costs (jk)	0.154	0.161	0.183	0.190
	(0.027)	(0.024)	(0.026)	(0.029)
technology, producing (j)	0.029	-0.002	0.031	0.028
	(0.005)	(0.007)	(0.008)	(0.009)
x Share of costs	0.863	1.352	0.469	-0.162
	(0.338)	(0.440)	(0.308)	(0.307)
technology, supplying (k)	-0.004	-0.031	0.0008	-0.005
	(0.003)	(0.005)	(0.0043)	(0.005)
x Share of costs	-0.762	-1.282	-1.252	-1.098
	(0.287)	(0.475)	(0.316)	(0.294)
ln Firm size (ij)	0.0052	0.0052	0.0052	0.0053
	(0.0002)	(0.0002)	(0.0002)	(0.0002)
ln Firm age (ij)	0.0009	0.0009	0.0009	0.0010
	(0.0001)	(0.0001)	(0.0001)	(0.0001)
ln Average firm size, producing (j)	-0.0012	-0.0001	-0.0007	-0.0003
	(0.0006)	(0.0006)	(0.0006)	(0.0006)
ln Average firm size, supplying (k)	-0.0022	0.0029	0.0022	0.0033
	(0.0004)	(0.0005)	(0.0006)	(0.0005)
ln Average firm age, producing (j)	0.010	0.009	0.009	0.008
	(0.002)	(0.002)	(0.002)	(0.003)
ln Average firm age, supplying (k)	0.017	0.017	0.017	0.016
	(0.002)	(0.002)	(0.002)	(0.002)
ln number of firms, producing (j)	-0.0018	-0.0019	-0.0015	-0.0017
	(0.0003)	(0.0003)	(0.0003)	(0.0003)
ln number of firms, supplying (k)	0.0055	0.0053	0.0056	0.0063
	(0.0003)	(0.0003)	(0.0003)	(0.0004)
Observations	2,973,008	2,973,008	2,839,954	2,509,849
Clustering		*3,840 industry pairs*		

Source: Authors' calculations using the United Kingdom Office of National Statistics data. All statistical results remain Crown Copyright.

Notes: The dependent variable is a dummy for whether a firm is vertically integrated in that industry pair at any time over the years 1996-2001. Standard errors in parentheses are clustered at the level indicated. The RHS variables firm size and firm age are measured at the firm-industry pair level in 1996 (age is equal to 1 if the firm enters that industry pair after 1996). R&D intensity is R&D in the UK divided by value-added produced in the UK, taken from plant level data, aggregated to the 2/3-digit industry level and average over the years 1994-1995, share of costs is from the 1995 input-output table and is at the industry pair level. Average firm size and age are averages over the years 1996-2001. Investment intensity is capital expenditure in the UK divided by value-added produced in the UK, growth in labour productivity is annual change in value-added produced in the UK divided by numbers employed in the UK, growth in TFP is measured using a superlative index (see section 3.2). All technology measures use plant level data aggregated to the 2/3-digit industry level and average over the years 1992-1995. Industries where growth in labour productivity or growth in total factor productivity were negative have been dropped. In regression with interactions, all main effects evaluated at sample means.

Table A.1: Number of single, small and single and multi-plant firms, by year

	Number of firm-industry observations	Number of single plant firm observations	Number of single plant firms with fewer than 20 employees	Number of foreign firm-industry observations	Number of multi-plant firm-industry observations	Number of firm-industry observations used
1996	155342	139749	125444	1990	15593	28146
1997	160432	146136	131090	1899	14296	27653
1998	158654	144295	130319	1093	14359	27273
1999	159771	146472	132801	1136	13299	25860
2000	156171	143446	130521	2659	12725	23644
2001	153402	140428	126275	3458	12974	24551

Source: Authors' calculations using the United Kingdom Office of National Statistics data. All statistical results remain Crown Copyright.
Notes: Total of 52,918 firms across all years and industries; sample excludes reporting units that report zero employment, industries classifications are those used in 1995 Input-Output Tables.

Table A2: Correlation between technology measures

Technology indicator	R&D intensity	investment intensity	GLP
R&D intensity	-	-	-
investment intensity	0.213	-	-
GLP	0.091	0.303	-
GTFP	-0.024	0.081	0.896

Source: Authors' calculations using the United Kingdom Office of National Statistics data. All statistical results remain Crown Copyright.

Table A.3: Summary of input-output table statistics

Supplying industry	% sales for intermediate consumption		Largest purchasing industry	% of total supplying industry sales going to this purchaser	% of total purchasing industry purchases coming from this supplier
	all industries	manufacturing			
8 Meat processing	0.441	0.250	29 Leather goods	0.019	0.502
9 Fish and fruit processing	0.461	0.195	9 Fish and fruit processing	0.085	0.141
10 Oils and fats	0.694	0.534	10 Oils and fats processing	0.161	0.208
11 Dairy products	0.403	0.183	11 Dairy products	0.109	0.143
12 Grain milling and starch	0.666	0.580	14 Bread biscuits etc	0.192	0.191
13 Animal feed	0.751	0.020	8 Meat processing	0.017	0.009
14 Bread biscuits etc	0.433	0.009	14 Bread biscuits etc	0.001	0.002
15 Sugar	0.817	0.639	16 Confectionery	0.217	0.153
16 Confectionery	0.380	0.160	16 Confectionery	0.097	0.176
17 Other food products	0.332	0.137	17 Other food products	0.043	0.075
18 Alcoholic beverages	0.100	0.070	18 Alcoholic beverages	0.065	0.127
19 Soft drinks and mineral waters	0.192	0.003	19 Soft drinks & mineral waters	0.003	0.005
20 Tobacco products	0.001	0.001	20 Tobacco products	0.001	0.001
21 Textile fibres	0.681	0.646	27 Knitted goods	0.189	0.269
22 Textile weaving	0.274	0.261	28 Wearing apparel & fur products	0.158	0.092
23 Textile finishing	0.976	0.415	23 Textile finishing	0.053	0.129
24 Made-up textiles	0.193	0.052	24 Made-up textiles	0.010	0.026
25 Carpets and rugs	0.356	0.115	25 Carpets and rugs	0.004	0.009
26 Other textiles	0.513	0.427	28 Wearing apparel & fur products	0.203	0.109
27 Knitted goods	0.030	0.019	28 Wearing apparel & fur products	0.013	0.013
28 Wearing apparel and fur products	0.099	0.018	28 Wearing apparel & fur products	0.017	0.048
29 Leather goods	0.312	0.078	30 Footwear	0.042	0.076
30 Footwear	0.219	0.065	30 Footwear	0.064	0.177
31 Wood and wood products	0.894	0.519	31 Wood and wood products	0.203	0.395
32 Pulp paper and paperboard	0.672	0.559	33 Paper and paperboard products	0.243	0.285
33 Paper and paperboard products	0.885	0.520	33 Paper and paperboard products	0.055	0.133
34 Printing and publishing	0.613	0.211	34 Printing and publishing	0.132	0.334
35 Coke ovens refined petroleum & nuclear	0.450	0.108	38 Organic chemicals	0.013	0.093
36 Industrial gases and dyes	0.535	0.459	19 Soft drinks & mineral waters	0.089	0.120

Supplying industry	% sales for intermediate consumption		Largest purchasing industry	% of total supplying industry sales going to this purchaser	% of total purchasing industry purchases coming from this supplier
	all industries	manufacturing			
37 Inorganic chemicals	0.676	0.603	37 Inorganic chemicals	0.043	0.111
38 Organic chemicals	0.056	0.052	41 Pesticides	0.005	0.051
39 Fertilisers	0.839	0.154	39 Fertilisers	0.146	0.273
40 Plastics & Synthetic resins etc	0.599	0.557	48 Plastic products	0.249	0.209
41 Pesticides	0.508	0.006	41 Pesticides	0.001	0.005
42 Paints varnishes printing ink etc	0.692	0.477	42 Paints varnishes printing ink etc	0.054	0.107
43 Pharmaceuticals	0.380	0.125	43 Pharmaceuticals	0.094	0.206
44 Soap and toilet preparations	0.229	0.105	44 Soap and toilet preparations	0.085	0.146
45 Other Chemical products	0.185	0.116	45 Other Chemical products	0.033	0.085
46 Man-made fibres	0.273	0.259	21 Textile fibres	0.058	0.100
47 Rubber products	0.552	0.243	47 Rubber products	0.041	0.102
48 Plastic products	0.759	0.405	48 Plastic products	0.081	0.179
49 Glass and glass products	0.775	0.549	49 Glass and glass products	0.133	0.276
50 Ceramic goods	0.402	0.125	50 Ceramic goods	0.046	0.113
51 Structural clay products	0.723	0.003	51 Structural clay products	0.001	0.004
52 Cement lime and plaster	0.882	0.336	53 Articles of concrete stone etc	0.286	0.136
53 Articles of concrete stone etc	0.851	0.024	53 Articles of concrete stone etc	0.022	0.044
54 Iron and steel	0.596	0.561	54 Iron and steel	0.138	0.253
55 Non-ferrous metals	0.658	0.611	55 Non-ferrous metals	0.218	0.450
56 Metal castings	0.973	0.790	62 Mechanical power equipment	0.175	0.107
57 Structural metal products	0.472	0.115	57 Structural metal products	0.025	0.050
58 Metal boilers and radiators	0.348	0.158	58 Metal boilers & radiators	0.084	0.174
59 Metal forging pressing etc	0.964	0.864	80 Aircraft and spacecraft	0.077	0.212
60 Cutlery tools etc	0.545	0.453	60 Cutlery tools etc	0.024	0.063
61 Other metal products	0.690	0.563	71 Insulated wire and cable	0.014	0.114
62 Mechanical power equipment	0.285	0.210	62 Mechanical power equipment	0.055	0.125
63 General purpose machinery	0.202	0.110	63 General purpose machinery	0.020	0.042
64 Agricultural machinery	0.132	0.009	64 Agricultural machinery	0.006	0.015
65 Machine tools	0.181	0.133	65 Machine tools	0.011	0.023
66 Special purpose machinery	0.293	0.246	66 Special purpose machinery	0.046	0.102
67 Weapons and ammunition	0.554	0.170	67 Weapons and ammunition	0.154	0.336

Supplying industry	% sales for intermediate consumption		Largest purchasing industry	% of total supplying industry sales going to this purchaser	% of total purchasing industry purchases coming from this supplier
	all industries	manufacturing			
68 Domestic appliances nec	0.187	0.019	68 Domestic appliances nec	0.007	0.014
69 Office machinery & computers	0.060	0.049	69 Office machinery & computers	0.035	0.094
70 Electric motors and generators etc	0.390	0.301	70 Electric motors and generators etc	0.072	0.165
71 Insulated wire and cable	0.550	0.304	71 Insulated wire and cable	0.031	0.073
72 Electrical equipment nec	0.491	0.388	74 Transmitters for TV radio and phone	0.112	0.274
73 Electronic components	0.126	0.115	69 Office machinery & computers	0.048	0.052
74 Transmitters for TV radio and phone	0.204	0.020	74 Transmitters for TV radio and phone	0.014	0.032
75 Receivers for TV and radio	0.134	0.091	75 Receivers for TV and radio	0.055	0.126
76 Medical and precision instruments	0.360	0.129	76 Medical and precision instruments	0.036	0.090
77 Motor vehicles	0.200	0.112	64 Agricultural machinery	0.005	0.200
78 Shipbuilding and repair	0.536	0.061	78 Shipbuilding and repair	0.061	0.142
79 Other transport equipment	0.275	0.154	79 Other transport equipment	0.152	0.305
80 Aircraft and spacecraft	0.107	0.011	80 Aircraft and spacecraft	0.011	0.029
81 Furniture	0.233	0.077	81 Furniture	0.053	0.114
82 Jewellery and related products	0.020	0.017	82 Jewellery & related products	0.016	0.044
83 Sports goods and toys	0.014	0.001	12 Grain milling and starch	0.001	0.001
84 Miscellaneous manufacturing nec & recycl	0.543	0.406	56 Metal castings	0.034	0.117

Source: United Kingdom Office of National Statistics, 1995 Input Output Tables

Table A.4: Robustness checks

	(1)	(2)	(3)	(4)
dependent variable: vi_{ijk}				
Technology indicator	R&D intensity	investment	growth labour productivity	growth TFP
exclude industry pairs where producing=supplying				
Share of costs (jk)	0.216	0.210	0.252	0.260
	(0.024)	(0.025)	(0.031)	(0.041)
technology, producing (j)	0.036	0.0006	0.038	0.029
	(0.006)	(0.0077)	(0.009)	(0.010)
x Share of costs	2.121	1.802	1.205	0.282
	(0.678)	(0.497)	(0.644)	(0.569)
technology, supplying (k)	-0.0003	-0.043	-0.017	-0.016
	(0.0024)	(0.005)	(0.005)	(0.005)
x Share of costs	0.011	-1.857	-1.393	-1.247
	(0.225)	(0.462)	(0.377)	(0.377)
Observations	2,916,478	2,916,478	2,783,895	2,456,625
exclude bottom quartiles of firms by size				
Share of costs (jk)	0.201	0.208	0.236	0.244
	(0.030)	(0.023)	(0.025)	(0.029)
technology, producing (j)	0.030	-0.020	0.027	0.025
	(0.006)	(0.008)	(0.009)	(0.010)
x Share of costs	1.146	1.582	0.531	-0.056
	(0.389)	(0.453)	(0.349)	(0.337)
technology, supplying (k)	-0.0074	-0.046	-0.014	-0.013
	(0.0038)	(0.005)	(0.004)	(0.005)
x Share of costs	-0.953	-1.770	-1.317	-1.072
	(0.352)	(0.468)	(0.277)	(0.249)
Observations	2,249,095	2,249,095	2,146,991	1,890,941
exclude top quartiles of firms by size				
Share of costs (jk)	0.103	0.105	0.124	0.131
	(0.021)	(0.020)	(0.023)	(0.026)
technology, producing (j)	0.014	0.010	0.036	0.026
	(0.003)	(0.006)	(0.007)	(0.007)
x Share of costs	0.477	0.618	0.146	-0.380
	(0.254)	(0.379)	(0.254)	(0.277)
technology, supplying (k)	-0.005	-0.023	-0.009	-0.009
	(0.002)	(0.004)	(0.003)	(0.003)
x Share of costs	-0.474	-1.013	-0.885	-0.691
	(0.211)	(0.415)	(0.270)	(0.239)
Observations	2,234,459	2,234,459	2,136,696	1,903,222

Table A.4: Robustness checks *continued.*

dependent variable: vi_{ijk}	(1)	(2)	(3)	(4)
Technology indicator	R&D intensity	investment	growth labour productivity	growth TFP
Probit estimation, marginal effects				
Share of costs (jk)	0.070	0.071	0.075	0.079
	(0.006)	(0.005)	(0.006)	(0.006)
technology, producing (j)	0.012	-0.008	0.025	0.020
	(0.002)	(0.005)	(0.006)	(0.006)
x Share of costs	0.171	0.269	0.024	-0.155
	(0.080)	(0.139)	(0.103)	(0.103)
technology, supplying (k)	-0.002	-0.036	-0.010	-0.010
	(0.002)	(0.005)	(0.004)	(0.005)
x Share of costs	-0.140	-0.157	-0.195	-0.117
	(0.100)	(0.141)	(0.065)	(0.059)
Observations	2,973,008	2,973,008	2,829,954	2,509,849
dependent variable: $\overline{vi}_{ijk}$				
Share of costs (jk)	0.114	0.116	0.131	0.135
	(0.016)	(0.014)	(0.015)	(0.017)
technology, producing (j)	0.022	-0.003	0.029	0.024
	(0.004)	(0.006)	(0.007)	(0.008)
x Share of costs	0.554	0.661	0.267	-0.141
	(0.224)	(0.299)	(0.223)	(0.197)
technology, supplying (k)	-0.004	-0.033	-0.013	-0.014
	(0.002)	(0.004)	(0.003)	(0.004)
x Share of costs	-0.413	-0.757	-0.729	-0.613
	(0.199)	(0.314)	(0.168)	(0.143)
Observations	2,973,008	2,973,008	2,839,954	2,509,849

Source: Authors' calculations using the United Kingdom Office of National Statistics data. All statistical results remain Crown Copyright.
Notes: The dependent variable is a dummy for whether a firm is vertically integrated in that industry pair at any time over the years 1996-2001. Standard errors in parentheses are clustered at the*3,840 industry pairs* level in all specifications. The RHS variables firm size and firm age are measured at the firm-industry pair level in 1996 (age is equal to 1 if the firm enters that industry pair after 1996). R&D intensity is R&D carried out in the UK divided by value-added produced in the UK, taken from plant level R&D data, aggregated to the 2/3-digit industry level and average over the years 1994-1995, share of costs is from the 1995 input-output table and is at the industry pair level. Average firm size and age are calculated from the firm-industry pair data and average over the years 1996-2001. Investment intensity is capital expenditure carried out in the UK divided by value-added produced in the UK, growth in labour productivity is annual change in value-added produced in the UK divided by numbers employed in the UK, growth in total factor productivity is measured using a superlative index (see section 3.2). All technology measures use plant level data aggregated to the 2/3-digit industry level and average over the years 1992-1995. Industries where growth in labour productivity or growth in total factor productivity were negative have been dropped. In regression with interactions, all main effects evaluated at sample means. All regressions include producing firm size, age, mean firm size and mean firm age in producing and supplying industries.
Covariates in all specifications include: firm size and age, producing and supplying industry average size and average age.

Table A.5: Nonlinearities

dependent variable: vi_{ijk}	(1)	(2)	(3)	(4)	(5)	(6)
Share of cost:						
Medium	0.0031			0.0039	0.0038	0.0035
	(0.0004)			(0.0005)	(0.0005)	(0.0005)
High	0.0171			0.0167	0.0167	0.0157
	(0.0009)			(0.0009)	(0.0009)	(0.0010)
Producing industry R&D intensity:						
2nd quartile		0.0034		0.0028	0.0015	0.0008
		(0.0009)		(0.0009)	(0.0009)	(0.0008)
3rd quartiles		0.0053		0.0040	0.0031	0.0027
		(0.0010)		(0.0009)	(0.0009)	(0.0008)
4th quartile		0.0054		0.0046	0.0031	0.0023
		(0.0010)		(0.0009)	(0.0009)	(0.0009)
Supplying industry R&D intensity:						
2nd quartile			-0.0076	-0.0059	-0.0059	-0.0048
			(0.0013)	(0.0011)	(0.0011)	(0.0010)
3rd quartiles			0.0032	-0.0021	-0.0021	0.0003
			(0.0014)	(0.0012)	(0.0012)	(0.0012)
4th quartile			-0.0038	-0.0038	-0.0038	-0.0034
			(0.0014)	(0.0012)	(0.0012)	(0.0012)
Observations	2,973,008	2,973,008	2,973,008	2,973,008	2,973,008	2,973,008
Clustering			3,840 industry pairs			
Covariates					firm size and age	all

Source: Authors' calculations using the United Kingdom Office of National Statistics data. All statistical results remain Crown Copyright.

Notes: The dependent variable is a dummy for whether a firm is vertically integrated in that industry pair at any time over the years 1996-2001. Standard errors in parentheses are clustered at the level indicated. The RHS variables firm size and firm age are measured at the firm-industry pair level in 1996 (age is equal to 1 if the firm enters that industry pair after 1996). R&D intensity is R&D carried out in the UK divided by value-added produced in the UK, taken from plant level R&D data, aggregated to the 2/3-digit industry level and average over the years 1994-1995, share of costs is from the 1995 input-output table and is at the industry pair level. Average firm size and age are calculated from the firm-industry pair data and average over the years 1996-2001. Investment intensity is capital expenditure carried out in the UK divided by value-added produced in the UK, growth in labour productivity is annual change in value-added produced. Covariates included where indicated are: producing firm size, age, mean firm size and mean firm age in producing and supplying industries. in the UK divided by numbers employed in the UK, growth in total factor productivity is measured using a superlative index (see section 3.2). All technology measures use plant level data aggregated to the 2/3-digit industry level and average over the years 1992-1995. Industries where growth in labour productivity or growth in total factor productivity were negative have been dropped. In regression with interactions, all main effects evaluated at sample means. The reference group is zero share of costs and bottom quartiles of R&D intensity in producing and supplying industries. share of costs is from the 1995 input-output table and is at the industry pair level.