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Abstract

Apart from the familiar holdup problem, we investigate another implication of specific investment that has not been examined systematically in the literature. That is, the presence of specific investment can make a supplier vulnerable to large negative shocks to its customer's business. In a theoretical model, we demonstrate that this vulnerability causes the supplier to under-invest. A higher degree of specificity induces the supplier to invest *more*, and it leads to a lower mean and higher volatility in the supplier's profit. Using panel data on over 5000 U.S. firms from 1990 to 2010, our empirical analysis shows the prevalence of the supplier vulnerability problem associated with specific investment.

Key Words: specific investment, holdup problem, supplier vulnerability, profit volatility

JEL Classification: L14, L24, G32

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1. Introduction

Relationship-specific investment is a central element in the theory of the firm. At the core of the theory is the holdup problem, that is, the problem of under-investment caused by incomplete contracting and opportunistic behavior. Voluminous theoretical analyses have been conducted to investigate contracts and organizational forms (*e.g.*, vertical integration and long-term contracting) that would remedy the holdup problem and achieve the optimal level of investment.[1] The predictions from many of these theories have been tested and received support in the empirical literature.[2]

In this paper, we investigate another implication of the specific investment that, to our knowledge, has not been examined systematically in this literature. That is, the presence of specific investment can make a supplier vulnerable to large negative shocks to its customer's business. Consider, for example, a situation where a supplier produces a custom-made product for a customer. If the customer later suffers a large shock that renders it incapable of fulfilling its commitment to purchase, the supplier will have to either sell its product to another buyer at a substantial discount or make significant modifications to the product to fit the needs of an alternative customer. The higher is the degree of asset specificity, the more vulnerable is the supplier to customer-specific risks.

The empirical relevance of this idea can be illustrated by the example of Getrag Transmission Manufacturing, a supplier of automobile transmission systems. In November 2008, Getrag put its unfinished plant in Tipton, Indiana into bankruptcy

[1] See, for example, Klein, Crawford, and Alchian (1978), Williamson (1985), MacLeod and Malcomson (1993), Hart (1995), Edlin and Reichelstein (1996), Che and Hausch (1999), Lyon and Rasmusen (2004), Schweizer (2006), Stremitzer (2012), and Itoh and Morita (2015).

[2] Contributions to the empirical literature include Monteverde and Teece (1982), Anderson and Schmittlein (1984), Joskow (1987), Crocker and Masten, (1988), Leffler and Rucker (1991), Lyons (1994), Saussier (2000), Bandiera, (2007) and Tang (2010). For an extensive survey, see Macher and Richman (2008).

protection, blaming its customer Chrysler's termination of an exclusive contract (Bennett 2008). The Tipton plant, 80% complete, was being built specially to supply Chrysler with dual clutch transmissions before Chrysler announced it was terminating the deal over financial issues in October 2008. Subsequently, Chrysler itself filed for bankruptcy in 2009. This example illustrates the devastating effect of a customer-specific shock can have on a supplier when substantial specific investments are involved.

In this paper, we conduct a theoretical and empirical analysis of the supplier vulnerability problem associated with specific investment. Specifically, we consider the following two questions: (1) How does the supplier vulnerability problem affect the level of specific investment, and how does it differ from the investment holdup problem? (2) How prevalent is the supplier vulnerability problem in reality?

To answer the first question, we construct a model of specific investment that incorporates both the holdup problem and the supplier vulnerability problem. In the model, a supplier makes a specific investment that, *ceteris paribus*, increases the value of its product to a buyer. The latter, however, is subject to random shocks. This creates the possibility that the realized value of the product to the buyer may fall below its alternative-use value. We use this model to investigate the impact of asset specificity on the supplier's incentive to invest in the specific asset and on the mean and volatility of the supplier's profit in the presence of the supplier vulnerability problem.

Our theoretical analysis reveals that in some respects, the supplier vulnerability problem has the same qualitative effects as the holdup problem. Specifically, it causes the supplier to under-invest in the specific asset, and a higher degree of specificity reduces the supplier's expected profit.

Of more interest are the differences between the supplier vulnerability problem and the holdup problem. With the supplier vulnerability problem, a higher degree of specificity increases the volatility of the supplier's profit, and it induces the supplier to increase, rather than decrease, the specific investment. Neither of these properties is shared by the holdup problem.

To answer the second question, we conduct an empirical analysis using panel data on U.S. firms from 1990 to 2010. Note that our theoretical model predicts a positive relationship between the volatility of supplier profit and the degree of specificity for the supplier vulnerability problem but not for the holdup problem. This gives us a convenient way to test the presence of the supplier vulnerability problem.

Findings from the empirical analysis confirm the predictions from our theoretical model. Specifically, we find that a higher degree of specificity reduces the level and increases the volatility of supplier profit. These relationships are robust to different specifications, including different measures of asset specificity and profit, and are consistent over different time periods. These findings, obtained from a large sample of more than 5000 firms across over 500 industries in the U.S., suggest that the supplier vulnerability problem exists and is quite prevalent.

In addition to contributing to the academic literature on specific investment, the findings from our analysis have practical implications for the management of supplier firms. They suggest that the risks associated with customer-specific investments go beyond the familiar investment holdup problem. When contracting with customers that involve specific investments, care should be taken not only to resolve the inefficiencies associated with the holdup problem, but also to mitigate the elevated risks to the supplier's profit.

This paper is organized as follows. We conduct the theoretical analysis in section 2, and the empirical analysis in section 3. Section 4 concludes.

2. Theoretical Model

2.1 Description of the Model

We adapt a standard model of specific investment (*e.g.*, Tirole 1988) to incorporate supplier vulnerability to customer risks. Suppose that a buyer, named firm B, procures 0 or 1 unit of a good from a supplier, named firm S. Firm S can make an investment that increases the value of the good to firm B. The investment is relationship-specific in the sense that firm S would receive a price less than the expected value of the good to firm B if firm S sells it in an open market.

Let I denote the level of investment (measured in the monetary unit) made by firm S. For simplicity, we assume that the cost of producing the good itself is 0.

The value of the good to firm B is represented by $V(I) + \varepsilon$, where ε is a random variable. We interpret the value of the good as the revenue that firm B can earn from using this good in its business. The investment by firm S increases the value of the good to firm B; accordingly, $V'(I) > 0$. Moreover, we assume that $V(I)$ is continuously differentiable, bounded above, and satisfies $V(0) > 0$, $V'(0) > 1$, and $V''(I) < 0$. The last two inequalities imply that the marginal benefit of the first unit of investment exceeds its marginal cost, but the investment is subject to diminishing returns.

The random variable ε represents the risks in firm B's business. The inclusion of the random variable enables us to model the idea that the specific investment may make firm S vulnerable to the risks in its customer's business. We assume that ε is uniformly distributed in the interval $[-\alpha, \alpha]$. This implies that $E(\varepsilon) = 0$ and hence the expected value of the good to the seller is $V(I)$. The standard deviation of ε is $\alpha/\sqrt{3}$; thus a larger α means greater risks in firm B's business.

The supplier has the option of selling the good in an open market. But it would receive a price less than $V(I)$ because the investment is relationship-specific. We use $r(\psi)$ to denote this price, where $r'(\psi) < 0$. Parameter $\psi \in [0,1]$ is an index that measures of the degree of specificity. A larger ψ represents a higher degree of specificity, in which case the supplier would receive a lower price for the good in the open market. Following the literature (*e.g.*, Itoh and Morita 2015), we will also refer to $r(\psi)$ as the alternative-use value of the good.[3]

As is standard in this literature, we assume that it is not possible for the two firms to write an enforceable contract on the level of specific investment and the firms negotiate the price of the good after firm S has made the investment. This assumption makes it possible for firm B to engage in opportunistic behavior, causing the holdup problem.

Accordingly, Firm S and Firm B play the following two-stage game. At stage 1, the two firms meet and firm S chooses the level of specific investment I without knowing the realization of random variable ε. At stage 2, the value of ε becomes known to both firms and they negotiate the price at which the good is traded, denoted by p. Depending on the outcome of the negotiation, firm S either sells the good to firm B at price p or in the open market at price $r(\psi)$.

Recall that the value of the good to firm B is random. Consequently, $V(I) > r(\psi)$

[3] To simplify presentation, here we assume that $r(\psi)$ is independent of the level of specific investment I. In the appendix, we present a more general model in which the alternative-use value is a monotonic function of I, and show that all our theoretical predictions are valid independent of whether I has a positive or negative effect on the alternative-use value.

does not necessarily mean that $V(I)+\varepsilon > r(\psi)$ for all realized values of ε. If α is sufficiently large (and hence $-\alpha$ is sufficiently small), there is a positive probability that the value of the good to firm B is lower than the price firm S can receive in the open market, *i.e.*, $V(I)+\varepsilon < r(\psi)$.

The negotiation between the two firms is modeled as the generalized Nash bargaining problem (Harsanyi and Selton 1972). If they reach an agreement, firm S earns a profit of $p - I$ and firm B obtains a surplus of $V(I)+\varepsilon-p$. If they fail to reach an agreement, firm S sells the good in the open market and receives a profit of $r(\psi) - I$. Firm B does not obtain the good and earns zero surplus. Note that the supplier's disagreement payoff depends on the degree of specificity ψ.

The generalized Nash bargaining problem can be expressed as:

$$max_p \, [p - I - (r(\psi) - I)]^{\gamma}[V(I) + \varepsilon - p]^{1-\gamma}, \qquad (1)$$

where $\gamma \in (0,1)$ measures the relative bargaining power of firm S. A larger γ enables firm S to receive a larger share of the gain from this transaction.

We will use this model to investigate the impact of asset specificity on the supplier's incentive to invest in the specific asset and on the mean and volatility of the supplier's profit. We will consider two factors that may drive these relationships, namely, the holdup problem and the supplier vulnerability problem.

2.2. Efficient Level of Investment

As the benchmark for later analysis, we start by characterizing the *ex ante* efficient level of investment that maximizes the expected total surplus from the transaction between firm S and firm B. That is, we solve the following optimization problem:

$$max_I \, E[V(I) + \varepsilon - I] = V(I) - I. \quad (2)$$

The solution, denoted by I^*, must satisfy the first-order condition:

$$V'(I^*) = 1. \qquad (3)$$

Equation (3) has the standard interpretation that the marginal benefit of an extra unit of investment must equal to its marginal cost.

2.3 Specific Investment and the Holdup Problem

Here we analyze the impact of specific investment on the supplier's profit due to the holdup problem. To do so, we focus on a situation where the potential gain from selling to firm B exceeds what firm S can receive from the open market even in the worst-case scenario (where $\varepsilon = -\alpha$), *i.e.*, $V(I) - \alpha > r(\psi)$. Rearranging the inequality, we obtain:

$$\alpha < V(I) - r(\psi). \qquad (4)$$

The analysis in this section is conducted under the assumption that (4) holds for I in the relevant range. This assumption enables us to remove the impact of the supplier's vulnerability to customer risks because (4) implies that the negative shock to firm B's business is never large. The alternative situation, where $\alpha > V(I) - r(\psi)$, will be considered in the next section.

Condition (4) ensures that both firms can gain from the transaction for any realization of $\varepsilon \in [-\alpha, \alpha]$. For given values of ε and I, we solve (1) to find the negotiated price of the good:

$$p^N = \gamma[V(I) + \varepsilon] + (1 - \gamma)r(\psi). \qquad (5)$$

Inequality (4) implies that $p^N > r(\psi)$ for any $\varepsilon \geq -\alpha$. Using (5) we find the profit of firm S:

$$\pi_S = p^N - I = \gamma[V(I) + \varepsilon] + (1 - \gamma)r(\psi) - I. \qquad (6)$$

At stage 1 of the game, firm S chooses the level of investment I to maximize its expected profit:

$$max_I\, E(\pi_S) = \gamma V(I) + (1-\gamma)r(\psi) - I. \quad (7)$$

We use subscript "H" to indicate the equilibrium in this case. Then the equilibrium level of investment, I^H, is determined by the first-order condition:

$$\gamma V'(I^H) = 1. \qquad (8)$$

Condition (8) has the familiar interpretation that the supplier's marginal revenue of investment equals to its marginal cost. Since $\gamma \in (0,1)$, a comparison of (3) and (8) yields the standard result: $I^H < I^*$. In other words, the holdup problem leads to under-investment.

Note that (8) does not contain ψ. This implies that the degree of asset specificity has no impact on the level of investment chosen by the supplier. The intuition behind this result can be understood by a close examination of the negotiated price given in (5). Recall that the degree of specificity influences the supplier's profit through its disagreement payoff $r(\psi)$. A higher degree of specificity weakens the supplier's bargaining position by reducing its disagreement payoff. This, as can be seen in (5), lowers the price and hence the total revenue the supplier can earn from its investment. However, the level of investment is determined by the supplier's marginal revenue rather than total revenue. From (5) we can see that the marginal revenue of investment is not affected by the degree of specificity.

In addition, from (8) we see that the level of investment is independent of α. In other words, the volatility in firm B's revenue does not have any impact on the level of investment chosen by the supplier. This is not surprising given that condition (4) ensures that the potential gain from selling to firm B never falls below what firm S can receive from selling in the open market

Next, we consider how the degree of specificity affects the level and volatility of the supplier's profit. Let μ be the mean and σ the standard deviation of the supplier's profit. Then the equilibrium value of μ is given by (7) with $I = I^H$. Using the envelope theorem, we find that

$$\frac{\partial \mu^H}{\partial \psi} = (1-\gamma) r'(\psi) < 0\,. \qquad (9)$$

That is, a higher degree of specificity reduces the supplier's expected profit as a result of the holdup problem.

Using (6) and (7) we calculate the variance of the supplier's profit:

$$\sigma^H = \sqrt{E(\pi_s - \mu^H)^2} = \sqrt{\gamma^2 E(\varepsilon^2)} = \frac{\gamma\alpha}{\sqrt{3}}\,, \qquad (10)$$

which is independent of ψ. In other words, the standard deviation of the supplier's profit is not affected by the degree of specificity. Therefore, the holdup problem associated with specificity neither increases, nor decreases, the risk in the supplier's profit.

The intuition behind the preceding results can be seen from the negotiated price given in (5). As pointed out earlier, a higher degree of specificity weakens the supplier's bargaining position by reducing its disagreement payoff. This lowers the price and hence the supplier's expected profit. Note from (5) that while the degree of specificity changes the price level, it has no impact on its variance. That is why an increase in the degree of specificity does not change the standard deviation of the supplier's profit.

To summarize the main results obtained so far, we have:

Proposition 1: Provided that (4) holds, an increase in the degree of specificity reduces the supplier's expected profit, but has no impact on either the variance of the supplier's profit or the equilibrium level of specific investment.

Proof: The results follow from (8) – (10). QED

2.3 Specific Investment and the Supplier Vulnerability Problem

Specific investment can influence the supplier's profit and its investment via a different channel than the holdup problem. If the customer's business is subject to large negative shocks, this downstream risk may be transmitted upstream to exert a negative impact on the supplier's profit. A higher degree of specificity makes the supplier more vulnerable to such upward transmission of downstream risks.

To explore the implication of this supplier vulnerability problem, we analyze our model under the assumption

$$\alpha > V(I) - r(\psi) \qquad (11)$$

for I in the relevant range. This assumption implies that the supplier cannot be assured that $V(I) - \alpha > r(\psi)$. With a positive probability, the opposite will be true, in which case firm B can only afford to pay a price lower than the open market price $r(\psi)$. If that happens, the two firms will not be able to reach an agreement and the supplier will sell the good in the open market at price $r(\psi)$.

To isolate the effects of the supplier vulnerability problem, we now assume that $\gamma = 1$. This removes the impact of the investment holdup problem from our analysis.

Given (11), the supplier will sell the good to firm B only if the realized value of ε satisfies $V(I) + \varepsilon \geq r(\psi)$, *i.e.*, if $\varepsilon \geq -[V(I) - r(\psi)]$. This implies that, at stage 2 of the game, firm S and firm B will be able to negotiate the price in accordance with (5) only if $\varepsilon \geq -[V(I) - r(\psi)]$. If $\varepsilon < -[V(I) - r(\psi)]$, on the other hand, they will not be able to reach an agreement with regard to the price and firm S will sell the good in the open market at price $r(\psi)$. Recalling that ε is uniformly distributed in the interval $[-\alpha, \alpha]$ and $\gamma = 1$, we write the expected value of the supplier's profit as:

$$E(\pi_S) = \int_{-\alpha}^{-[V(I)-r(\psi)]} \frac{r(\psi)}{2\alpha} d\varepsilon + \int_{-[V(I)-r(\psi)]}^{\alpha} \frac{V(I) + \varepsilon}{2\alpha} d\varepsilon - I. \qquad (12)$$

At stage 1 of the game, firm S chooses I to maximize (12). We use superscript SV to denote the equilibrium in the presence of the supplier vulnerability problem. The equilibrium level of investment, denote by I^{SV}, is determined by the following first-order condition:

$$\frac{V'(I^{SV})[V(I^{SV}) + \alpha - r(\psi)]}{2\alpha} = 1. \qquad (13)$$

The left-hand side of (13) represents the supplier's marginal revenue of investment. A close examination of (13) reveals:

Proposition 2: Suppose $\gamma = 1$ and the volatility in firm B's revenue is sufficiently high that condition (11) holds. The equilibrium level of investment is lower than the *ex ante* efficient level, *i.e.*, $I^{SV} < I^*$. Furthermore, an increase in the volatility of firm B's revenue reduces the level of investment, *i.e.*, $\partial I^{SV}/\partial \alpha < 0$. On the other hand, a higher degree of asset specificity raises the level of investment, *i.e.*, $\partial I^{SV}/\partial \psi > 0$.

Proof: Condition (11) implies $[V(I^{SV}) + \alpha - r(\psi)]/2\alpha < 1$. Hence, the LHS of (13) is less than $V'(I^{SV})$. Then (3) and (13) imply that $I^{SV} < I^*$. Conducting comparative statics on (13), we find:

$$\frac{\partial I^{SV}}{\partial \alpha} = \frac{V'(I^{SV})[V(I^{SV}) - r(\psi)]}{2\alpha^2[\partial^2 E(\pi_S)/\partial I^2]} < 0, \qquad (14)$$

where $\partial^2 E(\pi_S)/\partial I^2 < 0$ by the second-order condition of the supplier's profit-maximization problem. On the other hand, it can be shown that:

$$\frac{\partial I^{SV}}{\partial \psi} = \frac{V'(I^{SV})r'(\psi)}{2\alpha[\partial^2 E(\pi_S)/\partial I^2]} > 0, \tag{15}$$

where $V'(I) > 0$, $r'(\psi) < 0$ and $\partial^2 E(\pi_S)/\partial I^2 < 0$. QED

Proposition 2 suggests that the supplier's vulnerability to the volatility in the downstream market causes it to under-invest in the specific asset. The higher is the downstream volatility, the lower is the level of investment. It is worth emphasizing that the under-investment is not caused by the hold-up problem because the assumption $\gamma = 1$ ensures that the supplier receives the full marginal benefit of the investment as long as the good is sold to firm B.[4] The under-investment arises because there is a positive probability that the good is sold in an open market rather than to firm B, in which case the supplier does not receive the full marginal benefit of the investment.

The most surprising part of Proposition 2 is that a higher degree of specificity induces the supplier to increase the level of investment. On the surface, an increase in the degree of specificity appears to make the supplier more vulnerable to the downstream risks. Hence, one might have expected that the investment would fall with the degree of specificity.

To understand why this result arises, note that a higher degree of specificity reduces the alternative-use value $r(\psi)$. This increases the probability that the good will actually be sold to firm B. This, in turn, raises the supplier's marginal benefit of investment in (13). In other words, while a higher degree of specificity lowers the total benefit that firm S receives from the investment, it has an opposite effect on its marginal benefit.

Turning to the effects of specific investment on the supplier's profit, we use (12) to

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[4] We could turn on the effects of the holdup problem by setting $\gamma < 1$ in the analysis. It can be shown that this would further reduce the equilibrium level of investment.

calculate the mean and standard deviation of its profit and conduct comparative statics with respect to the degree of asset specificity.

Proposition 3: Suppose $\gamma = 1$ and the volatility in firm B's revenue is sufficiently high that condition (11) holds. An increase in the degree of specificity reduces the mean but increases the standard deviation of the supplier's profits.

Proof: We differentiate (12) to find:

$$\frac{\partial \mu^{SV}}{\partial \psi} = \frac{r'(\psi)}{2\alpha}\{\alpha - [V(I^{SV}) - r(\psi)]\} < 0. \qquad (16)$$

The expression for the variance of the supplier's profit is quite intricate. To simplify presentation, we define $x \equiv V(I^{SV}) - r(\psi)$. Condition (11) then becomes $\alpha > x$. It can be shown that:

$$(\sigma^{SV})^2 = \left[\frac{(\alpha - x)(\alpha + x)^4 + (\alpha + x)(\alpha - x)^4}{32\alpha^3} + \frac{\alpha^3 + x^3}{6\alpha} - \frac{(\alpha + x)(\alpha - x)^3}{8\alpha^2}\right]. \qquad (17)$$

Noting that the value of x depends on ψ and I^{SV}, we differentiate (17) to obtain:

$$\frac{\partial(\sigma^{SV})^2}{\partial \psi} = \frac{\partial \sigma^2}{\partial x}\left[\frac{\partial x}{\partial I}\frac{\partial I^{SV}}{\partial \psi} + \frac{\partial x}{\partial \psi}\right] = \frac{(\alpha - x)(\alpha + x)^2}{4\alpha^2}\left[V'(I^{SV})\frac{\partial I^{SV}}{\partial \psi} - r'(\psi)\right] > 0. \quad (18)$$

QED

Intuitively, a higher degree of asset specificity lowers the supplier's expected profit because it reduces its revenue in the event of a very bad shock to the customer's business. The volatility in the supplier's profit, on the other hand, is affected by asset specificity through two channels. First, holding the level of investment I constant, a higher degree of specificity raises σ through $r(\psi)$. Recall that the supplier would have to sell the good in the open market at the price $r(\psi)$ if firm B suffers a very large negative shock (*i.e.*, if $\varepsilon < -[V(I^{SV}) - r(\psi)]$). A smaller $r(\psi)$ means a lower price for the good in such a situation, thus increasing the standard deviation of the supplier's profit. Second, the volatility in the supplier's profit is increased also because a higher degree of specificity induces the supplier to boost the level of investment. The elevated level of investment raises the value of $V(I)$ and hence the maximum price the supplier can receive (recalling that $\gamma = 1$ in (5)), but it has no impact on the minimum price $r(\psi)$. The standard deviation of the supplier's profit is larger as a result.

2.4 Testable Predictions of the Model

The empirical question we would like to answer in this paper is: How prevalent is the supplier vulnerability problem in reality? To answer this question, we need to find a way to detect the presence of the supplier vulnerability effect. The results from our theoretical analysis imply two potential ways to do this.

The first way is to estimate the relationship between the degree of specificity and the level of specific investment. A comparison of Propositions 1 and 2 indicates that the supplier vulnerability problem is present if we find a positive relationship between these two variables. Implementing this approach, however, is very challenging because data on the level of specific investment made by individual firms are difficulty to identify and obtain.

The second way is to estimate the relationship between the degree of specificity and the supplier's profit. While the holdup problem and the supplier vulnerability problem both imply a negative relationship between asset specificity and the expected profit of the supplier, they have different implications for the relationship between asset specificity and the volatility of the supplier's profit. The holdup problem implies 0 correlations between the degree of asset specificity and the standard deviation of the supplier's profit.

But a positive correlation is expected if the supplier vulnerability problem is present.

The data requirement for the implementation of the second approach is much less demanding than the first approach. Data on profits of firms are relatively easy to find. Taking this into consideration, we conduct an empirical analysis on the relationship between asset specificity and the supplier's profit, with an aim to establish the prevalence of the supplier vulnerability effect.

With this mind, we highlight the following testable predictions from the theoretical analysis:

(1) There is a negative relationship between the degree of specificity and the expected profit of the supplier.

(2) There is a non-negative relationship between the degree of specificity and the standard deviation of the supplier's profit.

(3) A positive correlation between the degree of specificity and the standard deviation of the supplier's profit, in conjunction with a negative correlation between the degree of specificity and the supplier's expected profit, implies the presence of supplier vulnerability problem.

We test these predictions in the next section.

3. Empirical Implementation

3.1 Overview

To empirically test the theoretical predictions, we estimate two regressions of the following form:

$$PROFIT\ LEVEL = \beta_0 + \beta_1 RSI + \beta_2 CONTROL + \epsilon, \qquad (19)$$

$$PROFIT\ VOLATILITY = \delta_0 + \delta_1 RSI + \delta_2 CONTROL + \eta, \qquad (20)$$

where *PROFIT LEVEL* and *PROFIT VOLATILITY* represent the mean and standard deviation of a supplier firm's future profits, respectively. Among the right-hand side variables in (19) and (20), *RSI* denotes the degree of specificity, and *CONTROL* is a vector of control variables.

Our model predictions imply that $\beta_1 < 0$ and $\delta_1 \geq 0$. Moreover, a strictly positive δ_1 would imply the presence of the supplier vulnerability effect.

Key to our empirical implementation is how to measure the degree of specificity (*RSI*). Following the literature, we measure asset specificity by two sets of variables: R&D intensity of the supplier's customers, and the intensity of strategic alliances (SAs) and joint ventures (JVs) among the supplier's customers. We will discuss the rationale and construction of these variables below.

3.2 Data and Measurement

We estimate (19) and (20) using the data on U.S. firms covered by Compustat and the Center for Research in Security Prices (CRSP) from 1990 and 2010. To construct the proxies for asset specificity, we obtain the supplier-customer linkage data from the Use table of the benchmark input-output (IO) accounts for the US economy provided by the Bureau of Economic Analysis, and the data on SAs and JVs from the Merger and Acquisition database by the Securities Data Company (SDC).

3.2.1 Asset Specificity

In our main tests of (19) and (20), we use customer R&D intensity as the measure of the degree of specificity (*RSI*). Previous studies on transactions cost economics (Armour and Teece 1980, Levy 1985, Allen and Phillips 2000) suggest that R&D-intensive industries are more likely to create relationship-specific assets and incur complex interstage interdependencies. Therefore, it is common in the empirical literature on transactions cost economics to use R&D intensity as a proxy for asset specificity (Kale and Shahrur 2007; Macher and Richman 2008).

We use the method in Kale and Shahrur (2007) to construct our measure of R&D intensity in a supplier's customers. Specifically, we measure customer R&D intensity as the weighted average of the R&D expenditure intensities in the industries of a supplier firm's customers. The weight represents the importance of the output bought by each customer industry in the firm's total output.

In our main tests, the customer R&D intensity is calculated using the supplier-customer linkage at the industry level. In other words, for supplier firms in industry *i*, their customer R&D intensity is given by the following equation:

$$\text{Customer R\&D Intensity} = \sum\nolimits_j RDI_j \times S_{ij}, \qquad (21)$$

where RDI_j is the j^{th} customer industry's R&D expenditures divided by its total assets, and S_{ij} is the percentage of the i^{th} industry's output sold to the j^{th} customer industry. The latter measures the importance of the j^{th} customer industry as a buyer of the output of a supplier firm in industry i.

The advantage of relying on industry-level linkage of customer-supplier relationships for the calculations of customer R&D intensity is that it enables us to circumvent the limitation imposed by the fact that Compustat only includes major customer identity information of a few firms that voluntarily report it since 1997. This gives us a large sample of more than 5000 firms across over 500 industries. Since one of our goals is to test the prevalence of the supplier vulnerability problem, such a large sample is desirable.

To identify the supplier-customer linkage across industries and the importance of each customer industry to the supplier industry, we rely on the Use table of the benchmark input-output (IO) accounts for the US economy. For each pair of supplier and customer industries, the Use table reports an estimate on the dollar value of the supplier industry's output that is used as an input in the production of the customer industry's output. The Use tables are updated every five years. Since 1997, benchmark accounts are constructed based on the North American Industry Classification System (NAICS) instead of the SIC coding system. To be consistent across the sample period, we only use the NAICS-based Use tables. In particular, we use the 1997 and 2002 Use tables for the sample periods 1990–1999 and 2000-2010, respectively.

Table 1 lists the top 10 industries with highest and lowest customer R&D intensity. Those with highest customer R&D intensity are concentrated in high-tech industries such as information and communications technology and electronic engineering. On the other hand, those with lowest customer R&D intensity are concentrated in light or service industries such as water supplier facilities, prepared food and social services. We observe a significant variation in customer R&D intensity across different industries in the cross section, with 8.6% for the highest and close to zero for the lowest.

3.2.2 Profit level and profit volatility

Following the empirical literature in finance (Barber and Lyon 1996, Brav, *et al*. 2005 and 2008, Booth and Zhou 2013), we use two measures of profit. The first measure is the return on assets (ROA), defined as the operating income before depreciation scaled by book value of total assets. In order to avoid the bias introduced by potential earnings manipulations of the accrual-based operating income, we use a second measure that is the cash-flow return on assets (CFROA), defined as the operating cash flow scaled by the average of beginning and ending period book value of total assets. The operating cash flow in CFROA is equal to the operating income before depreciation plus the decrease in receivables, the decrease in inventory, the increase in accounts payable, the increase in other current liabilities, and the decrease in other current assets.

We calculate the mean of ROA and the mean of CFROA over a five-year period, from year $t + 1$ to year $t + 5$, as the proxies for the expected level of profit in year *t*. We obtain the standard deviations of ROA and CFROA over the same five-year period as the proxies for the volatility of profit in year *t*.

3.2.3 Control variables

In our regressions, we control for a set of known determinants of the level and volatility of firm profit (see, *e.g.*, Irvine and Pontiff 2009, Booth and Zhou 2013). They include the characteristics of a supplier firm such as firm size, firm R&D level, current profitability, asset growth rate, current stock return volatility, and leverage ratio. We calculate firm size as the natural logarithm of the firm's book value of total assets. A supplier firm's R&D level is measured by the ratio of its R&D expenses to the book value of total assets. Current profitability is calculated as earnings before interest and taxation over the book value of total assets. Asset growth rate is measured by total assets value over its lag value. Leverage is the ratio of firm long-term debt level to firm market value of total assets. To control for the overall risk of the firm, we use current volatility of stock return measured by the standard deviation of a firm's monthly returns during a one-year period.

Moreover, we use industry dummies to control for industry fixed effects associated with factors such as cross-industry differences in profit measures and intensity of horizontal competition. Year dummies are included in the regressions to control for time fixed effects.

3.2.4 Sample construction and summary statistics

To construct the sample, we use all U.S. firms covered by Compustat and CRSP from 1990 to 2010. We exclude financial firms (SIC codes between 6000 and 6999) and utility firms (SIC codes between 4900 and 4999) because their profit level and risk may be largely affected by government regulations rather than market forces. Our final sample covers firms across more than 500 different IO industries and 5000 different firms during the sample period. To ensure that our results are not driven by micro firms, we drop those observations with total assets smaller than 10 million dollars. To reduce the impact of outliers, we winsorize other variables at the 1% level.

Table 2 presents a description of all the variables used in the main tests, and Table 3 contains summary statistics of the sample. There is substantial variation in customer R&D intensity, which increases from 0.004% to 0.082% as the firm moves from the 5th percentile point to the 95th percentile point. Table 4 reports the correlation matrix among all variables. Note that firm expected profit, measured by ROA level and CFROA level, is negatively correlated with the degree of specificity, while the profit volatility (ROA volatility and CFROA volatility) is positively correlated with the degree of specificity. They are consistent with the testable predictions (1) – (3).

3.3 Empirical Results

We conduct fixed effects panel regressions to investigate the impact of specific investment on the level and volatility of a supplier firm's profit. Included in all regressions are (two-digit) industry dummies and year dummies to control for fixed effects across industries and time. For all the regressions, we calculate the standard errors by clustering at the firm level to account for within-firm correlation of the error terms.[5]

The regression results from our main tests are reported in Table 5. In columns (1)-(4), the dependent variable is the expected profit level of a supplier firm measured by its ROA level and CFROA level. We start in column (1) by regressing the firm's ROA level on its customer R&D intensity. The estimated coefficient of customer R&D intensity is negative (-1.218) and significant at the 1% level. In column (2), we augment the model in column (1) by adding controls for additional firm characteristics. The estimated coefficient of customer R&D intensity remains negative (-0.321) and significant at the 1% level. We use the level of CFROA as the measure of profit in columns (3) and (4), the coefficients for customer R&D intensity are consistently negative and statistically significant at the 1% level. These results suggest that a higher degree of specificity reduces the expected profit of supplier firms, and they provide empirical support for our testable prediction (1).

In columns (5)-(8), the dependent variable is the standard deviation of a supplier firm's profit, measured by its ROA standard deviation and CFROA standard deviation. The estimated coefficients of customer R&D intensity are significantly positive for all regressions reported in these columns. These results provide empirical support for our testable prediction (2). Most importantly, they confirm our testable prediction (3); in other words, the positive relationship between the volatility in profits and the degree of specificity, in conjunction with the negative relationship between the expected profit and the degree of specificity, proves the existence of the supplier vulnerability problem.

In addition, coefficient estimates of the control variables in Table 5 indicate that

[5] We also check the results by clustering errors at industry level and the results are consistent.

firms that are larger or are currently more profitable can expect higher and less volatile profits in the future. On the other hand, firms with high growth rates or large current volatility in profits will have lower expected level and higher volatility in profit in the future.

3.4 Robustness

3.4.1 Using customer SA/JV to measure the degree of specificity

To verify the robustness of our results to the choice of proxy for the degree of specificity, we use the strategic alliances and joint ventures (SA/JV) intensity of customer firms as an alternative proxy. It has been recognized in the theoretical literature that hybrid forms of organizations such as SAs and JVs can alleviate the holdup problem (Macher and Richman 2008). Moreover, an empirical study by Fee, Hadlock, and Thomas (2005) has found that a firm is more likely to establish SAs and JVs with trading partners that are expected to undertake relationship-specific investments. This implies that the degree of specificity is likely to be higher if the firm and its trading partners have established such arrangements.

We obtain data on SA/JV transactions during the period 1990-2010 from the Merger and Acquisition database provided by the Securities Data Company (SDC). The database contains information about the SIC industries of the participants in the SA/JV deals. Using the SIC-based 1992 IO Use tables and the SIC codes of the SA/JV participants, we determine whether at least one of the other participants in the SA/JV deal operates in a supplier industry. For each four-digit SIC code industry, we define SA/JV intensity as the number of SAs and JVs formed by firms in that industry with firms in a customer industry divided by the total number of firms in that industry.

In Table 6, we use customer SA/JV intensity as the target variable in the regression models. Columns (1)-(2) show that a firm's expected profit level decreases as customer SA/JV intensity increases, suggesting that a higher degree of specificity reduces the future profitability of the supplier firm. On the other hand, columns (3) and (4) demonstrate that the standard deviation of a firm's future profit rises as customer SA/JV intensity increases. Therefore, our findings regarding the relationships between asset specificity and the level and volatility of a firm's future profit are not restricted to a specific measure of the degree of specificity.

3.4.2 Using alternative IO tables and alternative time periods

As additional robustness checks, we also estimate our model using alternative IO tables and for different time periods. Specifically, we run three sets of additional tests. In the first set of additional tests, we use the 1992 SIC-based Use table to construct the *RSI* variable for the entire sample period. Recall that in the main tests we utilize the 1997 and 2002 Use tables, which are based on the NAICS system, for the sample periods 1990–1999 and 2000-2010, respectively.

In the second set of additional tests, we study a longer sample period from 1980 to 2010. As there are five IO tables from 1982 to 2002, we construct the *RSI* variable using all these IO tables for firms from 1980 to 2010. Specifically, we employ the 1982, 1987, 1992, 1997 and 2002 IO Use tables for the periods 1980-1984, 1985–1989, 1990–1994, 1995–1999, and 2000-2010, respectively.

In the third set of additional tests, we further control for the sub-periods by adding a dummy variable for every five years to all specifications. This is done for all three ways of matching IO industry information.

To conserve space, we do not present the details of all the robustness checks here. Instead, we report in Table 7 a set of results that are representative of these robustness tests. Specifically, the results in Table 7 are obtained from the regressions using the SIC-based IO table updated in 1992 for the sample period from 1990 to 2010. They show that the relationship between the degree of specificity and the level of expected profit is negative and statistically significant for both measures of profit, and the relationship between the degree of specificity and the volatility of profit is positive for both measures of profit and statistically significant for one of the two measures of profit. While these results are not as strong as those in our main tests, they do provide further evidence for the presence of the supplier vulnerability problem. Overall, these additional tests suggest that our empirical results are reasonably robust to the use of alternative IO tables and different time periods.

Finally, it is worth reiterating that our empirical results are obtained from a broad sample of over 5000 firms across more than 500 different IO industries. In all the specifications discussed above, we have consistently found a negative relationship between the degree of specificity and the expected profit, on the one hand, and a positive relationship between the degree of specificity and the volatility in profit, on the other hand. Considering the broadness of the sample used in these regressions, we view these findings as evidence that the supplier vulnerability problem is prevalent in reality.

4. Conclusion

This paper contributes to the literature on specific investment by investigating the effects of the supplier vulnerability problem. Using a theoretical model, we have demonstrated that this vulnerability causes the supplier to under-invest in the specific asset. A higher degree of asset specificity reduces the supplier's expected profit, but it also induces the supplier to increase its investment. Moreover, a higher degree of specificity leads to higher volatility in the supplier's profit, a property that distinguishes the supplier vulnerability problem from the hold-up problem. Based on panel data covering over 5000 firms in the U.S. from 1990 to 2010, our empirical analysis confirms the existence and prevalence of the supplier vulnerability problem associated with specific investment.

Table 1 Industries with Highest and Lowest Customer Specificity

This table shows industries with highest extent of customer RSI. Measure of customer RSI is the weighted average R&D intensity of all customer industries. R&D intensity of customer industries is defined based on the benchmark input-output (IO) accounts for the US economy at the Bureau of Economic Analysis website. Panel A shows Top 10 industries with highest average customer RSI over 1990 to 2010. Panel B shows Top 10 industries with lowest average customer RSI over 1990 to 2010.

Panel A: Top 10 industries with highest customer specificity

IO Code	Customer R&D Intensity	Industry Name
334113	0.086	Computer terminals and other computer peripheral equipment manufacturing
334111	0.073	Electronic computer manufacturing
334112	0.071	Computer storage device manufacturing
511200	0.065	Software publishers
33461A	0.048	Software, audio, and video media reproducing
334512	0.047	Automatic environmental control manufacturing
334290	0.047	Other communications equipment manufacturing
33441A	0.045	Electronic capacitor, resistor, coil, transformer, and other inductor manufacturing
334413	0.044	Semiconductor and related device manufacturing
334220	0.044	Broadcast and wireless communications equipment

Panel B: Top 10 industries with lowest customer specificity

IO Code	Customer R&D Intensity	Industry Name
337920	0.000	Blind and shade manufacturing
623000	0.000	Nursing and residential care facilities
120209	0.000	Water supply facilities
315119	0.000	Other hosiery and sock mills
770900	0.000	Social services, n.e.c.
331314	0.000	Secondary smelting and alloying of aluminum
760206	0.000	Other amusement and recreation services
339995	0.000	All other miscellaneous manufacturing
360600	0.000	Vitreous china plumbing fixtures
141200	0.000	Prepared fresh or frozen fish and seafoods

Table 2: Variable Descriptions

The table provides a detailed description of the construction of all of the variables used in the main tests.

Variables	Description
Customer R&D intensity	The weighted average R&D intensity of all customers; the weight is retrieved from the Use table of the benchmark input-output (IO) accounts for the US economy on the Bureau of Economic Analysis website: the weight is the percentage of the i^{th} industry's output that is sold to the j^{th} customer industry.
Size	The log value of book value of total assets (at).
R&D level	Firm's R&D expenses over book value of total assets (xrd/at).
Current profitability	Earnings before interest and taxation over book value of total assets (ebit/at).
Current volatility	Standard deviation of a firm's monthly returns during a year t.
Asset growth	Book value of total assets at year t over its lag value
Leverage	Long term debt level over firm market value at year t.
ROA level	The mean of ROA during year [t+1, t+5].
ROA volatility	The standard deviation of ROA during year [t+1, t+5].
CFROA level	The mean of CFROA during year [t+1, t+5].
CFROA volatility	The standard deviation of CFROA during year [t+1, t+5].

Table 3: Summary Statistics

The table reports summary statistics for the variables we use in the main tests. The sample covers the period 1990-2010 and excludes financial institutions (SIC codes 6000 to 6999) and utilities (SIC codes 4900 to 4999) from the sample. To mitigate the effect of outliers, we exclude firms with total assets less than 10 million. We winsorize all other variables at the 1% level.

Variable	Mean	Median	Std	p5	p95
Customer R&D intensity	0.032	0.023	0.026	0.004	0.082
Size	5.440	5.185	1.936	2.722	9.061
R&D level	0.054	0.001	0.106	0.000	0.257
Current profitability	0.018	0.064	0.192	-0.392	0.225
Current volatility	0.158	0.134	0.097	0.053	0.352
Asset growth	0.166	0.061	0.485	-0.301	1.000
Leverage	0.130	0.064	0.160	0.000	0.478
ROA volatility	0.055	0.035	0.058	0.009	0.180
ROA level	0.092	0.115	0.140	-0.200	0.260
CFROA volatility	0.072	0.054	0.062	0.015	0.198
CFROA level	0.094	0.111	0.127	-0.158	0.254

Table 4: Variable Correlation Matrix

The table reports the correlations among customer RSI and all other control variables. The sample covers the period 1990-2010 and excludes financial institutions (SIC codes 6000 to 6999) and utilities (SIC codes 4900 to 4999) from the sample.

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
Customer R&D intensity	1.000										
Size	-0.156	1.000									
R&D level	0.423	-0.241	1.000								
Current profitability	-0.159	0.249	-0.581	1.000							
Asset growth	0.037	-0.026	-0.025	0.093	1.000						
Current volatility	0.239	-0.343	0.308	-0.366	0.126	1.000					
Leverage	-0.220	0.211	-0.272	0.006	-0.075	-0.075	1.000				
ROA volatility	0.238	-0.349	0.476	-0.428	0.069	0.332	-0.204	1.000			
ROA level	-0.225	0.275	-0.524	0.705	-0.064	-0.352	0.113	-0.575	1.000		
CFROA volatility	0.157	-0.337	0.370	-0.386	0.041	0.285	-0.136	0.738	-0.505	1.000	
CFROA level	-0.210	0.307	-0.523	0.699	-0.073	-0.350	0.135	-0.528	0.956	-0.453	1.000

Table 5: The Impact of Specific Investment on Profit level and Volatility

This table presents the impact of specific investment, without and with controls, on a firm's profit level and volatility in the near future. The dependent variables are profit level measured by ROA level and CFROA level, and profit volatility measured by ROA standard deviation and CFROA standard deviation. Coefficients are estimated by OLS regression. Year fixed-effects and two-digit IO Industry fixed-effects are included for all the regressions. Clustered robust standard errors are at firm level and used to account for within-firm correlation of the error terms.

Variables	Dependent variable: Profit level				Dependent variable: Profit volatility			
	ROA		CFROA		ROA		CFROA	
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Customer R&D intensity	-1.218***	-0.321***	-0.997***	-0.182***	0.568***	0.131***	0.420***	0.051*
	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.05)
Size		0.005***		0.007***		-0.005***		-0.006***
		(0.00)		(0.00)		(0.00)		(0.00)
R&D level		-0.160***		-0.131***		0.141***		0.108***
		(0.00)		(0.00)		(0.00)		(0.00)
Current profitability		0.505***		0.484***		-0.074***		-0.084***
		(0.00)		(0.00)		(0.00)		(0.00)
Current volatility		-0.076***		-0.066***		0.071***		0.075***
		(0.00)		(0.00)		(0.00)		(0.00)
Asset growth		-0.032***		-0.033***		0.007***		0.004***
		(0.00)		(0.00)		(0.00)		(0.00)
Leverage		0.030***		0.045***		-0.026***		-0.012***
		(0.00)		(0.00)		(0.00)		(0.01)
Constant	0.158***	0.061***	0.148***	0.041***	0.010	0.058	0.037	0.083
	(0.00)	(0.00)	(0.00)	(0.00)	(0.10)	(0.00)	(0.00)	(0.00)
Year dummies	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Industry dummies	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Observations	42,585	37,339	40,519	35,624	42,585	37,339	40,519	35,624
R-squared	0.11	0.57	0.09	0.56	0.11	0.37	0.05	0.26

Table 6: The Impact of Specific Investment on Profit Level and Volatility
-Using Customer SA/JV Intensity

This table presents the impact of a firm's specific investment measured by customer SA/JV. The dependent variables are profit level measured by ROA level and CFROA level, and profit volatility measured by ROA standard deviation and CFROA standard deviation. For each 4-digit SIC industry, we define customer SA/JV intensity as the number of SAs and JVs formed by firms in that industry with firms in a customer industry divided by the number of firms in the industry. Year fixed-effects and two-digit IO Industry fixed-effects are included for all the regressions. Clustered robust standard errors are at firm level and used to account for within-firm correlation of the error terms.

Variables	Dependent variable: Profit level		Dependent variable: Profit volatility	
	ROA	CFROA	ROA	CFROA
	(1)	(2)	(3)	(4)
Customer SA/JV intensity	-0.010**	-0.000	0.010***	0.007***
	(0.01)	(0.96)	(0.00)	(0.01)
Size	0.005***	0.007***	-0.005***	-0.006***
	(0.00)	(0.00)	(0.00)	(0.00)
R&D level	-0.205***	-0.172***	0.148***	0.101***
	(0.00)	(0.00)	(0.00)	(0.00)
Current profitability	0.490***	0.470***	-0.072***	-0.086***
	(0.00)	(0.00)	(0.00)	(0.00)
Current volatility	-0.085***	-0.072***	0.075***	0.078***
	(0.00)	(0.00)	(0.00)	(0.00)
Asset growth	-0.032***	-0.033***	0.007***	0.004***
	(0.00)	(0.00)	(0.00)	(0.00)
Leverage	0.027***	0.041***	-0.028***	-0.012***
	(0.00)	(0.00)	(0.00)	(0.00)
Constant	0.054***	0.040***	0.060***	0.085***
	(0.00)	(0.00)	(0.00)	(0.00)
Year dummies	Yes	Yes	Yes	Yes
Industry dummies	Yes	Yes	Yes	Yes
Observations	40,135	38,200	40,135	38,200
R-squared	0.55	0.54	0.36	0.25

Table 7: The Impact of Customer RSI on Profit level and Volatility
-Using SIC-based IO Table

This table presents the impact of a firm's customer RSI basing on the 1992 SIC-based Use table for the entire sample period from 1990 to 2010. Coefficients are estimated by OLS panel regressions. Year fixed-effects and two-digit IO Industry fixed-effects are included for all the regressions. Clustered robust standard errors are at firm level and used to account for within-firm correlation of the error terms.

Variables	Dependent variable: Profit level		Dependent variable: Profit volatility	
	ROA	CFROA	ROA	CFROA
	(1)	(2)	(3)	(4)
Customer R&D intensity	-0.299***	-0.265***	0.011	0.082*
	(0.000)	(0.001)	(0.788)	(0.060)
Size	0.005***	0.007***	-0.005***	-0.006***
	(0.000)	(0.000)	(0.000)	(0.000)
R&D level	-0.125***	-0.110***	0.151***	0.097***
	(0.000)	(0.000)	(0.000)	(0.000)
Current profitability	0.495***	0.465***	-0.063***	-0.084***
	(0.000)	(0.000)	(0.000)	(0.000)
Current volatility	-0.075***	-0.063***	0.071***	0.072***
	(0.000)	(0.000)	(0.000)	(0.000)
Asset growth	-0.029***	-0.031***	0.006***	0.004***
	(0.000)	(0.000)	(0.000)	(0.000)
Leverage	0.022***	0.034***	-0.026***	-0.009**
	(0.000)	(0.000)	(0.000)	(0.018)
Constant	0.118***	0.110***	0.058***	0.092***
	(0.00)	(0.00)	(0.00)	(0.00)
Year dummies	Yes	Yes	Yes	Yes
Industry dummies	Yes	Yes	Yes	Yes
Observations	38,072	38,072	38,072	38,072
R-squared	0.55	0.56	0.35	0.27

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Appendix

A More General Model

Here we present a more general model where the alternative-use value of the good depends on both ψ and I. Specifically, we augment the alternative-use value function in the main text by adding a function of I, so that the price firm S can receive in the open market becomes: $r(\psi) + \rho(I)$. As explained in Itoh and Morita (2015), one can come up with examples where the alternative-use value decreases with specific investment and examples where the opposite is true. Accordingly, we allow $\rho(I)$ to be either monotonically decreasing or monotonically increasing in I. Consistent with the definition of specific investment, we assume that $V'(I) > \rho'(I)$. This assumption is automatically satisfied in the case $\rho'(I) < 0$. In the case where $\rho(I)$ is an increasing function, this assumption means that the marginal value of an extra unit of specific investment for firm B is larger than the marginal increase in the alternative-use value. On $r(\psi)$, We maintain the same assumptions as in the main text.

Below we prove that all theoretical results in the main text continue to hold in this more general model. To distinguish from the case in the main text, we add a † to indicate the equilibrium in this more general model.

A1. The Holdup Problem

Condition (4) now becomes $\alpha < V(I) - r(\psi) - \rho(I)$. The profit of firm S now becomes:

$$\pi_S = \gamma[V(I) + \varepsilon] + (1-\gamma)[r(\psi) + \rho(I)] - I. \quad (A1)$$

Its choice of the specific investment is governed by:

$$\gamma V'(I^{H\dagger}) + (1-\gamma)\rho'(I^{H\dagger}) = 1. \quad (A2)$$

The assumption $V'(I) > \rho'(I)$ implies that the LHS of (A2) is less than $V'(I^{H\dagger})$. Then from (A2) and (3) we conclude that $I^{H\dagger} < I^*$; that is, firm S under-invests. Note that (A2) is independent of ψ. Using (A1), we calculate the mean and standard deviation of firm S's profit, and find that $\partial\mu/\partial\psi$ and σ are the same as (9) and (10). Therefore, the results in Proposition 1 continue to hold.

A2. The Supplier Vulnerability Problem

Condition (11) now becomes $\alpha > V(I) - r(\psi) - \rho(I)$. Given the assumption $\gamma = 1$, the expected profit of firm S is:

$$E(\pi_S) = \int_{-\alpha}^{-[V(I)-r(\psi)-\rho(I)]} \frac{r(\psi)+\rho(I)}{2\alpha} d\varepsilon + \int_{-[V(I)-r(\psi)-\rho(I)]}^{\alpha} \frac{V(I)+\varepsilon}{2\alpha} d\varepsilon - I. \qquad (A3)$$

The level of specific investment is determined by the supplier's first-order condition:

$$\frac{V'(I^{SV\dagger})[V(I^{SV\dagger}) + \alpha - r(\psi) - \rho(I^{SV\dagger})] + \rho'(I^{SV\dagger})[\alpha + r(\psi) + \rho(I^{SV\dagger}) - V(I^{SV\dagger})]}{2\alpha} = 1. \quad (A4)$$

The assumption $V'(I) > \rho'(I)$ implies that the LHS of (A4) is less than $V'(I^{SV\dagger})$. Then from (A4) and (3) we conclude that $I^{SV\dagger} < I^*$. Conducting comparative statics on (A4), we find:

$$\frac{\partial I^{SV\dagger}}{\partial\alpha} = \frac{[V'(I^{SV\dagger}) - \rho'(I^{SV\dagger})][V(I^{SV\dagger}) - r(\psi) - \rho(I^{SV\dagger})]}{2\alpha^2[\partial^2 E(\pi_S)/\partial I^2]} < 0; \qquad (A5)$$

$$\frac{\partial I^{SV\dagger}}{\partial\psi} = \frac{[V'(I^{SV\dagger}) - \rho'(I^{SV\dagger})]r'(\psi)}{2\alpha[\partial^2 E(\pi_S)/\partial I^2]} > 0. \qquad (A6)$$

Hence, the results in Proposition 2 remain valid.

Furthermore, we differentiate (A3) to obtain:

$$\frac{\partial\mu^{SV\dagger}}{\partial\psi} = \frac{r'(\psi)}{2\alpha}\{\alpha - [V(I^{SV\dagger}) - r(\psi) - \rho(I^{SV\dagger})]\} < 0. \qquad (A7)$$

The variance of the supplier's profit can be written in the same form as (17) with x being revised to $x \equiv V(I^{SV}) - r(\psi) - \rho(I^{SV})$. We differentiate it to find:

$$\frac{\partial(\sigma^{SV})^2}{\partial\psi} = \frac{(\alpha - x)(\alpha + x)^2}{4\alpha^2}\left[[V'(I^{SV\dagger}) - \rho'(I^{SV\dagger})]\frac{\partial I^{SV\dagger}}{\partial\psi} - r'(\psi)\right] > 0. \quad (A8)$$

Equations (A7) and (A8) confirm Proposition 3.