Investment Strategies for Sourcing a New Technology in the Presence of a Mature Technology

Wei Zhang[a], Hsiao-Hui Lee[b]

[a]Faculty of Business and Economics, the University of Hong Kong

[b]Department of Management Information Systems, National Chengchi University

[a]wzhang15@hku.hk;[b]hsiaohui@nccu.edu.tw

Abstract

To stay competitive, high-technology manufacturers not only frequently source new technologies from their suppliers, but also financially support the development of these new technologies into component products or production tools. We consider a manufacturer that can either source a new but immature technology from a financially constrained supplier, or source a mature technology from an existing supplier if and only if the development of the new technology fails. To support the new technology, the manufacturer can choose to inject capital in the form of an equity or a loan. The investment strategy not only affects the new supplier's development effort and the probability of technical success (PTS), but also affects the existing supplier's effort to improve the mature technology, which presents the manufacturer with a trade-off. Following the debt financing literature, we find that a loan contract is associated with a cost-shifting effect and often leads to a higher PTS. However, because the manufacturer not only maintains an investment but also a procurement relationship with the new supplier, we find a profit-sharing effect associated with an equity investment, which does not exist in the traditional equity issuance literature. In particular, we show that the profit-sharing effect can dominate the cost-shifting effect and lead to a higher PTS when the new supplier's technological capability is sufficiently high. Nonetheless, we also show that the strategy that derives a higher PTS does not necessarily generate a higher payoff for the manufacturer. On the one hand, a loan can be preferred even when it leads to a lower PTS because the cost-shifting effect allows the manufacturer to offer a sufficiently low procurement payment while maintaining a sufficiently high PTS. On the other hand, when the existing supplier is very capable of reducing its costs, a loan can over-incentivize the new supplier to exert excessive effort and backfire.

Keywords: New technology adoption; supply chain financing; collaborative R&D

1 Introduction

Rapid technology advancements and intense market competition compel high-technology firms to continually launch products that feature novel technologies. A typical example is the smartphone market, in which companies such as Apple, Samsung, and Huawei release products with new features almost every year. Another example is the microprocessor market, in which companies such as Intel and AMD are always chasing Moore's Law and frequently introducing new products based on process technologies that enable smaller and faster microprocessors. In many cases, firms must bet on new technologies that are not ready for large-scale production; a significant amount of effort and investment is required—in further research and development (R&D), validation, and/or capacity expansion—before these new technologies can be used. However, despite these upfront efforts, a successful product development is not always guaranteed.

To complicate matters further, these new technologies are often offered by upstream component (or equipment) suppliers with financial constraints, which adds uncertainty to on-time delivery. To enhance a new technology's probability of success, buying firms (manufacturers) often need to invest in these suppliers in various ways; however, it remains unclear which way is optimal. Loan and equity investments are two commonly-used strategies that buying firms pursue. In a loan investment, a manufacturer often provides a supplier with a pre-payment, and the supplier, in turn, is expected to pay back the loan if the technology is successfully delivered. However, if the R&D fails, then the manufacturer may not be able to fully recover the investment because the loan is mostly secured by the supplier's technology-specific assets, the market value of which could be greatly reduced should the development of the new technology fail (see the Apple-GTAT example below). In an equity investment, a manufacturer acquires shares of the supplier, the value of which will be affected by the outcome of the R&D. Unlike a loan investment, an equity investment does not require that the supplier pays back that investment, but does require that the supplier shares the firm value with the manufacturer. These two investment strategies offer different incentives for both manufacturers and suppliers, so manufacturers must carefully consider such differences when they choose how to invest.

In practice, investment strategy decisions also consider whether a backup technology exists. In general, a backup technology, if any, is a *mature* technology that offers a reliable but perhaps inferior level of cost or performance compared with the new one. If the new technology cannot be successfully delivered, then a manufacturer can return to the mature one (without significant product redesign). Intuitively, the worse the mature technology performs when compared to the new one, the more a manufacturer desires the new technology and, hence, intends to offer more financial support. Knowing this, the supplier (which we call the existing supplier) that offers the mature technology may want to improve the mature technology (e.g., shorten the performance gap, lower costs) to increase the chance of winning the business. Hence, in addition to the investment strategy choice and the uncertainty of the new product development process, and the manufacturer also must consider a trade-off between supporting the new technology and motivating the improvement of the mature technology during the sourcing process. We illustrate the costs, benefits, and decisions faced by high-technology manufacturers when they invest in a new technology with the following two examples (see Appendix I for a more detailed case study of these two examples).

We start with the loan investment case in which Apple Inc. invested in the sapphire screen offered by GT Advanced Technology Inc. (GTAT). Expecting to differentiate new iPhones with scratch-and-fracture-resistant screens, Apple entered a five-year, $589 million contract in November 2013 with GTAT. GTAT expected to use this investment to accelerate its development of Advanced Sapphire Furnace, and in turn, GTAT planned to reimburse Apple for purchasing sapphire screens over five years, beginning in 2015 (the screens were originally planned for iPhone 6 and future products). However, if the sapphire screen production could not meet Apple's operational targets, the contract allowed Apple to exit and revert to its existing supplier: Corning Inc. In particular, Corning was still trying to enhance its product (e.g., the new Antimicrobial Gorilla Glass launched in January 2014), despite Apple's signing the contract with GTAT. Eventually, the collaboration failed, and Apple decided to exit the contract with GTAT around September 2014 and did not pay the last loan installment of $139 million due at the end of October 2014, which led to GTAT's bankruptcy. While Apple still had time (at least one quarter) to sign a supply contract with Corning, the payback of the loan from GTAT was only secured by the 2,036 Advanced Sapphire Furnaces purchased and installed for the Apple. The market value of these furnaces was unknown.[1]

The second case illustrates the equity investment of Intel Corp. in ASML Holding N.V. (ASML) for its new wafer and lithography technologies. Intel announced in July 2012 that it would enter into a series of agreements with ASML in order to accelerate the development of ASML's two new technologies for up to two years. According to these agreements, Intel would spend, in total, $4.1 billion to acquire 15 percent of ASML's equity and commit to advanced purchase orders from ASML. In turn, ASML would provide certain commercial discounts in the form of credits to be applied to Intel's future tool purchases. On the other hand, Intel's backup option was to stick with the current wafer and lithography technologies, which could not

[1] http://investor.gtat.com/common/download/sec.cfm?companyid=AMDA-1AHIQM&fid=1445305-14-4770&cik=1394954.

be significantly improved, so that Intel had an exogenous backup option. Eventually, the new production line successfully started its operation in 2017, and Intel exited the collaboration by selling its shares (Blake 2017). We note that Intel needed to consider not only the investment problem but also the procurement problem under this supply-chain context, which is different from the traditional equity issuance literature that only considers the former.

These two examples raise important questions for manufacturers before they commit to their respective investment choices. First, given the moral hazard caused by unobservable R&D effort, which investment strategy can better motivate a new supplier's effort and its chance of success? It is well-known that a loan investment will incentivize the new supplier to invest more in R&D because the non-labor cost (e.g., the furnaces in the Apple-GTAT case) will not be internalized in the case of a failure due to a limited liability (i.e., cost-shifting effect); in turn, higher (non-labor) investments motivate higher effort. Nonetheless, an equity investment under such a supply-chain setting allows a manufacturer to offer a higher procurement payment and, thus, a higher incentive to the new supplier because the manufacturer shares the profit (as an increase in equity value) when the new supplier succeeds. We call this phenomenon the profit-sharing effect, which generally does not exists in the equity issuance literature as there is no procurement between investors and investees. In this paper, we first explore when this profit-sharing effect can dominate the cost-shifting effect and lead to a higher probability of technical success (PTS). That said, whether the PTS fully determines the investment choice remains unclear. Hence, we next explore whether the strategy with a higher PTS leads to a higher expected payoff for the manufacturer. Finally, we determine the extent to which the existence of a backup option impacts a manufacturer's investment decision.

Using a stylized game-theoretic model, we find non-intuitive answers to these questions. First, we find that the profit-sharing effect associated with an equity can dominate the cost-shifting effect associated with a loan by leading to a higher PTS when a new supplier's technological capability (or a new technology's maturity level) is high. However, the PTS alone cannot explain a manufacturer's optimal choice of investment strategy. We find that when the new supplier's new technology is neither too mature nor too immature, a manufacturer may prefer a loan investment strategy that leads to a lower PTS than an equity because the cost-shifting effect allows the manufacturer to offer a sufficiently low procurement payment while maintaining a fair PTS. Moreover, we find that when the new supplier's new technology is sufficiently immature and the existing supplier has a sufficiently high incentive and ability to reduce costs (i.e., the existing supplier not only is very capable of cost reduction, but also has relatively similar bargaining power against the manufacturer), a manufacturer may prefer an equity investment strategy that leads to a lower PTS. In this case, the cost-shifting effect overly incentivizes the new supplier to exert effort and, thus, disincentivizes the very capable existing supplier, a phenomenon that is not identified in the literature. To ensure that our findings are robust, we build extensions in Appendix II to consider a more complicated alternative cost function, a technology-dependent demand, and a convertible debt option.

In sum, our contributions are threefold. First, we study the dual role of an investment strategy in directly and indirectly motivating two different suppliers, respectively, in technology sourcing, and we point out an interesting phenomenon of incentive over-correction associated with a loan. Second, we identify the profit-sharing effect associated with an equity investment. Third, we provide guidelines for manufacturers facing investment decisions when supporting their new suppliers in developing new technologies. Such guidelines can be extremely valuable, especially in cases that may affect industry standards (e.g., the Apple-GTAT collaboration).

2 Related Literature

Our paper is most relevant to four streams of literature: debt financing with limited liability, new technology adoption, supply chain financing, and collaborative R&D in supply chains. To the best of our knowledge, our paper is the first to study the choice of supply chain financing strategies for sourcing a new technology.

First, our work is closely related to the literature that studies debt financing (or a loan contract in our context) for a firm with limited liability. Early studies (e.g., Jensen and Meckling 1976; Myers 1977; Brander and Lewise 1986) examine incentives that induce firms to make risky inventory decisions due to limited losses that result from a limited liability when violating contract terms. In the corporate finance literature, several studies (e.g., Innes 1990; Dam and Ruiz-Pérez 2012; Héber 2018) compare a loan and an equity contract, though both can be preferred under different model considerations In the operations management literature, Buzacott and Zhang (2004) is the first to incorporate asset-based financing (loans) in production decisions. Chod and Zhou (2014) find that resource flexibility mitigates agency conflicts associated with debt financing. Also, Chod (2017) studies how limited liability distorts a retailer's ordering decisions for multiple items with various costs, revenues, and demand patterns, and shows that financing from suppliers (as a form of trade credit) can mitigate a retailer's risky behavior. Ning and Babich (2018) find knowledge spillover induces firms to under-invest in R&D projects, and hence, may cancel out the over-investment effect due to limited liability. Finally, our paper is most closely related to de Véricourt and Gromb (2017), which examine optimal financing choices (e.g., loan, equity, convertible bonds) for a firm's capacity. Similar to all papers in this stream, we find that loan investment with limited liability in new technology adoption is associated with a cost-shifting effect. However, our paper offers a key distinction: we show that an equity in a supply-chain setting can induce a profit-sharing effect, and it may dominate a loan contract.

In the new technology adoption literature, early studies mainly focus on the timing of adoption related to a single technology, and some studies consider the impact of either strategic interactions of firms in the product market or an uncertainty about the value of new technology (see Hoppe (2002) for a detailed review of studies in this category). More recently, Goyal and Netessine (2007) study the selection between a flexible and a dedicated technology before capacity investment. Boyabatlı and Toktay (2011) and Boyabatlı et al. (2016) study a similar problem, but they consider a budget-constrained firm and focus on the impacts of credit terms, capital budget, financial flexibility, and demand uncertainty. Using a setting very similar to ours, Krishnan and Bhattacharya (2002) study the selection of component technology (i.e., a mature or a prospective, but unproven, technology) in the development stage of a new product. As most studies in this stream of research ignore firm interactions, our paper contributes to this stream by investigating the impact of strategic interactions with the supplier of the new technology, the impact of investment strategies, and the impact of the existence of an existing supplier as a backup option with respect to technology selection.

Supply chain financing is an emerging topic in the field of operations management. The majority of studies in this stream of literature focus on trade credit or deferred payments, which can be used to deal with suppliers' moral hazard (e.g., Babich and Tang 2012; Rui and Lai 2015) or act as a profit-sharing mechanism (e.g., Kouvelis and Zhao 2012; Yang and Birge 2017). We, however, consider how a manufacturer can financially support a budget-constrained supplier. In this category, Tunca and Zhu (2017) analyze the role and efficiency of manufacturer intermediation in supplier financing. Using a similar setting, Tang et al. (2018) compare purchase order financing with manufacturer direct financing, though their setting does not induce the cost-shifting effect. Our paper contributes to this stream by incorporating the cost-shifting effect in a supply-chain financing setting and comparing the cost-shifting with the profit-sharing effect during technology adoption.

Finally, our study is also related to collaborative R&D in supply chains. This stream of literature traces back to Bhaskaran and Krishnan (2009), who consider collaboration between supply chain partners through either sharing development costs or sharing development work in the presence of technology risk. Kim and

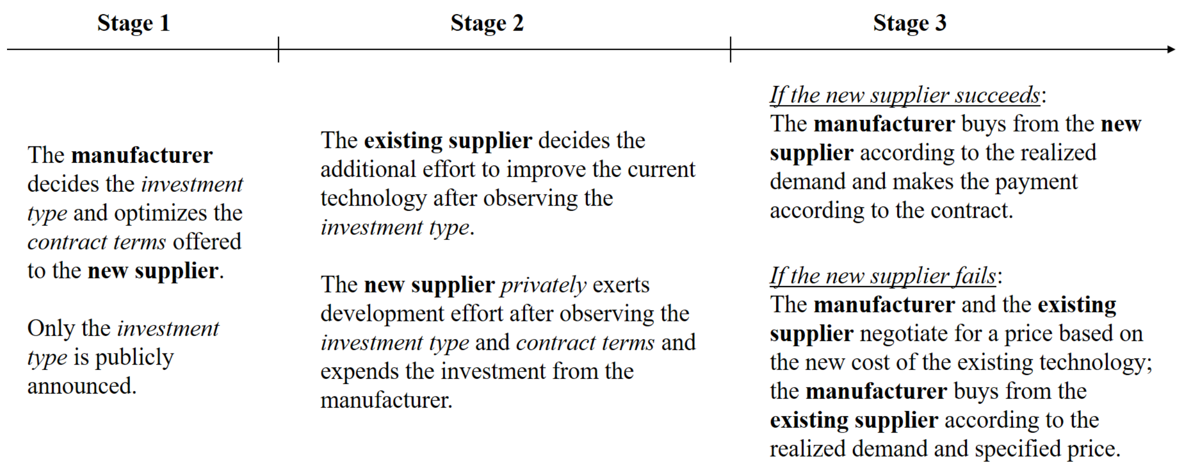


Figure 1: The sequence of events

Netessine (2013) study collaboration between supply chain partners during the development of an innovative product and focus on the impact of information asymmetry and commitment strategies. Savva and Scholtes (2014) consider co-development, licensing, and co-development with opt-out options to study how a large technology firm can collaborate with an innovative but financially constrained supplier, and show that an option clause in a co-development contract helps a supplier avoid profitable project abandonment and capital depletion. Our paper also explores the sharing of development costs or efforts (in the case of an equity investment) in the presence of technology uncertainty, but our focus is different: we allow for the presence of an existing supplier and compare the effects between different investment strategies.

3 Model

Motivated by the two examples in our introduction, we consider a three-stage game with a manufacturer (e.g., Apple and Intel), a new supplier (e.g., GTAT and ASML), and an existing supplier (e.g., Corning) in our model. First, the manufacturer offers an investment contract (in the form of a loan or an equity) and a contingent procurement contract to the new supplier. In the second stage, the new supplier jointly uses the manufacturer's investment and its own (monetary and unverifiable) effort to develop its component, while the existing supplier exerts its own effort to further reduce its production cost after learning the investment type (but not the contract details) from the first stage. Finally, if the R&D is successful, then the contingent procurement contract will be executed; otherwise, the manufacturer will source from the existing supplier. We provide a graphical illustration of the timeline in Figure 1.

In this section, we first introduce our model setup in Section 3.1, and isolate minor model simplifications and justification for our model choices in Appendix I. We then illustrate how the three parties makes their decisions under an equity and a loan contract in Section 3.2 and 3.3, respectively.

3.1 Model Setup

The new supplier's decisions: the PTS and effort-cost expenses. The new supplier is financially constrained and has zero initial wealth. To capture the superiority of the new technology, we normalize to zero the unit cost of the successfully developed component with the new technology. We use $\theta \in [0,1]$ to denote the probability of technical success (PTS) and assume that θ is jointly determined by the amount of the new supplier's effort (e.g., labor hours allocated to R&D), G, and non-labor investment in R&D, K. We assume that K is verifiable through means such as auditing and reimbursements, but G is neither observable nor verifiable. We use S to denote the value that the new supplier files as expenses for the cost of effort. Therefore, only K and S are contractible. In sum, the new supplier decides $\theta(K,G)$ and S.

The two inputs of PTS, K and G, are perfectly complementary, which is consistent with the setting used in the literature of collaborative new product development (e.g., Bhaskaran and Krishnan 2009). Mathematically, given an investment level K_0 and an effort level G_0, we assume that the PTS is $\theta(K_0,G_0) = \min\left\{K^{-1}(K_0), G^{-1}(G_0)\right\}$, in which K^{-1} and G^{-1} measure, respectively, the highest possible PTS that can be achieved given the input level. We also assume that $K(\theta)$ and $G(\theta)$ (the required investment and effort levels to achieve the PTS θ) follow $K(\theta) = \theta^2/a$ and $G(\theta) = \theta^2/b$, wherein $a > 0$ and $b > 0$ measure the new supplier's technological capability in utilizing investments and effort. Moreover, a and b can also be viewed as a new technology's maturity; that is, when the new technology is more mature (a higher a and/or b), it is less costly for the new supplier to achieve a certain level of PTS. We assume that a and b are publicly known, as the capability of a supplier can often be publicly observed through its current products, and they are proportional to each other (i.e., $a \propto b$) such that the technological maturity is consistent in these two aspects. Note that θ is not contractible because G is not contractible. Hence, the new supplier has the freedom to decide θ, which determines $K(\theta)$ and $G(\theta)$.

The manufacturer's decisions: the contract type and terms. The manufacturer first decides between an equity or a loan investment with the new supplier. Given this investment strategy, the manufacturer will determine an upfront investment B, an upper limit B^G to be expended as non-verifiable costs, the manufacturer's equity share γ (in the case of an equity investment), the interest payment r (in the case of a loan), and the expected total procurement payment P. Specifically, the upper limit B^G helps mitigate the moral hazard issue and forces the new supplier to decide how much to expend as the cost of effort such that $S \leq B^G$. Intuitively, the new supplier will always report $S = B^G$ regardless of the real effort level; therefore, the real cost of effort will always be internalized by the new supplier. In contrast, the non-labor investments K will not be internalized under a loan contract if the R&D fails because of the new supplier's limited liability. This is an important feature of our model, and thus the non-labor investments cannot be assumed away. In sum, the investment-procurement contract can be summarized as (B, B^G, γ, r, P).

If the component is successfully developed, the new supplier will receive the milestone payment (if any), and the manufacturer will purchase the component at the specified price, according to the realized demand. We denote D as the expected demand. In our model, as the demand uncertainty does not affect our results (see Appendix I for justification), the manufacturer may solely focus on the expectation of the total payment P to the new supplier when signing the contract. We denote as R the selling price of the end product, which is publicly observable, and we assume $R > 1$ so that, even in the worst case scenario (i.e., the new technology fails and the mature technology cannot make any cost reduction), the manufacturer will still produce this product at the cost of 1 per unit. Without qualitatively affecting our results, we assume that R and the demand realization are independent of the technology used. In our Appendix II, we present a model with a technology-dependent revenue (demand or selling price).

Existing supplier's decision: the final production cost. The existing supplier may continue to improve its current technology, because the manufacturer will retreat to the existing supplier if the new supplier's R&D fails. Assuming normal progress, the existing supplier will incur a unit cost of \$1 in the future to produce the component. However, the improvement can be accelerated by extra investments and effort after the existing supplier learns about the manufacturer's investment strategy with the new supplier through their public announcements (Dilger 2013). Hence, we assume that the existing supplier can further lower the production cost to φ by incurring an additional cost of $C(\varphi) = c\,(1-\varphi)^2$, wherein $\varphi \leq 1$ and $c > 0$. When c is sufficiently large, the mature technology cannot easily outperform the new technology, although we still allow for this possibility. We assume that the manufacturer knows about the existing supplier's default unit production cost and efficiency level c, because the manufacturer and the existing supplier have worked together in the past. However, the future unit cost φ is unknown to the manufacturer when it decides upon its investment strategy and contract terms with the new supplier. In sum, given the investment strategy, the existing supplier privately decides its final production cost φ without knowing the contract terms.

If the new supplier fails, the manufacturer and the existing supplier will determine the component purchase price through a Nash bargaining (Nash 1950). Specifically, we let $\beta \in [0,1]$ denote the relative bargaining power of the manufacturer. We note that the total supply-chain profit then is $(R-\varphi)D$; $\beta(R-\varphi)D$ is allocated to the manufacturer, and the rest, $(1-\beta)(R-\varphi)D$, is allocated to the existing supplier.

3.2 Equity Investment

For an equity contract, we refer to the original equity holder as the new supplier, who acts as a self-interested single player. We let U_E^N, U_E^O, and U_E denote the expected payoffs of the new supplier, the existing (old) supplier, and the manufacturer, respectively, in the case of an equity investment. We describe the optimization problems for the three parties below.

First, we present the new supplier's problem. We let Π_E^N denote the expected *equity value* of the new supplier with the manufacturer's equity investment (and the contingent procurement contract), and Π_E^N equals the sum of the unexpended cash and the expected net payment made by the manufacturer:

$$\Pi_E^N = [B - K(\theta) - S] + \theta P. \tag{1}$$

We note that S can be greater than the true cost of R&D effort (i.e., $S \geq G(\theta)$). Accordingly, the new supplier's payoff with an equity contract is:

$$U_E^N(\theta, S) = (1-\gamma)\,\Pi_E^N + [S - G(\theta)], \tag{2}$$

which includes its share of equity plus the cash overly expended as the cost of effort. We let the new supplier's reservation value to be zero, and hence, the new supplier accepts the contract if and only if $U_E^N \geq 0$.

The new supplier aims to maximize U_E^N by optimizing over θ and S subject to the following budget and PTS constraints:

$$G(\theta) \leq S \leq B^G,\ S + K(\theta) \leq B, \text{ and } \theta \leq \min\left\{G^{-1}\left(B^G\right), G^{-1}\left(aB/(a+b)\right)\right\}. \tag{3}$$

The first and the second constraints are results of the expense limits of the cost of effort and the total budget constraint. Under these two constraints, the PTS ranges between 0 and $\min\left\{G^{-1}\left(B^{G}\right), G^{-1}\left(aB/(a+b)\right)\right\}$. The former is a result from $G(\theta) \leq B^{G}$, whereas the latter is because the efficient allocation of the total budget B gives the upper bound of θ (i.e., if $K_{*}+G_{*}=B$ and $K^{-1}(K_{*}) = G^{-1}(G_{*})$, then $G_{*} = aB/(a+b)$). We let $\hat{\theta}$ and $\hat{S}$ denote the new supplier's best responses to the contract terms $\left\{B, B^{G}, \gamma, P\right\}$.

Next, anticipating the existing supplier's future unit cost φ (i.e., for any given value of φ), the manufacturer optimizes the contract terms offered to the new supplier, subject to the incentive compatibility (IC) and individual rationality (IR) constraints. Without loss of generality (see Appendix I for justifications), we assume that the manufacturer's share of equity is determined by a fair valuation of the new supplier's cash flows, i.e., $\hat{\gamma} = B/\Pi_{E}^{N}\left(B, P, \hat{\theta}, \hat{S}\right)$. Thus, the manufacturer's problem ($\mathscr{P}_{E}$) is:

$$
\begin{aligned}
\max_{B, B^{G}, P} \quad U_{E} = \quad & -B + \hat{\gamma}\Pi_{E}^{N}\left(\hat{\theta}, \hat{S}\right) + \hat{\theta}\left(DR - P\right) + \left(1-\hat{\theta}\right)\beta\left(R-\varphi\right)D \\
s.t. \quad \text{IC}: \quad & \left(\hat{\theta}, \hat{S}\right) = \arg\max_{s.t.(3)} U_{E}^{N}\left(\theta, S\right), \\
\text{IR}: \quad & U_{E}^{N}\left(\hat{\theta}, \hat{S}\right) \geq 0.
\end{aligned}
$$

Recall that the manufacturer must pay the investment B to the new supplier and share the equity value, regardless of the R&D outcome. If the new supplier succeeds (with a probability of θ), the manufacturer is expected to obtain the revenue minus the total payment to the new supplier. If the new supplier fails, the manufacturer will receive the profit from collaborating with the existing supplier. We let $\left\{\hat{B}(\varphi), \hat{B^{G}}(\varphi), \hat{P}(\varphi)\right\}$ denote the manufacturer's best response to φ.

Finally, the existing supplier needs to determine φ given the manufacturer's investment type (i.e., loan or equity). As the new supplier's PTS is an important consideration for the existing supplier's decision on φ, which in turn affects the manufacturer's contract design and thus the PTS, there is a static game between the existing supplier and the manufacturer. In other words, anticipating θ (i.e., for any given value of θ), the existing supplier's problem is to solve:

$$
\max_{\varphi} \quad U_{E}^{O}\left(\varphi|\theta\right) \quad = (1-\theta)(1-\beta)(R-\varphi)D - C(\varphi), \tag{4}
$$

in which the first term represents the expected share of surplus obtained from the manufacturer when the new technology fails, and the second term is the cost of the additional investment. We let $\hat{\varphi}(\theta)$ denote the existing supplier's best response to θ, and it is ultimately a function of $\left\{B, B^G, P\right\}$ because $\hat{\theta}$ only depends on these contract terms, and the form of $\hat{\theta}$ is known by the existing supplier.

3.3 Loan Investment

In the case of a loan investment, the manufacturer can fully retrieve its investment when the new supplier is successful in developing the component. If the R&D fails, the manufacturer will take back either the principal and interest or the new supplier's residual cash, whichever is smaller. Similarly, we let U_L^N, U_L^O, and U_L denote the expected payoffs of the new supplier, the existing (old) supplier, and the manufacturer, respectively, in the case of a loan investment. We describe the payoff optimizations for the three parties below.

First, the new supplier's problem is to maximize $U_L^N(\theta, S)$ by optimizing over θ and S subject to the PTS and budget constraints in (3). The new supplier's payoff includes the residual cash, the overly expended cash, the expected net payment if the R&D is successful, and the payback amount if the R&D fails:

$$U_L^N(\theta, S) = [B - K(\theta) - S] + [S - G(\theta)] + \theta(P - B - r) - (1-\theta)\min\{B - S - K(\theta), B + r\}. \quad (5)$$

We let $\hat{\theta}$ and $\hat{S}$ denote the new supplier's best response to the contract terms $\left\{B, B^G, r, P\right\}$.

Second, anticipating the existing supplier's future unit cost φ (i.e., for any given value of φ), the manufacturer optimizes the contract terms offered to the new supplier, subject to the IC and IR constraints. Note that the interest payment r and the procurement payment P will be made together and only their net value matters to the firms; hence, we can normalize r to zero without loss of generality. Thus, the manufacturer's problem ($\mathscr{P}_L$) is:

$$\begin{aligned}
\max_{B, B^G, P} \quad U_L = \quad & -B + \hat{\theta}(DR - P + B) + \left(1-\hat{\theta}\right)\left(\min\left\{B - K\left(\hat{\theta}\right) - \hat{S}, B\right\} + \beta(R-\varphi)D\right) \\
s.t. \quad \text{IC}: \quad & \left(\hat{\theta}, \hat{S}\right) = \arg\max_{s.t.(3)} U_L^N(\theta, S), \\
\text{IR}: \quad & U_L^N\left(\hat{\theta}, \hat{S}\right) \geq 0,
\end{aligned}$$

in which the manufacturer's payoff involves the amount of loan B, the expected payoff if the R&D is successful, and the sum of the payback amount from the new supplier as well as the share of profits from collaborating with the existing supplier should the R&D fail.

Finally, anticipating θ (i.e., for any given value of θ), the existing supplier's problem is to maximize $U_L^O(\varphi|\theta)$, which has the same functional form as $U_E^O(\varphi|\theta)$ and leads to an identical best response $\hat{\varphi}(\theta)$.

4 Model Analysis

In this section, we first solve the equilibrium under the two investment strategies in Section 4.1. Next, we discuss the manufacturer's optimal strategy in Section 4.2, and we pay particular attention to the difference between the two investment strategies, the impact of the technological maturity of the new supplier, and the impact of the bargaining power of the existing supplier. Finally, we provide numerical illustration of the results in Section 4.3. We acknowledge that we only consider the parameter settings that yield an uncertain R&D ($\theta < 1$), so we may avoid trivial cases for which there is no uncertainty during the product development process.

4.1 Equilibrium Analysis

We denote the Nash equilibrium under an equity contract as $\{B_E, B_E^G, P_E, \gamma_E, \varphi_E, \theta_E^*\}$ and under a loan contract as $\{B_L, B_L^G, P_L, r_L, \varphi_L, \theta_L^*\}$. We provide $(\varphi_E, \theta_E^*, \varphi_L, \theta_L^*)$ in the following lemma, and the remaining contract terms can be found in the proof of Lemma 1.

Lemma 1. *In equilibrium, the probability of technical success for the new technology is θ_E^* under an equity contract and is θ_L^* under a loan contract, wherein:*

$$\theta_E^* = \frac{W(\beta) - L(\beta)}{\frac{3}{a} + \frac{3}{b} + \frac{\sqrt{9a^2+10ab+b^2}}{ab} - L(\beta)}, \text{ and} \tag{6}$$

$$\theta_L^* = \frac{\sqrt{\left(1 + \frac{3a}{b} - \frac{a}{2}L(\beta)\right)^2 + 6a\left(W(\beta) - L(\beta)\right)} - \left(1 + \frac{3a}{b} - \frac{a}{2}L(\beta)\right)}{6}, \tag{7}$$

in which $W(\beta) = [(1-\beta)R + \beta]D$ and $L(\beta) = D^2(1-\beta)\beta/(2c)$. In addition, $\partial\theta_E^*/\partial a > 0$ and $\partial\theta_L^*/\partial a > 0$ if $W(\beta) > L(\beta)$. Finally, the existing supplier's final production cost is $\varphi_i = \varphi(\theta_i^*)$, in which $i \in \{E, L\}$ and $\varphi(\theta) = 1 - D(1-\beta)(1-\theta)/(2c)$.

Two key factors drive the equilibrium: $W(\beta)$ and $L(\beta)$. First, $W(\beta)$ equals the payment made to the existing supplier in the worst case scenario (i.e., when the new supplier fails and the existing supplier does not conduct additional cost reductions). Second, $L(\beta)$ can be approximately regarded as the total additional production cost savings with the existing supplier (i.e., the demand multiplies the unit production cost savings) by rewriting $L(\beta)$ as a function of $\varphi(\theta)$:

$$L(\beta) = D[1 - \varphi(1 - \beta)]. \tag{8}$$

Intuitively, the magnitude of $W(\beta) - L(\beta)$ implies the importance of the new supplier, and thus a higher value of $W - L$ motivates the manufacturer to achieve a higher PTS. Therefore, to ensure that the manufacturer would like to invest in the new technology (i.e., we have positive PTS under both contracts), we assume that $W(\beta) > L(\beta)$ hereafter; i.e., the worst-case payment made to the existing supplier is higher than the potential savings.

Second, we learn from Lemma 1 that θ_L^* is a square-root function of $W(\beta) - L(\beta)$, whereas θ_E^* is linear in $W(\beta) - L(\beta)$. In other words, θ_L^* is more sensitive to $W(\beta) - L(\beta)$ when θ_L^* is low and less sensitive when θ_L^* is high. Although the specific functional forms stem from our model assumptions, the relative magnitudes of the PTS reflect the difference of two effects: *cost shifting* versus *profit sharing*.

It is well known in the finance literature that, if a borrower has a limited liability, it will not internalize its cost in the case of bankruptcy and, thus, will take riskier actions to increase the upside. This kind of agency conflict under a loan investment is called cost shifting and may make itself manifest in a variety of ways (e.g., Brander and Lewis 1986; Buzacott and Zhang 2004). In our model, a loan investment coupled with a limited liability induces the new supplier to invest more in R&D, because the new supplier does not need to pay back the loan beyond its payback ability if the R&D fails. Hence, the cost-shifting effect with a loan investment in our problem results in an incentive for the new supplier to invest more, which in turn motivates higher effort. However, the investment incentive will be weakened as the PTS increases, because the new supplier must pay back the loan and interest in full and internalize the full R&D cost if the development is successful. Hence, θ_L^* is increasing concave in $W(\beta) - L(\beta)$.

Under an equity investment, the manufacturer shares the new supplier's equity (i.e., the residual value that results from the manufacturer's investment as well as the contingent procurement contract) and, hence, their incentives are more aligned, compared to the situation under a loan investment if we ignore the cost-shifting effect. As such, the manufacturer is willing to offer a higher incentive to the new supplier (by increasing the total expected payment P), which will motivate a higher PTS and lead to a higher expected equity value for the new supplier; the increase in the expected value of equity share compensates the manufacturer that offers a higher incentive and could benefit the manufacturer. We call this a profit-sharing effect, which does not exist in the equity issuance literature as there is not a contingent procurement.

With this lemma, we show that when the new technology is more mature (i.e., a is larger), the manufacturer will prefer the new supplier more by incentivizing a higher PTS, regardless of the investment type (i.e., θ_E^* and θ_L^* are increasing in a). However, the role of the existing supplier (represented by β) is complex. First, when β increases (the less powerful the existing supplier is), the manufacturer is less willing to support the new supplier because the surplus is higher sourcing from the existing supplier. However, a high β also leads to a lower incentive from the existing supplier to further reduce costs, which in turn reduces the cost-shifting and profit-sharing effects (due to the reduced $L(\beta)$ using Equation 8). As a result, it is not clear how β affects the relative effects of equity and loan investments in equilibrium. In the following proposition, we show the overall effects of a and β on the comparison between θ_E^* and θ_L^* in equilibrium.

Proposition 1. *(i) Given the bargaining power, when the technological maturity exceeds a threshold, $\bar{a}_T(\beta)$, the PTS under an equity contract is higher than that under a loan contract (i.e., given β, $\theta_E^* > \theta_L^*$ if and only if $a > \bar{a}_T(\beta)$).*

(ii) Given the technological maturity, when the existing supplier is sufficiently weak or strong, the PTS under an equity contract is higher than that under a loan contract (i.e., given a, there could exist $\bar{\beta}_L(a)$ and $\bar{\beta}_H(a)$ in $[0,1]$ such that $\bar{\beta}_L(a) \leq \bar{\beta}_H(a)$ and $\theta_E^* > \theta_L^*$ if and only if $\beta < \bar{\beta}_L(a)$ or $\beta > \bar{\beta}_H(a)$).

In contrast to findings in the debt financing literature (e.g., Héber 2018), our results in Proposition 1 show that the profit-sharing effect in such a supply-chain setting dominates the cost-shifting effect (i.e., $\theta_E^* > \theta_L^*$) either when the new technology is sufficiently mature (i.e., $a > \bar{a}_T(\beta)$) or when the cost of using the mature technology is sufficiently high (i.e., $\beta < \bar{\beta}_L(a)$ or $\beta > \bar{\beta}_H(a)$). In these cases, the cost-shifting effect is significantly weakened as the new technology has a high PTS.

Next, we explain why the cost of using the mature technology is high when $\beta < \bar{\beta}_L(a)$ or $\beta > \bar{\beta}_H(a)$. When the manufacturer's bargaining power, β, is low, the existing supplier charges a high price and thus the manufacturer is willing to offer a high investment and a high incentive to the new supplier in order to induce a high PTS. When β increases, both θ_E^* and θ_L^* decrease because the manufacturer is more willing to source from the existing supplier, leading to a stronger cost-shifting effect and causing $\theta_E^* < \theta_L^*$. However, when β further increases, the existing supplier has less incentive to decrease its production cost (i.e., $\varphi(\theta)$ increases with β); hence, the manufacturer has a higher incentive to increase the new supplier's PTS. In certain cases (e.g., when the existing supplier's cost-reduction capability is high, according to our numerical examples in Section 4.3), the increases of φ and θ are so significant that, when β is high enough (i.e., when $\beta \geq \bar{\beta}_H(a)$), we find $\theta_E^* \geq \theta_L^*$ once more, due to a weakened cost-shifting effect. Such non-monotonic effects of β, without modeling the existing supplier's dynamics (i.e., making φ an exogenous decision), will not exist, which highlights the importance of this existing supplier.

4.2 Choice of Investment Strategy

Although we have analyzed the new supplier's R&D decision and can find the investment strategy that leads to a higher PTS in equilibrium, a more motivated supplier does not necessarily guarantee a higher payoff for the manufacturer, because the manufacturer's expected payoff also depends on the contract terms. Therefore, we study the manufacturer's payoff and find the optimal investment strategy.

To find the optimal choice of the investment strategy, we substitute $\{P_E, B_E^G, B_E, \gamma_E\}$ and $\{P_L, B_L^G, B_L, r_L\}$ into U_E and U_L, respectively, to obtain the manufacturer's equilibrium payoffs:

$$U_E^* = u(\theta_E^*) + 2\theta_E^{*2} \cdot \frac{\gamma_E - (1-\theta_E^*)}{a} \text{ and } U_L^* = u(\theta_L^*), \tag{9}$$

in which $u(x) := RD - x^2/a - 2x^3/a - 3x^2/b - [W(\beta) - (1-x)L(\beta)](1-x)$. Accordingly to (9), if $\theta_E^* = \theta_L^* = \theta$, we have $U_E^* - U_L^* = 2\theta^2\gamma_E/a - 2\theta^2(1-\theta)/a$, in which $2\theta^2\gamma_E/a$ represents the benefit from an equity investment due to the profit-sharing effect, and $(1-\theta)2\theta^2/a$ represents the benefit from a loan investment due to the cost-shifting effect. Therefore, even with the same PTS, the optimal investment strategy still depends on the interaction of the cost-shifting effect and the profit-sharing effect associated with a loan and an equity investment, respectively. This is because, besides the effect on PTS, the cost-shifting effect allows the manufacturer to save money by offering smaller incentives under a loan investment, whereas the profit-sharing effect allows the manufacturer to earn extra money by sharing the equity value of the new supplier. In Proposition 2, we show how the technological maturity (the value of a) affects the optimal choice of investment strategy.

Proposition 2. *(i) There exists a threshold value higher than $\bar{a}_T(\beta)$ (the threshold points indicated in Proposition 1(i)), such that the manufacturer will choose an equity over a loan contract when the technological maturity is higher than this threshold (i.e., there exists $\bar{a}_H > \bar{a}_T(\beta)$ such that $U_E^* > U_L^*$ for any $a > \bar{a}_H$);*

(ii) there exist two thresholds values, one lower and one higher than $\bar{a}_T(\beta)$ such that the manufacturer will choose a loan over an equity contract when the technological maturity is in between these two thresholds (i.e., there exist $\bar{a}_L < \bar{a}_T(\beta)$ and $\bar{a}_M > \bar{a}_T(\beta)$ such that $U_E^* < U_L^*$ for any $\bar{a}_L < a < \bar{a}_M$); and

(iii) finally, the manufacturer may choose an equity over a loan if the technological maturity is sufficiently low, and the existing supplier has a sufficiently high incentive and ability to reduce costs. Specifically, $U_E^* > U_L^*$ if $W(\beta) - L(\beta) \to 0$ and

$$\frac{2}{a} + \frac{6}{b} < L(\beta) < W(\beta) < \frac{3}{a} + \frac{3}{b} + \frac{\sqrt{9a^2 + 10ab + b^2}}{ab}.$$

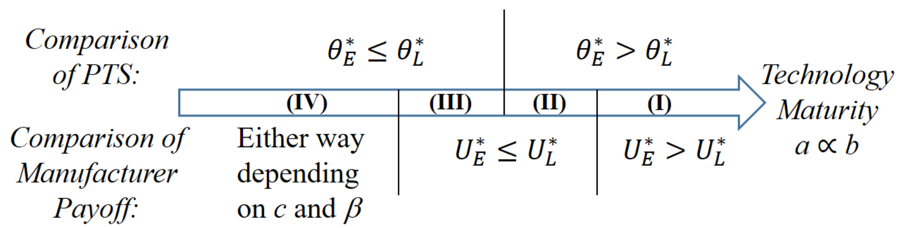


Figure 2: A Qualitative Illustration of the Main Findings

We illustrate our main findings in Propositions 1 and 2 in Figure 2. While the manufacturer often prefers an investment strategy that leads to a high PTS, we find two exceptions. Specifically, we find that when $a \in (\bar{a}_T(\beta), \bar{a}_M)$ (region (II) in Figure 2), although a loan investment leads to a lower PTS, a loan investment is still preferred because it allows the manufacturer to offer a lower total procurement payment.

Moreover, Proposition 2(iii) shows that when the technological maturity is sufficiently low, the manufacturer may, again, prefer an equity that incentivizes a lower PTS (see region (IV) in Figure 2). The first condition that $W(\beta)$ is closed to $L(\beta)$ is more likely to be satisfied when further reducing the existing supplier's is not very costly (i.e., c is sufficiently small) and when the bargaining power between the manufacturer and the existing supplier are fairly equal (i.e., β is close to 1/2 so that $L(\beta)$ is as large as possible). The second condition is more likely to be satisfied when the technological maturity, a, is sufficiently low. The result implies that, when a is sufficiently low such that $a < \bar{a}_L$, the mature technology plays an important role if the existing supplier can potentially achieve a sufficiently high cost reduction. In this case, the manufacturer may prefer the equity investment that leads to a lower PTS if the existing supplier is neither too weak nor too strong, which differs from the choice-making logic when the new technology is more mature.

4.3 Numerical Examples

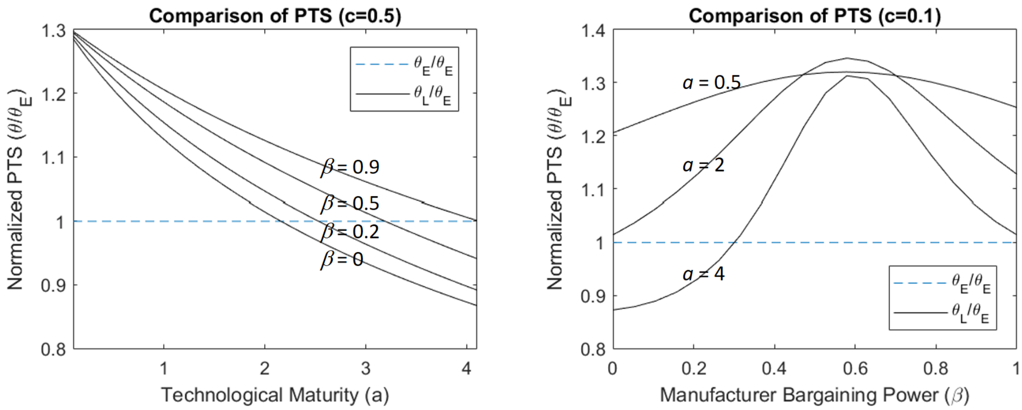
In this section, we show with numerical examples that, in many cases, there exists only two regions (i.e., Proposition 2(i) and 2(ii)) for the choice of investment strategy by showing that U_E^* and U_L^* cross only once in many cases (i.e., $\bar{a}_M = \bar{a}_H > \bar{a}_T$); in some cases (i.e., when a and c are both small), U_E^* and U_L^* may cross multiple times (e.g., twice, as shown in the last plot), which can lead to the interesting third region that we illustrate in Proposition 2(iii). Specifically, we set $b = a$, $R = 2$, $D = 1$, and vary the values for a, β, and c. We show the results related to the comparison between θ_E^* and θ_L^* in Figure 3, and those related to the comparison between U_E^* and U_L^* in Figure 4.

First, we show how the normalized PTS depends on a and β in the left and right panels of Figure 3, respectively. In particular, from the left panel, we see that θ_L/θ_E decreases in technological maturity a, and there exists at most one value of a that achieves $\theta_L = \theta_E$ (i.e., crossing the dashed line), which echoes the results in Proposition 1(i). From the right panel, we see that θ_L/θ_E has an increasing and then decreasing shape with respect to β, implying that θ_L/θ_E intersects $1(= \theta_E/\theta_E)$ at most twice, thereby validating the results in Proposition 1(ii). To magnify the impact of β, we use $c = 0.1$, instead of $c = 0.5$ (the value used in the left panel).

Next, we show the manufacturer's normalized optimal profits in Figure 4. To facilitate our discussion of the optimal contract choice, we focus on the impact of the new technology's maturity (and hence, use a in the horizontal axis) and vary the manufacturer's bargaining power (the value of β) in the four graphs in Figure 4, each of which has a different value of c that measures the existing supplier's cost-reduction ability. Apparently, the optimal contract choice depends on both a and β. In most cases, a loan contract is a better choice, but an equity may be preferred if and only if the technological maturity of the new supplier is sufficiently high, as we explained previously. Similarly, in most cases, the existence of the mature supplier exhibits a second-order effect: the optimal contract choice depends on β monotonically when the new technology is sufficiently–but not extremely–mature. Specifically, as β increases from 0.2 to 0.9 (from a weak manufacturer to a strong one), the manufacturer's payoff under a loan contract becomes relatively higher when compared to that under an equity contract. This is because the cost-shifting effect under a loan contract gets stronger as β increases and the PTS decreases, thereby allowing the manufacturer to pay less to the new supplier to achieve the same–or even a higher–PTS.

Finally, the third region (i.e., the optimal investment strategy that depends on c and β when a is low)

Figure 3: Numerical Examples: Comparison of PTS



appears in the graph of the bottom right panel. Specifically, when $c = 0.1$ and $a = 3$, a loan contract is a better choice if $\beta = 0.2$ and 0.9, but not 0.5. Mathematically, this is because $\bar{a}_L|_{\beta=0.5}$ is relatively high but $\bar{a}_L|_{\beta=0.2}$ and $\bar{a}_L|_{\beta=0.9}$ are relatively low. Regarding the dynamics among the three parties, we find that when it is easy to achieve additional cost reductions with the mature technology and the bargaining power is relatively balanced between the manufacturer and the existing supplier, the additional production cost savings could potentially be high. Thus, a higher PTS (induced by a loan investment) will backfire by reducing the existing supplier's incentive to further reduce its production costs.

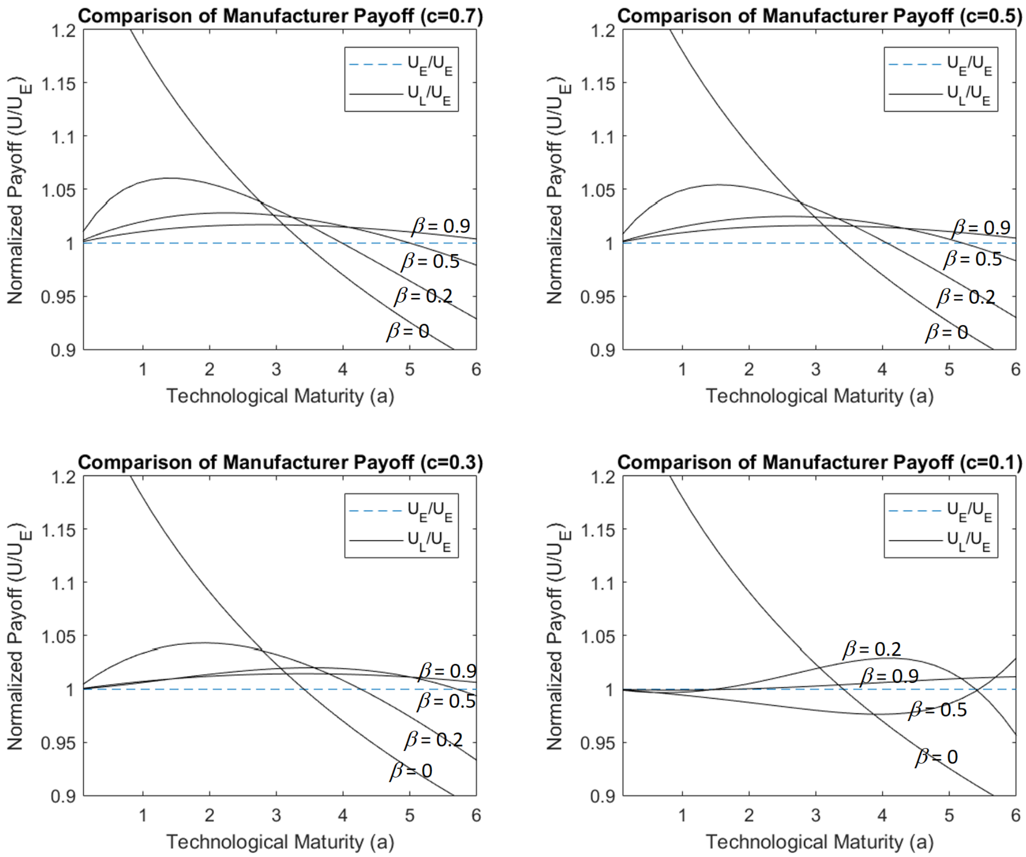
5 Benchmarks

In this section, we consider two more scenarios and observe how a supply chain with the options of loan and equity contracts shapes different parties' decisions. First, we consider a partially integrated firm consisting of the manufacturer and the new supplier to investigate how the two contracts lead to over- or under-investment in R&D. Second, we exclude the option of a manufacturer's investment, such that the new supplier can only resort to outside (e.g., bank) financing.

5.1 Internal Development of the New Technology

In this section, we study the situation when the manufacturer can vertically integrate the new supplier and develop the new technology internally. In particular, we study the interaction between this "partially integrated" firm (i.e., the manufacturer and the new supplier) and the existing supplier, derive the internally

Figure 4: Numerical Examples: Comparison of Manufacturer Payoff



optimal PTS for the manufacturer and compare it with the PTS in decentralized cases.

Given the net payoff for the partially integrated firm, which is:

$$U_{PI}(\theta) = \theta RD + (1-\theta)\beta(R-\varphi)D - K(\theta) - G(\theta), \tag{10}$$

we show the internally optimal PTS (denoted as θ_{PI}^{*}) in equilibrium in the following proposition.

Proposition 3. *The Nash equilibrium with a valid PTS (i.e., between 0 and 1) exists if and only if*

$$\min\left\{0, \frac{2}{a} + \frac{2}{b} - L(\beta)\right\} \leq W(\beta) - L(\beta) \leq \max\left\{0, \frac{2}{a} + \frac{2}{b} - L(\beta)\right\}. \tag{11}$$

In equilibrium, the internally optimal PTS is higher than those under a loan or an equity:

$$\theta_{PI}^* = \frac{W(\beta) - L(\beta)}{\frac{2}{a} + \frac{2}{b} - L(\beta)} > \max\{\theta_E^*, \theta_L^*\}. \tag{12}$$

As shown in the proposition, in the circumstances in which the Nash equilibrium exists between the partially integrated firm and the existing supplier, we find that $\theta_{PI}^* > \max\{\theta_E^*, \theta_L^*\}$, indicating that the moral hazard caused by unobservable effort in a decentralized system (as in our base model) will lead to under-provision of the new supplier's R&D effort. Although such under-provision of effort is common in a moral hazard setup, the cost-shifting effect associated with a loan and the profit-sharing effect associated with an equity can help mitigate the moral hazard.

5.2 Outside Financing

We next consider the scenario in which the new supplier can apply for a bank loan with the manufacturer's contract. Following the setting introduced by Tang et al. (2018) for purchase order financing, we specify the sequence of events as follows. The manufacturer first offers the new supplier the purchasing contract with an expected payment P that is contingent on successful R&D. Next, the new supplier determines the amount of money B to borrow from the bank. Observing P and B, the bank decides on the interest rate r_b that allows itself to break even. Finally, the new supplier determines its investment and effort levels. In the meantime, the existing supplier decides on the additional cost reduction without knowing P or B, because there is no need for the new supplier to disclose its own internal information to the public.

Importantly, we assume that the bank does not specify how the new supplier should use the money; thus, the supplier can spend the money in any way. This assumption removes the cost-shifting effect because the new supplier can always expend the borrowed money to benefit itself without making any effort; as a result, the entire R&D cost will be internalized. Also, as there is no profit-sharing effect, outside financing can serve as a benchmark that allows us to tease out these two effects. In the following proposition, we solve the equilibrium and compare our result against those derived from the base model.

Proposition 4. *(i) Under outside financing, we have the optimal PTS as:*

$$\theta_{OF}^* = \frac{W(\beta) - L(\beta)}{\frac{6}{a} + \frac{6}{b} - L(\beta)}. \tag{13}$$

(ii) The PTS under outside financing will be lower than that under an equity as long as the manufacturer receives a positive share (i.e., if $\gamma_E > 0$, we have $\theta^*_{OF} < \theta^*_E$), and there exists a threshold value such that when the technological maturity is lower than this threshold, the PTS under outside financing will be lower than that under a loan (i.e., there exists $a_{OF} > \bar{a}_T(\beta)$ such that $\theta^*_{OF} < \theta^*_L$ if and only if $a < a_{OF}$).

(iii) The manufacturer prefers an equity investment if the total payment made to the existing supplier is sufficiently higher than the total additional cost reduction achieved by the existing supplier (i.e., $U^*_E > U^*_{OF}$ if and only if $W(\beta) > (3 - \theta^*_E - \theta^*_{OF})L(\beta)$).

Therefore, without the cost-shifting and profit-sharing effects, the new supplier's R&D effort under outside financing is always lower than that under an equity investment. In fact, a_{OF} is very large according to our proof, so the effort under outside financing should also be lower than that under a loan investment, given a reasonable parameter setting. Regarding the optimal choice of investment strategy for the manufacturer, we find that an equity investment dominates outside financing as long as the total additional cost reduction ($L(\beta)$) to be achieved by the existing supplier is much less than the total payment ($W(\beta)$) made to the existing supplier. Otherwise, the existing supplier becomes an attractive option and a lower PTS is preferred by the manufacturer, in which case outside financing can be preferable to either of these two investment strategies. Finally, while Tang et al. (2018) show that outside financing (i.e., purchase order financing) is equivalent to a loan investment (i.e., buyer direct financing), our result is different. This is because there is no non-labor investment in Tang et al. (2018) and the cost is always internalized by the supplier (i.e., cost shifting does not exist), whereas the cost-shifting effect under a loan investment (but not under outside financing) exists in our setting.

6 Concluding Remarks

In this paper, we offer managerial insights for a high-technology manufacturer regarding its investment choice (an equity or a loan) in a critical component/equipment sourcing process that involves a financially constrained but innovative supplier. We seek to answer three key questions: First, given the moral hazard caused by unobservable R&D effort, which investment strategy can better motivate the new supplier's effort and the PTS? Second, to what extent does the strategy with a higher PTS lead to a higher expected payoff for the manufacturer? Third, what is the role of an existing supplier with a mature technology?

Using a stylized game-theoretic model, we first show that a loan does not always dominate an equity in terms of motivating a higher PTS, and the comparison is driven by the competition between the cost-shifting effect associated with a loan investment and the profit-sharing effect associated with an equity investment. Contrary to the traditional corporate finance literature that finds that a cost-shifting effect often causes agency conflicts, we find that, in the presence of unobservable R&D effort and complementarity between labor and non-labor inputs in R&D, this cost-shifting effect could better motivate R&D investments and effort, as higher levels of investment and effort could be preferred by both the manufacturer and the new supplier. However, the profit-sharing effect associated with an equity may still incentivize a higher PTS when the new supplier's technological capability is sufficiently high.

In many situations, the investment strategy leading to a higher PTS is a better choice for the manufacturer. However, we show that this is not true in certain situations. In particular, a loan can over-incentivize the new supplier and backfire when the new technology is not mature enough and the existing supplier is very capable of reducing costs, which serves as quite an attractive backup option. Additionally, a loan may be preferable even if the PTS is lower than that under an equity investment, as long as the monetary savings of the manufacturer from this cost-shifting effect is larger than the benefit brought by the profit-sharing effect under an equity investment.

Intuitively, when the backup option is endogenous (as is the case in the Apple-GTAT example), manufacturers may consider choosing a strategy that leads to a lower PTS in order to incentivize the existing supplier to exert more cost-reduction effort. However, our analysis shows that the backup option matters, and a lower PTS is preferred only when the new technology is sufficiently immature and the existing supplier has a sufficiently high incentive and ability to reduce costs. Moreover, although the optimal contract choice largely depends on the technological maturity, the threshold point of the technological maturity still depends on the manufacturer's bargaining power against the existing supplier.

Finally, our result enables us to offer a new perspective to reappraise both Apple's loan investment in GTAT and Intel's equity investment in ASML. The two examples differ in two main aspects. One aspect is that Apple had an endogenous backup option (Corning) while Intel had an exogenous one (300-millimeter wafer and immersion lithography). The other aspect is that the sapphire technology was not mature enough for smartphone screens, while the EUV technology had been developed for many years and thus was sufficiently mature. Hence, it seems natural for Intel to have chosen an equity investment. Regarding the Apple-GTAT example, the optimal choice would depend on Corning's capability to further improve the Gorilla Glass. If Corning could not significantly improve Gorilla Glass while GTAT worked on the sapphire technology, then Apple's choice should have been correct.

In our Appendix II, we use a number of model extensions to test our results for robustness, which include (1) an exponential, instead of a quadratic, R&D cost function; (2) a technology-dependent demand or price such that a new technology can generate a higher revenue; and (3) a convertible debt investment strategy.

Acknowledgement

The authors thank Prof. Charles Corbett, the anonymous Associate Editor, and four anonymous reviewers for their valuable comments in the review process. This work was partially supported by a grant sponsored by the Ministry of Science and Technology in Taiwan [Grant 109-2628-E-004-001-MY3]. The authors benefited from discussing with Dr. S. Alex Yang from the London Business School. H.-H. Lee thanks the E.SUN Commercial Bank for supporting her research, and thanks Dr. Hung-Chia Hsu from University of Arkansas and Dr. Cheng-Wei Wu from National Taiwan University for their corporate venture capital data.

References

Babich V, Tang CS (2012) Managing Opportunistic Supplier Product Adulteration: Deferred Payments, Inspection, and Combined Mechanisms. *Manufacturing & Service Operations Management* 14(2):301–314.

Bhaskaran SR, Krishnan V (2009) Effort, Revenue, and Cost Sharing Mechanisms for Collaborative New Product Development. *Management Science* 55(7):1152–1169.

Blake M (2017) Intel Cuts Stake in ASML to below 5 Percent. Reuters December 1 2017. https://www.reuters.com/article/us-asml-holding-intel-stake/intel-cuts-stake-in-asml-to-below-5-percent-idUSKBN1DV42G.

Boyabatlı O, Toktay LB (2011) Stochastic Capacity Investment and Flexible vs. Dedicated Technology Choice in Imperfect Capital Markets. *Management Science* 57(12):2163–2179.

Boyabatlı O, Leng T, Toktay LB (2016) The Impact of Budget Constraints on Flexible vs. Dedicated Technology Choice. *Management Science* 62(1):225–244.

Brander JA, Lewis TR (1986) Oligopoly and Financial Structure: The Limited Liability Effect. *The American Economic Review* 76(5): 956–970.

Buzacott JA, Zhang RQ (2004) Inventory Management with Asset-Based Financing. *Management Science* 50(9): 1274–1292.

Chod J (2017) Inventory, Risk Shifting, and Trade Credit. *Management Science* 63(10): 3207–3225.

Chod J, Zhou J (2014) Resource Flexibility and Capital Structure. *Management Science* 60(3): 708–729.

Dam K, Ruiz-Pérez D (2012) On the Existence of Share Contracts under Limited Liability. *Economics Letters* 117(3):552–555.

de Véricourt F, Gromb D (2018) Financing Capacity Investment under Demand Uncertainty: An Optimal Contracting Approach. *Manufacturing & Service Operations Management* 20(1): 85–96.

Dilger DE (2013) Apple Signs $578M Sapphire Deal with GT Advanced Technology. *Appleinsider* (November 04), http://appleinsider.com/articles/13/11/04/apple-signs-578m-sapphire-deal-with-gt-advanced-technology/.

Goyal M, Netessine S (2007) Strategic Technology Choice and Capacity Investment Under Demand Uncertainty. *Management Science* 53(2):192–207.

Hébert B (2018) Moral Hazard and the Optimality of Debt. *Rev. Econ. Stud.* 85(4): 2214–2252.

Hoppe HC (2002) The Timing of New Technology Adoption: Theoretical Models and Empirical Evidence. *The Manchester School* 70(1):56–76.

Innes RD (1990) Limited Liability and Incentive Contracting with Ex-ante Action Choices. *Journal of Economic Theory* 52(1): 45–67.

Jensen MC, Meckling WH (1976) Theory of the Firm: Managerial Behavior, Agency Costs and Ownership Structure. *Journal of Financial Economics* 3(4): 305–360.

Kim SH, Netessine S (2013) Collaborative Cost Reduction and Component Procurement under Information Asymmetry. *Management Science* 59(1):189–206.

Kouvelis P, Zhao W (2012) Financing the Newsvendor: Supplier vs. Bank, and the Structure of Optimal Trade Credit Contracts. *Operations Research* 60(3):566–580.

Krishnan V, Bhattacharya S (2002) Technology Selection and Commitment in New Product Development: the Role of Uncertainty and Design Flexibility. *Management Science* 48(3):313–327.

Myers SC (1977) Determinants of Corporate Borrowing. *Journal of Financial Economics* 5(2):147–175.

Ning J, Babich V (2018) R&D Investments in the Presence of Knowledge Spillover and Debt Financing: Can Risk Shifting Cure Free Riding? *Manufacturing & Service Operations Management* 20(1) 97–112.

Nash J (1950) The Bargaining Problem. *Econometrica* 18(2):155-162.

Rui H, Lai G (2015) Sourcing with Deferred Payment and Inspection under Supplier Product Adulteration Risk. *Production Operations Management* 24(6):934–946.

Savva N, Scholtes S (2014) Opt-Out Options in New Product Co-development Partnerships. *Production Operations Management* 23(8):1370–1386.

Tang CS, Yang SA, Wu J (2018). Sourcing from Suppliers with Financial Constraints and Performance Risk. *Manufacturing & Service Operations Management* 20(1):70–84.

Tunca TI, Zhu W (2017) Manufacturer Intermediation in Supplier Finance. *Management Science*, https://doi.org/10.1287/mnsc.2017.2863.

Yang SA, Birge JR (2017) Trade Credit, Risk Sharing, and Inventory Financing Portfolios. *Management Science*, https://doi.org/10.1287/mnsc.2017.2799.

Table 1: Notation Table.

Variable	Definition
B and B^G	The manufacturer's upfront investment and the upper limit of investment that can be expended on the new supplier's effort costs
γ	The manufacturer's equity share in the case of an equity investment
r	The interest payment from the new supplier to the manufacturer in the case of a loan investment
S	The amount of money that the new supplier expended
P and D	The expected payment, and the expected demand
R	The selling price of the end product
θ	The new supplier's probability of technical success
$K(\theta)$	The manufacturer's investment required in order to achieve θ
$G(\theta)$	The new supplier's private effort required in order to achieve θ
a and b	The new supplier's technological capability or the new technology's maturity
φ	The existing supplier's production cost (after cost reduction improvement)
$C(\varphi)$	The cost needed in order to achieve a production of of φ, in which $C(\varphi) = c(1-\varphi)^2$
β	The relative bargaining power of the manufacturer against the existing supplier
$W(\beta)$	The payment made to the existing supplier in the worst case scenario
$L(\beta)$	The approximate, additional production cost savings with the mature technology
Π_E^N	The expected equity value of the firm operated by the new supplier with the manufacturer's investment
U_j^i	The payoff for party i with an investment strategy j, in which $i = \{\text{null}, N, O\}$ representing the manufacturer, the new supplier, and the existing supplier, respectively, and $j = \{E, L, PI, OF, CD\}$, representing equity, loan, partially integrated firm, outside financing, and convertible debt, respectively.

Note: A variable with a hat (e.g., $\hat{\theta}$) often represents the best response, a variable with an asterisk (e.g., θ^*) often represents the equilibrium outcome, and a variable with a upper bar (e.g., $\bar{a}$) often represents the threshold in a comparison. A variable with a subscript of L (E) represents the case under a loan (an equity) investment.

Appendix I: Case Study and Model Justifications

In this Appendix, we provide two detailed case studies to support the motivation of our paper as well as to justify our model assumptions. In particular, we will start with the Apple-GTAT case and then the Intel-ASML case. We note that it is impossible for companies like GTAT and ASML to hire other companies to do R&D for their specialized, advanced technologies; rather, they must rely on the effort of their own technical teams. Moreover, in both examples, no intellectual property created by the supplier would be shared or transferred to the manufacturer.

We also note that buying firms investing in new technologies and/or their potential suppliers are not uncommon. More examples can be found in addition to the two detailed examples that we provided. For example, since 1997, Hewlett-Packard invested in the technology of its suppliers, such as Palm Inc, Autonomy Corp., Aruba Networks, and Mercury Interactive Corp., among others. Moreover, firms can form corporate venture capital (CVC) to invest in new technologies. For example, Samsung announced its decision to invest KRW 25 trillion in AI, 5G, automotive electronics parts, and biopharmaceuticals in 2018[A1], and had made investments via Samsung Venture Investment Corp. (Samsung's CVC) to its suppliers, such as Advanced Analogic Technologies, Inc., AlphaChips Corp., and Cloudant Inc.

Apple-GTAT case

This case starts with an investment deal signed in 2013 between Apple and GTAT, a sapphire technology supplier in operation for more than 40 years (Dilger 2013), for the procurement of the scratch-and-fracture-resistant screens to be used in iphone 6 and future products. Second in hardness to diamond, sapphire glass is durable and nearly unbreakable. These properties could reduce the issues of cracked or broken screens that roughly 11% of iPhone owners had experienced (Wakabayashi 2014). Although Apple had already used sapphire glass to cover camera lenses and fingerprint readers on iPhones, sapphire glass, when compared with conventional (i.e., silicon dioxide) glass, still has some drawbacks. Its density is higher (thus leading to heavier glasses), its light transmission rate is slightly lower, and more importantly, its production process is more complex and often costlier. To address this last drawback, Apple counted on GTAT's next-generation furnaces, which are capable of producing much larger sapphire crystals, and, as a result, drive down the

[A1] https://news.samsung.com/global/samsung-steps-up-investment-for-future-growth-takes-initiative-to-build-innovation-ecosystem price by scale.

R&D investments are often costly and risky, and this one is no exception. First, producing sapphire requires a very clean environment and uninterrupted supplies of water and electricity. Contamination and outages will adversely affect sapphire quality. Second, growing a sapphire crystal inside a furnace (which takes about a month) is a process that cannot be monitored; if something goes wrong, then a month's worth of time is wasted. Third, GTAT had never grown sapphire crystals this large (more than 50% larger than previous products), and the time it would take to slice the crystals into thin pieces was also unknown. If any of these potential problems occurred during the production process, the delivery of sapphire screens would be delayed, and Apple might not be able to launch the new iPhone in time. Nevertheless, GTAT could lower some of the risks by means such as installing backup power supplies to help GTAT avoid power outages, though these investments are costly and may need external funding supports.

Even though GTAT's ability to produce the screens successfully remained unknown, to accelerate GTAT's research and development process, Apple decided to enter a five-year, $589 million loan contract (as four pre-payments) in November 2013 with GTAT. If the sapphire screen production could be scaled up, Apple would contract with GTAT to provide the much needed sapphire screens, and in turn, GTAT would reimburse Apple for purchasing sapphire screens over five years, beginning in 2015. However, If the sapphire screen production failed Apple's targets, this loan contract would allow Apple to exit and reclaim the residual value of the loan investment.

In September 2014, Apple decided to exit the contract with GTAT and refused to pay the last of its four pre-payments, which then led to GTAT's bankruptcy. Both parties accused each other for the failure of this investment. Apple accused GTAT of failing to produce any meaningful quantity of usable sapphire (Bullis 2014), whereas GTAT accused Apple of failing to provide sufficient assistance. GTAT's bankruptcy filing indicates that the sapphire was grown in a highly contaminated environment caused by ongoing construction at the factory. In addition, Apple decided not to install backup power supplies in order to save costs, which allowed multiple outages to ruin batches of sapphire. Furthermore, it turned out that it took 20 hours to cut the large sapphire crystals, instead of the originally expected 3.6 hours. Moreover, although Apple had a claim of $439 million (the first three pre-payments made) against GTAT, the claim is only secured by the Advanced Sapphire Furnaces that Apple purchased and installed. Eventually, Apple reverted to its existing supplier: Corning Inc., a Gorilla Glass supplier. Despite the investment contract made by Apple to GTAT, Corning continued its product enhancement process and launched a new generation of Gorilla Glass in January 2014, which could be quickly modified for Apple's new product.

Intel-ASML case

ASML Holding N.V. (ASML) developed two wafer and lithography technologies in 2012. The two technologies would allow its customers, including Intel and others, to create state-of-the-art factories and production techniques that would allow it to differentiate itself from other chipmakers. In particular, producing silicon disks of a 450-millimeter (mm) diameter—compared with the current 300-millimeter standard—would enable manufacturers to produce more chips faster, and the extreme ultra-violet (EUV) lithography would be used to make semiconductors that would be more powerful, even when they became smaller. When deployed in conjunction with 450-mm wafer technology, the productivity and cost benefits of EUV would be substantial for Intel and other semiconductor manufacturers. Hence, the use of these two technologies was not independent and would take multiple years if ASML were self-developing these two technologies. According to Intel Chief Operating Officer, Intel was "asking for two extremely large technical transitions to occur at ASML, and it was beyond their capabilities on their own" (King and Rahn 2012). Moreover, the deployment of the EUV technology had historically been delayed several times.

Despite the uncertainty and difficulty associated with the R&D linked to these two technologies, ASML attracted Intel, TSMC, and Samsung to invest in itself by using equity. In particular, in July 2012, Intel announced that it would collaborate with ASML to accelerate the development of the 450-mm wafer technology and EUV lithography for up to two years.[A2] Specifically, Intel would spend around $3.1 billion to acquire 15 percent of ASML's shares via a synthetic share buyback from the original shareholders and commit approximately $1.0 billion to ASML's R&D programs as a premium paid to acquire the equity. In addition, the shares owned by Intel were subject to voting restrictions, so ASML would stay fully independent. As part of these agreements, Intel also committed to advanced purchase orders for the 450-mm and EUV development and production tools from ASML under agreed upon conditions of sales. In turn, ASML would provide certain commercial discounts in the form of credits to be applied to Intel's future tool purchases. However, the purchase obligations were contingent upon ASML achieving certain milestones. Eventually, the new production line successfully started its operation in 2017, and Intel started to exit the collaboration by selling its shares (Blake 2017).

[A2]https://newsroom.intel.com/news-releases/intel-and-asml-reach-agreements-to-accelerate-key-next-generation-semiconductor-manufacturing-technologies/.

Model Simplification and Justifications

In our model, we make assumptions so as to have a setting that fits the practice and yet remains tractable in finding the optimal contracts. Motivated by the two examples, we assume that a high-technology manufacturer is trying to adopt a new technology for one of its critical components from a new supplier in our model. However, the new technology is not readily applicable, and the new supplier is financially constrained. In order to meet the technical specifications within the time frame required by the manufacturer (or to achieve the technical success), the supplier must make further investments (e.g., acquiring equipment and facilities) and exert effort in R&D. To capture the risk inherent in R&D, we assume that the investment amount (acquired from the manufacturer) and effort level (exerted by the supplier) jointly determine the product's PTS. We provide our assumptions and justify our model choices below following the same order in Section 3.1.

First, we study the situation in which the new supplier is financially constrained due to a relatively small business size. Specifically, we assume that the amount of cash available to the new supplier in addition to the amount required for day-to-day operations is zero. In the investment contract, we assume that in the case of a loan contract, regardless of the development outcome, the new supplier will repay the loan and interest as much as possible, if not entirely, until its cash is depleted, and the liquidation value of the new supplier's assets is zero. Whereas, in the case of an equity contract, we ignore any dividend gains.

Moreover, we assume a perfect complementarity between the investment $K(\theta)$ and the effort $G(\theta)$. In other words, the PTS cannot be increased if the new supplier does not exert more effort in R&D or does not invest more in equipment and facilities, and is consistent with the setting used in the literature of collaborative new product development (e.g., Bhaskaran and Krishnan 2009) because the amount of investment required is independent of the amount of effort exerted (i.e., time spent) and vice versa. Specifically, the functional form $\theta(K_0, G_0)$ we use is known as the Leontief utility function (Scarf 1982) and has been used in the literature to represent complementary inputs in coproductive systems (Roels 2014). Given $\partial K/\partial\theta > 0$, $\partial G/\partial\theta > 0$, and any $G_2 > G_1 \geq 0$, it is easy to verify that we have $\partial\theta(K_0, G_1)/\partial K_0 \leq \partial\theta(K_0, G_2)/\partial K_0$ in general. For $K_0 \in (K_1, K_2)$, in which $K^{-1}(K_1) = G^{-1}(G_1)$ and $K^{-1}(K_2) = G^{-1}(G_2)$, we have $\partial\theta(K_0, G_1)/\partial K_0 < \partial\theta(K_0, G_2)/\partial K_0$, because $\theta(K_0, G_1) = G^{-1}(G_1)$ and $\theta(K_0, G_2) = K^{-1}(K_0)$. Moreover, the quadratic function form, $K(\theta)$ and $G(\theta)$, captures the decreasing marginal returns possibly driven by the Pareto principle (Koch 1998). To ensure that we are not constrained by this specific functional form, we try different forms of $K(\theta)$ and $G(\theta)$ in Appendix II, and we obtain similar findings.

Second, we assume that the manufacturer is not financially constrained and that the cost of capital is zero. We also note that the investment amount can be zero in our model. Therefore, if the manufacturer finds the investment non-profitable, it can choose not to invest in the new supplier. Following our motivating examples as well as the traditional literature, we assume that the new supplier's non-labor investment in R&D is verifiable through means such as auditing and reimbursements. However, the new supplier's effort level (e.g., labor hours allocated to R&D) is neither observable nor verifiable. Given that effort and investments are perfectly complementary, the manufacturer thus cannot enforce the level of PTS. To deal with the moral hazard issue, we assume that the manufacturer can require the new supplier to allocate at least a minimum amount of investment to non-labor investments. Or equivalently, we assume that the manufacturer imposes an upper limit B^G for the amount to be expended as the cost of effort, and that the new supplier needs to decide how much to expend as the cost of effort.

Moreover, for the equity investment, we assume that the manufacturer's share of equity γ is determined by a fair valuation of the new supplier's cash flows. This simplification preserves the generality of our results because the profit-sharing effect associated with an equity investment exists as long as $\gamma \in (0,1)$. In practice, the manufacturer cannot freely decide the equity share, which will be jointly determined by the investment value and the new supplier's future cash flows (including those from other businesses) or the new supplier's original firm value (denoted as Π_0^N). The magnitude of γ is positively associated with Π_0^N. However, the value of Π_0^N does not qualitatively affect the comparison of the manufacturer's payoffs under equity and loan contracts. This is because the individual rationality (IR) constraint applies to both type of investments (i.e., $U_E^N \geq \Pi_0^N$ and $U_L^N \geq \Pi_0^N$) and that there always exists the trade-off between the investment return and the cost of procurement: to obtain a larger equity share and maintain the same chance of success, the manufacturer has to pay a higher procurement price. In other words, a larger Π_0^N can allow the new supplier to keep a larger share of the firm, but it also allows the manufacturer to offer a lower procurement price under an equity contract. In order to avoid assuming an arbitrary value, we normalize Π_0^N to zero. However, this may mathematically allow the manufacturer to squeeze the new supplier's equity share to zero, which is practically not reasonable. As such, it is more reasonable to assume that the equity share is determined by a fair valuation (rather than to assume that the new supplier has an arbitrary reservation value), and the manufacturer focuses on optimizing the contract terms and the PTS to maximize the net payoff.

In the procurement contract, the manufacturer designs the procurement price of the component and a milestone payment contingent on a successfully developed component (e.g., in the Apple-GTAT example, the first three installments are attributed to the upfront investment B, but the last (unpaid) one is attributed to the milestone payment in our model). If the component is successfully developed, the new supplier will receive the milestone payment (if any), and the manufacturer will purchase the component at the specified price, according to the realized demand; otherwise, the manufacturer will purchase the component from the existing supplier without making additional payments. We denote $\tilde{D}$ as the realized demand (i.e., the manufacturer's final production quantity) and $p\left(\tilde{D}\right)$ as the total contingent payment—the sum of the milestone payment (if any) and the procurement value—to the new supplier, conditional on successful R&D. Although the manufacturer, in practice, needs to specify all the details (e.g., milestone payment, unit price) in the contract, we abstract from these details and instead aggregate these terms as $p\left(\tilde{D}\right)$. Furthermore, we note that demand uncertainty does not affect our results as long as (1) all firms in our model are risk neutral, (2) they do not need to fix procurement and production quantities at this early stage, and (3) the development effort does not affect the manufacturer's procurement quantity from the new supplier when R&D succeeds. Hence, firms may solely focus on the expectation of the total payment, or $P := \mathbf{E}\left[p\left(\tilde{D}\right)\right]$, when signing the contract. We note that the main focus at this stage is to offer the new supplier an appropriate incentive to develop the new component. Price is a more viable option than quantity as an incentive device because the procurement quantity is almost exogenous, given that the end product usually consists of numerous different components sourced from different suppliers. It is difficult to manipulate the quantity for a single supplier. Although the manufacturer may commit to certain minimum quantity, doing so does not affect the procurement flexibility.

Finally, for the existing supplier, we make the following assumptions. First, we consider the case in which the existing supplier, at the time when the manufacturer decides upon the contract, appears to be a less attractive option when compared to the new supplier. This assumption allows us to avoid the trivial case that the manufacturer does not want to collaborate with the new supplier at the beginning of the game. Moreover, the existing supplier can only learn about the contract type but *not* the details of the contract between the manufacturer and new supplier. Even if the total investment value is publicly announced, the purchase price is usually a secret, and the specific milestones are not disclosed (e.g., Apple required GTAT to achieve the technical success before a specified date, or otherwise a certain amount of the investment would be withdrawn). Hence, the actual amount of investment allocated to the new supplier's R&D before the required technical success and the PTS are unknown to the existing supplier.

Our stylized and yet flexible model captures a variety of scenarios between the manufacturer and the existing supplier. Specifically, $\beta = 0$ is equivalent to a single-supplier problem, because the manufacturer will obtain a zero profit for not sourcing from the new supplier. When $\beta = 1$, the existing supplier has no incentive to further improve the mature technology (i.e., $\varphi = 1$), and thus the manufacturer has a exogenous backup option with a fixed profit of $(R-1)D$. When $\beta \in (0,1)$, the manufacturer has a backup option with an endogenous profit, and must therefore decide how its decisions with respect to the new supplier influence the existing supplier's decision.

Appendix II: Robustness and Extensions

Here, we test the robustness of our model insights in three extensions: we consider (1) an exponential, instead of a quadratic, R&D cost function; (2) a technology-dependent demand, such that a new technology can generate a higher revenue; and (3) a convertible debt investment strategy.

Alternative Cost Function

To check whether our results (especially those shown in Propositions 1 and 2) are sensitive to the assumption of quadratic cost functions, we consider a set of $K(\theta)$ and $G(\theta)$ with the following form: $K(\theta) = G(\theta) = [\exp(-\zeta \ln(1-\theta)) + \zeta \ln(1-\theta) - 1]/a$, in which a still measures the technological capability of the new supplier or the maturity of the new technology. We note that $K(\theta)$ and $G(\theta)$ are increasing in θ, with a zero marginal cost when θ approaches zero, and an infinite marginal cost when θ approaches one. All other assumptions remain the same.

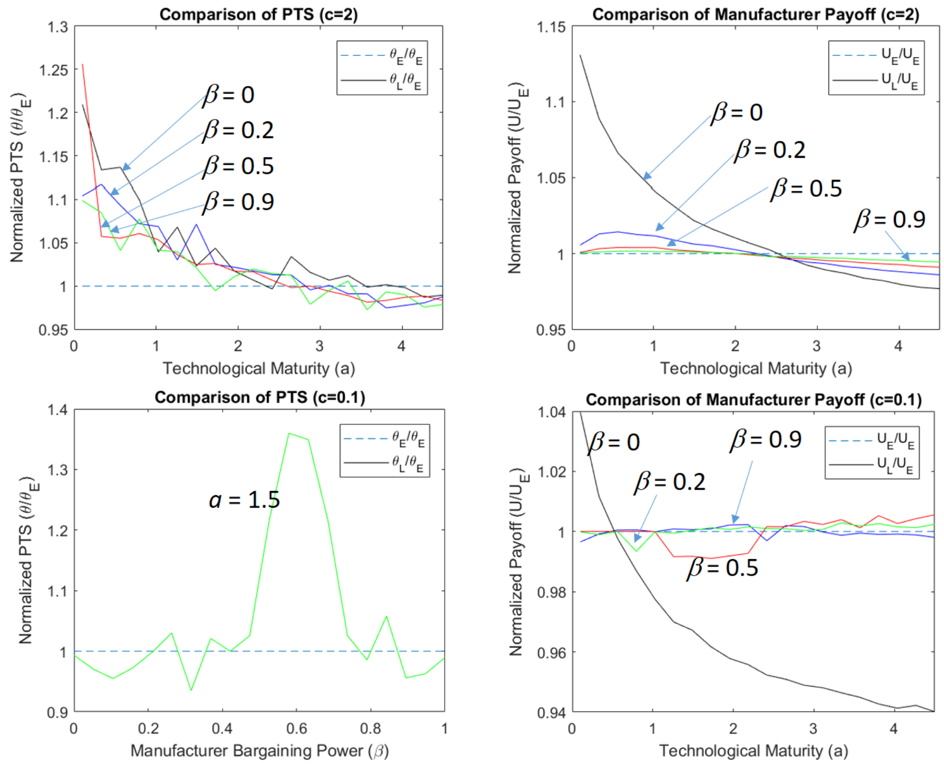
Due to the complexity of the function form, we use numerical examples to show that our results are similar to those of the base model. In our numerical examples, we set $R = 2$, $D = 1$, $\zeta = 1.5$, and vary the values for a, β, and c. The algorithm we use to derive the equilibrium outcome is shown below. Figure A1 presents the equilibrium outcomes under different parameter settings.

Algorithm for Numerical Solutions with the Alternative Cost Function

[0] Set $\varphi = 1$ and $\hat{\varphi}(\theta) = 0$.

[1] Try different combinations of contract terms: $\{B, P, \gamma\}$ for an equity investment and $\{B, P-r\}$ for a loan

Figure A1: Numerical Examples with the Alternative Cost Function



investment. For a given contract design, we find the optimal θ numerically with the first-order condition for the new supplier given that $B \geq G(\theta) + K(\theta)$ and $S = B^G = B/2$. Under equity investment, let θ solve the equation of:

$$(1-\gamma) P = (1-\gamma) K'(\theta) + G'(\theta),$$

or $G(\theta) + K(\theta) = B$, whichever solution is smaller. Under a loan investment, we let θ solve the equation of:

$$P - r - \frac{1}{2} B = K(\theta) + G'(\theta) + \theta K'(\theta),$$

or $G(\theta) + K(\theta) = B$, whichever solution is smaller. We then calculate the manufacturer's expected payoff given a contract design and the corresponding θ.

[2] Return the contract design and the corresponding θ that achieves the maximum payoff.

[3] Calculate $\hat{\varphi}(\theta)$ according to $\hat{\varphi}(\theta) = 1 - D(1-\beta)(1-\theta)/(2c)$.

[4] Check if $\varphi = \hat{\varphi}(\theta)$: if the two converge, we stop; otherwise, we set $\varphi = \hat{\varphi}(\theta)$ and repeat these steps beginning with [1].

Technology-Dependent Demand

Next, we relax the assumption that the demand is technology-independent by considering an additional sales (due to either a greater demand or a higher price) to the manufacturer when the new technology is successfully adopted. Specifically, we assume that the manufacturer will obtain a net expected revenue (revenue minus costs other than the focal component) of $\delta \cdot R \cdot D$ (in which $\delta > 1$) from the end market if the manufacturer uses the new technology, but will only obtain $R \cdot D$ if it uses the existing technology.

It is easy to check that similar results can be obtained when we use the same analysis procedure, except that the PTS is higher under both contracts. In particular, we have:

$$\theta^*_{TD,E} = \frac{[(\delta-\beta)R+\beta]D-L(\beta)}{\frac{6-4\gamma_E}{a}+\frac{6}{b}-L(\beta)} > \theta^*_E \tag{A-1}$$

under an equity contract, and

$$\theta^*_{TD,L} = \frac{1}{6}\sqrt{\left(1+\frac{3a}{b}-\frac{a}{2}L(\beta)\right)^2+6a\left([(\delta-\beta)R+\beta]D-L(\beta)\right)}-1-\frac{3a}{b}+\frac{a}{2}L(\beta) > \theta^*_L \tag{A-2}$$

under a loan contract.

Convertible Debt

Finally, we consider a hybrid investment strategy–convertible debt–with five parameters, $\{B, P, B^G, \gamma, r\}$. This investment is a loan at the beginning with a loan amount B, a total contingent payment P, and the interest to pay r. If the R&D is successful, the investment will be converted into an equity with a prespecified percentage γ. A convertible debt enables the manufacturer to not only leverage the cost-shifting effect that motivates a high PTS, but also to share the profit with the new supplier in case of a successful R&D at the same time.

To analyze the effectiveness of this contract, we calculate the net payoff for the new supplier as:

$$U^N_{CD} = S - G(\theta) + \theta(1-\gamma)(B-K(\theta)-S+P) + (1-\theta)\max\{0, B-K(\theta)-S-B-r\}.$$

The new supplier aims to maximize U^N_{CD} subject to the constraints of $G(\theta) \leq S \leq B^G$ and $S+K(\theta) \leq B$.

The manufacturer's net payoff is:

$$U_{CD} = -B + \theta\left[DR - P + \gamma(B - K(\theta) - S + P)\right] + (1-\theta)\left[\beta(R-\varphi)D + \min\{B - K(\theta) - S, B + r\}\right].$$

The manufacturer aims to maximize U_{CD} subject to IC and IR constraints. To make the results under different investment strategies more comparable (i.e., equity versus convertible debt), we assume again that the manufacturer's equity share under convertible debt contract is the same as that under the equity contract. The existing supplier's optimal effort remains the same as that in Lemma 1. We summarize the optimal PTS and the manufacturer's payoff in Proposition A.1.

Proposition A.1. *Given the existing supplier's new production cost φ and the contracted equity share γ, the optimal PTS $\hat{\theta}$ solves the following equation:*

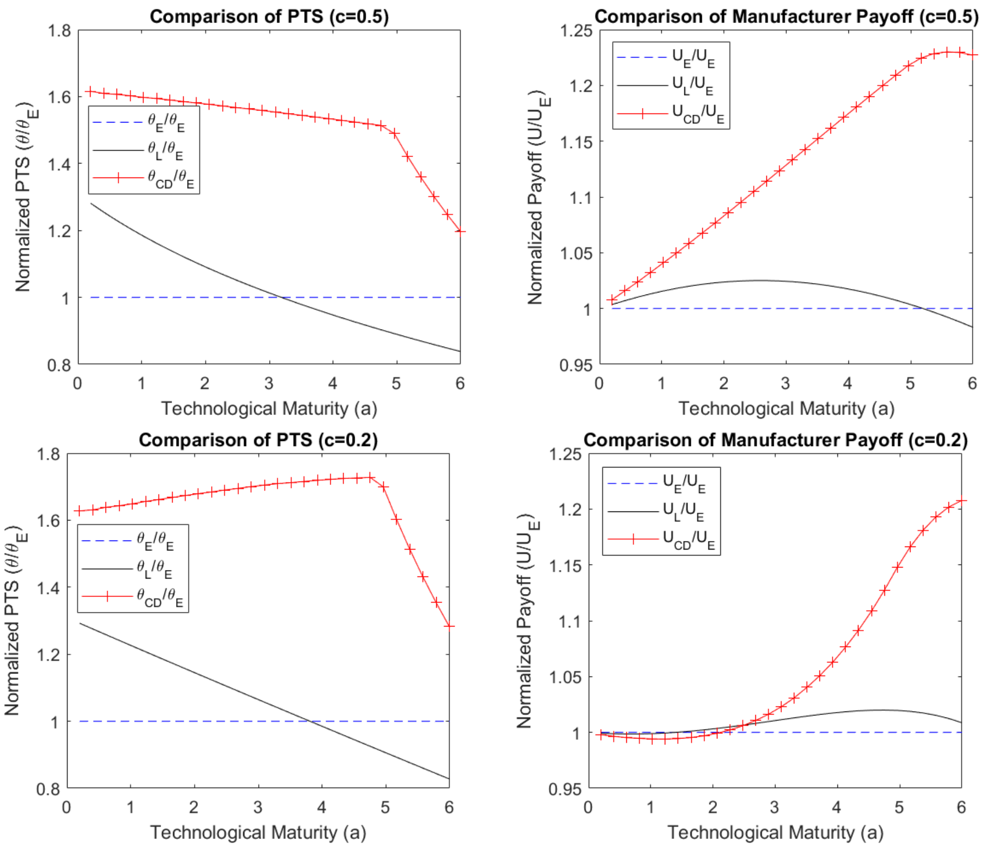
$$D\bar{R} - \left[\frac{2}{a} + \frac{2(3-2\gamma)}{b}\right]\hat{\theta} + \left[\frac{3(1-\gamma)(3\gamma-2)}{a} + \frac{3\gamma(1-\gamma)}{b}\right]\hat{\theta}^2 = 0,$$

and the manufacturer payoff is given by:

$$U_{CD} = \hat{\theta}D\bar{R} + D\beta(R-\varphi) - \left[\frac{1}{a} + \frac{3-2\gamma}{b}\right]\hat{\theta}^2 + \left[\frac{(1-\gamma)(3\gamma-2)}{a} + \frac{\gamma(1-\gamma)}{b}\right]\hat{\theta}^3.$$

Next, we use the following numerical example to compare the new supplier's PTS and illustrate the manufacturer's optimal contract choice. Figure A2 shows the PTS and the manufacturer's payoff under three different investment strategies. The default parameter values are $b = a$, $R = 2$, $D = 1$, and $\beta = 0.5$. First, we see that a convertible debt leads to a higher PTS in equilibrium, when compared to a loan or an equity contract. This is simply because a convertible debt allows both cost-shifting and profit-sharing. In addition, a convertible debt can generate a higher payoff for the manufacturer (see the graphs on the right) when c is not too low or when the new technology is sufficiently mature. However, when both c and a are low (i.e., the third region described in Proposition 2(iii)), the manufacturer prefers not to invest too much in the new technology and prefers a low PTS (but not zero), in which case a convertible debt could be the worst choice for the manufacturer (as shown by the bottom-right panel).

Figure A2: Comparison among Three Investment Strategies



Appendix III: Technical Proofs

Proof of Lemma 1.

To prove this lemma, we will first find the best responses for the three players in the following proposition and then find the equilibrium accordingly.

Lemma A.1. *Given the existing supplier's new production cost* φ*, the optimal PTS for the new supplier and the manufacturer is* $\hat{\theta}_E(\varphi)$ *under an equity contract and is* $\hat{\theta}_L(\varphi)$ *under a loan contract, in which:*

$$\hat{\theta}_E(\varphi) = \pi(\varphi) / \left(\frac{3}{a} + \frac{3}{b} + \frac{\sqrt{9a^2 + 10ab + b^2}}{ab}\right); \textit{and} \tag{A-3}$$

$$\hat{\theta}_L(\varphi) = \pi(\varphi) / \left[\sqrt{\left(\frac{1}{a} + \frac{3}{b}\right)^2 + \frac{6\pi(\varphi)}{a}} + \left(\frac{1}{a} + \frac{3}{b}\right)\right], \tag{A-4}$$

in which $\pi(\varphi) := D[R - \beta(R - \varphi)]$*. Given the PTS, the best response of the existing supplier are the same for both investments, and it is:*

$$\hat{\varphi}(\theta) = 1 - \frac{D(1-\beta)(1-\theta)}{2c}. \tag{A-5}$$

With Lemma A.1, we obtain the equilibrium outcome under an equity contract by substituting $\hat{\varphi}(\theta)$ into Equation (A-3) and solving θ_E^*, whereas for the outcome under a loan contract, we substitute $\hat{\varphi}(\theta)$ into Equation (A-4) and obtain θ_L^*. From the proof of Lemma A.1, we obtain the optimal contract design: The contract terms and the existing supplier's cost reduction are $B_i = (1/a + 1/b)\,\theta_i^{*2}$ and $B_i^G = aB_i/(a+b)$. Moreover, under an equity investment, we have $\gamma_E = \left(3a + 3b - \sqrt{9a^2 + 10ab + b^2}\right)/(4b)$ and $P_E = \theta_E^*\left[2/a + 2(1-\gamma_E)^{-1}/\right.$ whereas under a loan investment, we have $r_L = 0$, and $P_L = 2\theta_L^*/b + (3/a + 1/b)\,\theta_L^{*2}$.

To find how θ_E^* responds to a, we take the first-order derivative as follows:

$$\frac{\partial \theta_E^*}{\partial a} = \frac{W(\beta) - L(\beta)}{\left([6 - 4\hat{\gamma}]/a + 6/b - L(\beta)\right)^2} \cdot \frac{6 - 4\hat{\gamma} + 4a\frac{\partial \hat{\gamma}}{\partial a}}{a^2}.$$

It is easy to obtain that $\partial\hat{\gamma}/\partial a = -(1-2\hat{\gamma})(1-\hat{\gamma})/\left[a^2\left((3-4\hat{\gamma})/a + 3/b\right)\right]$. Plugging $\partial\hat{\gamma}/\partial a$ and $\hat{\gamma}$, we have:

$$\frac{\partial \theta_E^*}{\partial a} = \frac{W(\beta) - L(\beta)}{\left([6 - 4\hat{\gamma}]/a + 6/b - L(\beta)\right)^2} \cdot \frac{14 - 24\hat{\gamma} + 8\hat{\gamma}^2 + (18 - 12\hat{\gamma})\,a/b}{a^3\left(\frac{3-4\hat{\gamma}}{a} + \frac{3}{b}\right)}.$$

We can check that $\hat{\gamma} < 0.5$ and $14 - 24\hat{\gamma} + 8\hat{\gamma}^2$ is decreasing in $\hat{\gamma}$ from 0 to 0.5. When $\hat{\gamma} = 0.5$, $14 - 24\hat{\gamma} + 8\hat{\gamma}^2 > 0$. Hence, $\partial\theta_E^*/\partial a > 0$ if $W(\beta) > L(\beta)$. Similarly, given that $W(\beta) > L(\beta)$, we have $\theta_L^* > 0$, and thus:

$$\frac{\partial \theta_L^*}{\partial a} = \frac{[W(\beta) - L(\beta)]^2}{\left[\sqrt{\chi} + 1 + \frac{3a}{b} - \frac{a}{2}L(\beta)\right]^2\sqrt{\chi}}\left(\frac{a}{\theta_L^*} + 3a\right) = \frac{\theta_L^{*2}}{a\sqrt{\chi}}\left(\frac{1}{\theta_L^*} + 3\right) > 0,$$

in which $\chi = (1 + 3a/b - aL(\beta)/2)^2 + 6a(W(\beta) - L(\beta)) > 0$. ■

Proof of Proposition 1.

First, we can rewrite θ_L^* as:

$$\theta_L^* = \frac{W(\beta) - L(\beta)}{\sqrt{\left(\frac{1}{a} + \frac{3}{b} - \frac{1}{2}L(\beta)\right)^2 + \frac{6}{a}\left(W(\beta) - L(\beta)\right)} + \frac{1}{a} + \frac{3}{b} - \frac{1}{2}L(\beta)}.$$

With simple algebra, we have $\theta_E^* \geq \theta_L^*$ if and only if:

$$\frac{6-4\hat{\gamma}}{a} + \frac{6}{b} - L(\beta) \leq \sqrt{\left(\frac{1}{a} + \frac{3}{b} - \frac{1}{2}L(\beta)\right)^2 + \frac{6}{a}\left(W(\beta) - L(\beta)\right)} + \frac{1}{a} + \frac{3}{b} - \frac{1}{2}L(\beta)$$

$$\Leftrightarrow\ W(\beta) - \left[\frac{1}{3} + \frac{2}{3}\hat{\gamma}\right]L(\beta) - \frac{2}{3}\sqrt{\frac{9}{b^2} + \frac{10}{ab} + \frac{1}{a^2}} - \frac{2}{3a} - \frac{2}{3b} \geq 0.$$

We note that $\hat{\gamma}$ is decreasing in a and, hence, the left-hand side of the above inequality is an increasing function of a and a quadratic, convex function of β. We let $\bar{a}_T(\beta)$ denote the value of a and $\{\bar{\beta}_L(a), \bar{\beta}_H(a)\}$ the values of β that achieve equality in the above inequality. Therefore, $\theta_E^* > \theta_L^*$ if and only if $a > \bar{a}_T(\beta)$, and vice versa. Similarly, for a given a, we have $\theta_E^* < \theta_L^*$ if $\bar{\beta}_L(a) < \beta < \bar{\beta}_H(a)$ and $\theta_E^* \geq \theta_L^*$ if $\beta \leq \bar{\beta}_L(a)$ or $\beta \geq \bar{\beta}_H(a)$. Some of the three regions may disappear if $\bar{\beta}_L(a)$ and/or $\bar{\beta}_H(a)$ are not between 0 and 1. ■

Proof of Proposition 2.

(i) We know that when $a = \bar{a}_T(\beta)$, we have $\theta_E^* = \theta_L^* = 2(1-\hat{\gamma})/3$ (by substituting this equation above into Equation 7). Hence, when $a = \bar{a}_T(\beta)$, we have:

$$U_L^* = u(\theta_L^*) > u(\theta_E^*) - 2\theta_E^{*2} \cdot \left(\frac{1-\hat{\gamma}}{3a}\right) = u(\theta_E^*) + 2\theta_E^{*2} \cdot \left(\frac{\theta_E^*}{a} - \frac{1-\hat{\gamma}}{a}\right) = U_E^*.$$

As a result, due to continuity, there exists $\bar{a}_L < \bar{a}_T(\beta)$ and $\bar{a}_M > \bar{a}_T(\beta)$ such that $U_L^* > U_E^*$ for $a \in (\bar{a}_L, \bar{a}_M)$.

(ii) Note that $U_E^* - U_L^* = u(\theta_E^*) - u(\theta_L^*) + 2\theta_E^{*2} \cdot (\theta_E^*/a - (1-\hat{\gamma})/a)$. We complete this part of the proof in two steps. First, we show that $\theta_E^* > 1 - \hat{\gamma}$ when a is large. Second, we show $u(\theta_E^*) - u(\theta_L^*) > 0$ when a is large. For the ease of exposition, we define $\tilde{R} = R - \beta(R-1)$.

To show that $\theta_E^* > 1 - \hat{\gamma}$, it is equivalent to show:

$$D\tilde{R} - \hat{\gamma}L(\beta) > \frac{-4\hat{\gamma}(1-\hat{\gamma})}{a} + \frac{6(1-\hat{\gamma})}{a} + \frac{6(1-\hat{\gamma})}{b} \Leftrightarrow D\tilde{R} - \hat{\gamma}L(\beta) > 4\left(\frac{1-\hat{\gamma}}{a} + \frac{1}{b}\right).$$

If $D\tilde{R} - L(\beta) > 0$, then there exists a threshold for a such that the above inequality holds when a is greater than the threshold. Then, it is sufficient to have $D\tilde{R}-L(\beta)>0$.

To show that $u(\theta_E^*)-u(\theta_L^*)>0$, it is equivalent to show:

$$u(\theta_E^*)-u(\theta_L^*)=(\theta_E^*-\theta_L^*)\left[D\tilde{R}-(2-\theta_E^*-\theta_L^*)L(\beta)-\frac{3(\theta_E^*+\theta_L^*)}{b}-\frac{\theta_E^*+\theta_L^*+2\left(\theta_E^{*2}+\theta_L^*\theta_E^*+\theta_L^{*2}\right)}{a}\right]>0.$$

We know from Proposition 1 that $\theta_E^*>\theta_L^*$ when a is large. In addition, when both a and b are large (due to $a\propto b$), it is easy to see that θ_E^* and θ_L^* both approach one. Hence, it is equivalent to show that:

$$D\tilde{R}-(2-\theta_E^*-\theta_L^*)L(\beta)-\frac{3(\theta_E^*+\theta_L^*)}{b}-\frac{\theta_E^*+\theta_L^*+2\left(\theta_E^{*2}+\theta_L^*\theta_E^*+\theta_L^{*2}\right)}{a}>0,$$

which can be achieved if $D\tilde{R}-L(\beta)>0$ and a is large enough provided that $\theta_E^*+\theta_L^*+2\left(\theta_E^{*2}+\theta_L^*\theta_E^*+\theta_L^{*2}\right)$ is positive and finite. Given that $U_L^*>U_E^*$ for $\bar{a}_L<a<\bar{a}_M$, we know that there must exist $\bar{a}_H\geq\bar{a}_M>\bar{a}_T(\beta)$ such that $U_L^*<U_E^*$ for any $a>\bar{a}_H$ due to continuity.

(iii) Observing Equation (6), we find that when $W(\beta)<(6-4\hat{\gamma})/a+4/b$ and $L(\beta)\nearrow W(\beta)$, we have $\theta_E^*\searrow 0$ and $U_E^*\to DR$. On the other hand, observing Equation (7), we find that when $L(\beta)\nearrow W(\beta)$ and $L(\beta)>2/a+6/b$, we have:

$$\theta_L^*\to\frac{1}{3}\left[1+\frac{2a}{b}-\frac{a}{2}L(\beta)\right]>0.$$

Given the conditions of this proposition, we then have:

$$U_L^*-U_E^*\to\frac{\theta_L^{*2}+2\theta_L^{*3}}{a}+\frac{3\theta_L^{*2}}{b}+(1-\theta_L^*)\,\theta_L^*L(\beta)>0$$

when the conditions are satisfied. The result follows. ■

Proof of Proposition 3.

Applying the first-order condition of $U_{PI}(\theta)$ with respect to θ, we can easily obtain that:

$$\hat{\theta}_{PI}(\varphi)=\pi(\varphi)\cdot\left(\frac{2}{a}+\frac{2}{b}\right)^{-1}.$$

Given the existing supplier's best response, $\hat{\varphi}(\theta)$, in Equation (A-5), we know that the equilibrium exists if and only if $\hat{\theta}_{PI}(\hat{\varphi}(\theta))=\theta\in[0,1]$. To find the condition for a valid internally optimal PTS, we consider two cases that will not achieve an equilibrium: (1) $\hat{\theta}_{PI}(\hat{\varphi}(\theta)) > \theta$ for any $\theta \in [0,1]$ and (2) $\hat{\theta}_{PI}(\hat{\varphi}(\theta)) < \theta$ for any $\theta \in [0,1]$.

In the first case, the inequality, $\hat{\theta}_{PI}(\hat{\varphi}(\theta)) > \theta$ for any $\theta \in [0,1]$, is equivalent to:

$$W(\beta) - L(\beta) > \left[\frac{2}{a} + \frac{2}{b} - L(\beta)\right]\theta,$$

in which we use Equation (A-5) and the definition of $L(\beta)$. If $2/a + 2/b > L(\beta)$, it must be $W(\beta) - L(\beta) > 2/a + 2/b - L(\beta)$; if $2/a + 2/b \leq L(\beta)$, it must be $W(\beta) - L(\beta) > 0$. In sum, we must have $W(\beta) - L(\beta) > \max\{0, 2/a + 2/b - L(\beta)\}$ in this case. Similarly, we can derive that $\hat{\theta}_{PI}(\hat{\varphi}(\theta)) < \theta$ for any $\theta \in [0,1]$ is equivalent to $W(\beta) - L(\beta) < \min\{0, 2/a + 2/b - L(\beta)\}$. Therefore, the equilibrium exists if the above two conditions do not hold.

Given that the equilibrium exists, we can obtain θ^*_{PI} by combining $\hat{\theta}_{PI}(\varphi)$ and $\hat{\varphi}(\theta)$. Note that $2/a + 2/b < [6 - 4\gamma_E]/a + 6/b$, it is easy to see that $\theta^*_{PI} > \theta^*_E$. According to Proposition 1, we know that $\theta^*_L \geq \theta^*_{PI}$ if and only if:

$$\sqrt{\left(\frac{1}{a} + \frac{3}{b} - \frac{1}{2}L(\beta)\right)^2 + \frac{6}{a}(W(\beta) - L(\beta))} + \frac{1}{a} + \frac{3}{b} - \frac{1}{2}L(\beta) \leq \frac{2}{a} + \frac{2}{b} - L(\beta),$$

which is impossible, given that $W(\beta) > L(\beta)$. The result follows. ■

Proof of Proposition 4.

Given that the new supplier (or a dedicated subsidiary) initially has no cash on hand, the amount of payback from the new supplier to the bank in the case of failed R&D will be $\min\{B - M, B + Br_b\} = B - M$, wherein M is the total amount of money expended by the new supplier. Hence, given (P, B, r_b), the new supplier solves the problem of:

$$\begin{aligned}
\max_{\theta, M} U^N_{OF} =& B - K(\theta) - G(\theta) + \theta(P - B - Br_b) - (1-\theta)[B - M] \\
=& \theta[P - Br_b - M] + M - K(\theta) - G(\theta) \qquad \text{(A-6)} \\
s.t. \qquad & \theta \leq \sqrt{abM/(a+b)} \text{ and } M \leq B.
\end{aligned}$$

It is easy to see that $\hat{M} = B$. We let $\hat{\theta}_{OF}(P, B, r_b)$ denote the new supplier's optimal PTS. Given $\hat{\theta}_{OF}$, the bank's required interest r_b satisfies the following breakeven condition that the expected return must be equal to the money lent to the new supplier:

$$B = \hat{\theta}_{OF}\left(B + Br_b\right) + \left(1 - \hat{\theta}_{OF}\right)\left(B - \hat{M}\right), \tag{A-7}$$

which can be simplified to $1 + r_b = 1/\hat{\theta}_{OF}$. Therefore, r_b only depends on $\hat{\theta}_{OF}$ as long as the new supplier is able to payback if the R&D succeeds (i.e., $P \geq B + Br_b$). Then, we combine the first-order condition on $U^N_{OF}(\theta)$ with respect to θ, the constraint, and the simplified Equation (A-7), and obtain $\hat{\theta}_{OF}$ that satisfies the following in equilibrium:

$$\hat{\theta}_{OF} = \min\left\{\frac{P - B/\hat{\theta}_{OF}}{2\left(\frac{1}{a} + \frac{1}{b}\right)}, \sqrt{\frac{B}{\frac{1}{a} + \frac{1}{b}}}\right\}. \tag{A-8}$$

Therefore, the more money the new supplier borrows from the bank, the lower the incentive to achieve the success in R&D. Taking this into consideration, the optimal B is obtained by solving the following problem:

$$\max_B U^N_{OF} = \hat{\theta}_{OF}\left[P - B/\hat{\theta}_{OF}\right] + B - K\left(\hat{\theta}_{OF}\right) - G\left(\hat{\theta}_{OF}\right),$$

in which $\hat{\theta}_{OF}$ is given by (A-8). It is easy to obtain that the optimal B achieves $P - B/\hat{\theta}_{OF} = 2\sqrt{B\left(1/a + 1/b\right)}$; thus, we have $\hat{B} = abP^2/\left(9a + 9b\right)$ and $\hat{\theta}_{OF} = P/\left(3/a + 3/b\right)$.

Given φ, the manufacturer's problem is:

$$\max_P U_{OF} = \hat{\theta}_{OF}\left(DR - P\right) + \left(1 - \hat{\theta}_{OF}\right)\beta\left(R - \varphi\right)D. \tag{A-9}$$

We note that the existing supplier's problem is the same as that in our main model. Applying the first-order condition, it is easy to obtain the optimal $\hat{\theta}_{OF}$ for the manufacturer is $\hat{\theta}_{OF} = \pi\left(\varphi\right) \cdot \left(6/a + 6/b\right)^{-1}$. We then can obtain the final PTS θ^*_{OF} in equilibrium by plugging in $\hat{\varphi}\left(\theta\right)$. It is easy to see that $\theta^*_{OF} < \theta^*_E$ as long as $\gamma_E > 0$. Because $\theta^*_{OF} = \theta^*_E|_{\gamma_E = 0}$, it is easy to check that $\theta^*_{OF} \geq \theta^*_L$ if and only if:

$$\frac{4}{3} \cdot \left(\frac{3}{a} + \frac{3}{b}\right) \leq W(\beta) - \frac{1}{3}L(\beta).$$

Therefore, there exists a threshold value a_{OF} such that $\theta^*_{OF} \geq \theta^*_L$ if and only if $a \geq a_{OF}$. Suppose $a_{OF} \leq \bar{a}_T$. Then, when $a = a_{OF}$, we have $\theta^*_{OF} \geq \theta^*_L \geq \theta^*_E$, a contradiction. Hence, we must have $a_{OF} > \bar{a}_T$.

Inserting θ^*_{OF} into U_{OF}, we have:

$$U^*_{OF} = DR - 3\theta^{*2}_{OF}\left(\frac{1}{a}+\frac{1}{b}\right) - (1-\theta^*_{OF})\left[D\tilde{R} - (1-\theta^*_{OF})L(\beta)\right].$$

Therefore, by using simple algebra, we have:

$$U^*_E - U^*_{OF} = \frac{2\gamma_E\theta^*_E}{a}\cdot\frac{D\tilde{R} - (3-\theta^*_E-\theta^*_{OF})L(\beta)}{\frac{6}{a}+\frac{6}{b}-L(\beta)}.$$

Given $6/a+6/b > L(\beta)$, the proof is complete. ■

Proof of Proposition A.1.

Similar to the base model, we start with solving the new supplier's best response to $\{B,P,B^G,\gamma\}$ (note that r is irrelevant) via the first-order condition, given that $S = \min\{B^G, B-K(\theta)\}$:

$$0 = \frac{\partial U^N_{CD}}{\partial\theta} = \begin{cases} -\frac{2\theta}{b} - 3(1-\gamma)\frac{\theta^2}{a} + (1-\gamma)\left(B-B^G+P\right), & B^G \le B-K(\theta), \\ -\frac{2\theta}{b} - \frac{2\theta}{a} + (1-\gamma)P, & B^G > B-K(\theta). \end{cases}$$

We let $\hat{\theta}_{high}$ and $\hat{\theta}_{low}$ denote the two respective solutions, or $G^{-1}\left(B^G\right)$, whichever is smaller. Hence, the new supplier's best response is $\hat{\theta} = \hat{\theta}_{high}$ if $B^G \le B-K\left(\hat{\theta}_{high}\right)$, $\hat{\theta} = \hat{\theta}_{low}$ if $B^G > B-K\left(\hat{\theta}_{low}\right)$, or $\hat{\theta} = K^{-1}\left(B-B^G\right)$. We define $\bar{R} = R-\beta(R-\varphi)$. The manufacturer's payoff can thus be rewritten as:

$$U_{CD} = \hat{\theta}\left[D\bar{R}-(1-\gamma)P\right] + D\beta(R-\varphi) - B + \left(\hat{\theta}\gamma+1-\hat{\theta}\right)\left[B-K\left(\hat{\theta}\right)-B^G\right]^+.$$

We check the optimal B^G. First, suppose $B^G > G_* = aB/(a+b)$. In this scenario, we have $\hat{\theta} \in \left\{\hat{\theta}_{high}, \hat{\theta}_{low}, G^{-1}(G_*)\right\}$ and thus $\hat{\theta}$ is decreasing in B^G. As a result, it is easy to show that U_{CD} is decreasing in B^G as long as $\left[D\bar{R}-(1-\gamma)P\right] > \left[B-K\left(\hat{\theta}\right)-B^G\right]^+$ or a large enough D. Given this condition, it is optimal to reduce B^G as much as possible until $B^G \le G_*$. Given $B^G \le G_*$, we must have $B^G \le B-K(\theta)$ and $\hat{\theta} = \min\left\{\hat{\theta}_{high}, G^{-1}\left(B^G\right)\right\}$. If $G^{-1}\left(B^G\right) > \hat{\theta}_{high}$, then it is optimal to further reduce B^G until $G^{-1}\left(B^G\right) \le \hat{\theta}_{high}$. Now suppose $\hat{\theta} = G^{-1}\left(B^G\right) < \hat{\theta}_{high}$. Further, $(B+P)$ should be reduced as much as possible until $\hat{\theta} = G^{-1}\left(B^G\right) = \hat{\theta}_{high}$. According to the first-order condition, we know that:

$$B + P = \frac{2\theta}{b} + (1-\gamma)\,\theta^2\left(\frac{3}{a} + \frac{1}{b}\right),$$

and the manufacturer's payoff can thus be rewritten as:

$$U_{CD} = \hat{\theta}D\bar{R} + D\beta\,(R-\varphi) - \frac{\hat{\theta}^2}{a} - (3-2\gamma)\,\frac{\hat{\theta}^2}{b} + (1-\gamma)\,(3\gamma-2)\,\frac{\hat{\theta}^3}{a} + \gamma(1-\gamma)\,\frac{\hat{\theta}^3}{b}.$$

Applying the first order condition, we know that the optimal $\hat{\theta}$ solves:

$$D\bar{R} - \left[\frac{2}{a} + \frac{2\,(3-2\gamma)}{b}\right]\hat{\theta} + \left[\frac{3\,(1-\gamma)\,(3\gamma-2)}{a} + \frac{3\gamma(1-\gamma)}{b}\right]\hat{\theta}^2 = 0.$$

The proof is complete. ■

Proof of Lemma A.1.

In this proof, we find the best responses under the two investment strategies respectively. For either strategy, we start with the new supplier's decisions, in which increasing the cost of effort, S, always leads to a higher payoffs, thereby leading to $S = \min\left\{B^G, B - K(\theta)\right\}$ in equilibrium. As a result, by taking the first-order derivative of the payoffs with respect to the PTS, we can find three regions of θ in a form of $B^G < B - K(\theta), B^G > B - K(\theta)$, and $B^G = B - K(\theta)$. Based on these three regions, we then find the best responses of the contracts for the manufacturer. Finally, with the best responses of the new supplier and the manufacturer obtained, we next find the best response of the existing supplier by solving the problem in (4), and the best responses are the same for both investments:

$$\hat{\varphi}(\theta) = 1 - \frac{D\,(1-\beta)\,(1-\theta)}{2c}.$$

Next, we provide the detailed analysis of the new supplier's and the manufacturer's best responses under the two investment strategies.

We first consider an equity investment.

We start from the new supplier's decisions. Given θ, we have $\partial U_E^N/\partial S = \gamma > 0$, and thus $S = \min\left\{B^G, B - K(\theta)\right\}$

in equilibrium. We then apply the first-order condition with respect to θ and obtain:

$$0=\frac{\partial U_E^N}{\partial \theta}=\begin{cases}(1-\gamma)P-2\theta/a-2\theta/b, & \text{if } B^G>B-K(\theta);\\ (1-\gamma)(P-2\theta/a)-2\theta/b, & \text{if } B^G<B-K(\theta).\end{cases}$$

For the ease of notation, we denote that:

$$\nu_{high}=\frac{(1-\gamma)P}{2(1-\gamma)/a+2/b} \text{ and } \nu_{low}=\frac{(1-\gamma)P}{2/a+2/b},$$

as the values of θ that solve the two equations. Furthermore, we denote the upper bound of PTS given by (3) as $\bar{\theta}\left(B,B^G\right)=\min\left\{G^{-1}\left(B^G\right),G^{-1}(G_*)\right\}$ (recall that we define $G_*=aB/(a+b)$ and $K_*=bB/(a+b)$), and define:

$$\hat{\theta}_{low}\equiv\min\left\{\nu_{low},\bar{\theta}\left(B,B^G\right)\right\} \text{ and } \hat{\theta}_{high}\equiv\min\left\{\nu_{high},\bar{\theta}\left(B,B^G\right)\right\}.$$

Because $1-\gamma<1$, we have $\nu_{high}\geq\nu_{low}$ and thus $\hat{\theta}_{high}\geq\hat{\theta}_{low}$. Accordingly, we know that (I) $\hat{\theta}=\hat{\theta}_{high}$ if $B^G<B-K\left(\hat{\theta}_{high}\right)$, (II) $\hat{\theta}=\hat{\theta}_{low}$ if $B^G>B-K\left(\hat{\theta}_{low}\right)$, and (III) $\hat{\theta}=K^{-1}\left(B-B^G\right)$ if otherwise.

Next, we look at the manufacturer's problem. Plugging $\hat{S}$ and $\hat{\theta}$ into U_E, we have:

$$\begin{aligned}U_E&=-B+\gamma\left[B-K\left(\hat{\theta}\right)-B^G\right]^++\gamma\hat{\theta}P+\hat{\theta}(DR-P)+\left(1-\hat{\theta}\right)\beta(R-\varphi)D\\&=-B+\beta(R-\varphi)D+\gamma\left[B-K\left(\hat{\theta}\right)-B^G\right]^++\left[\gamma P-P+DR-D\beta(R-\varphi)\right]\hat{\theta},\end{aligned}$$

in which x^+ represents $\max\{x,0\}$. We then check the optimal B^G by considering the following three scenarios that are mutually exclusive and collectively exhaustive: (i) $G^{-1}(G_*)\leq\nu_{low}$; (ii) $\nu_{low}<G^{-1}(G_*)\leq\nu_{high}$; (iii) $G^{-1}(G_*)>\nu_{high}$.

In Scenario (i), $\hat{\theta}=\bar{\theta}$. When B^G is in the range of $[0,G_*]$, we have $\hat{\theta}=G^{-1}\left(B^G\right)\leq G^{-1}(G_*)=K^{-1}(K_*)$, and thus $B-K\left(\hat{\theta}\right)\geq B-K_*=G_*\geq B^G$. Hence, the first-order condition with respect to B^G leads to:

$$\frac{\partial U_E}{\partial B^G}=-\gamma\left[\frac{b}{a}+1\right]+\left[D\bar{R}-(1-\gamma)P\right]\frac{b}{2\sqrt{bB^G}}=0,$$

in which $\bar{R} = R - \beta(R - \varphi)$, and we denote the solution of B^G as Δ, in which:

$$\Delta = \frac{1}{b}\left(\frac{D\bar{R} - (1-\gamma)P}{2\gamma(1/a + 1/b)}\right)^2.$$

When $B^G \geq G_*$, we have $\hat{\theta} = G^{-1}(G_*) = K^{-1}(K_*)$ and $S = B - K(\hat{\theta}) \leq B^G$, which indicates that $\partial U_E / \partial B^G = 0$. As a result, in Scenario (i), the optimal $B^G = \min\{G_*, \Delta\}$. In Scenario (ii), when B^G is strictly less than $G(v_{low})$, we have $\hat{\theta}_{high} = \hat{\theta}_{low} = G^{-1}(B^G) = \hat{\theta}$ and $B - K(\hat{\theta}) \geq B^G$. Thus, $\partial U_E / \partial B^G = 0$ at $B^G = \Delta$. When $G(v_{low}) \leq B^G \leq G_*$, we still have $B - K(\hat{\theta}) \geq B^G$, and thus $\hat{\theta} = \hat{\theta}_{high} = G^{-1}(B^G)$. Similarly, $\partial U_E / \partial B^G = 0$ when $B^G = \Delta$. When $B^G \geq G_*$, we have $S = B - K_*$ and $\hat{\theta}_{high} = G^{-1}(G_*)$, so $B - K(\hat{\theta}_{high}) \leq B^G$. Hence, $\hat{\theta} = K^{-1}(B - B^G)$ or $\hat{\theta} = v_{low}$, indicating that $\partial U_E / \partial B^G \leq 0$, and thus in Scenario (ii), the optimal $B^G = \min\{G_*, \Delta\}$. In Scenario (iii), when B_G is in the range between 0 and $G(v_{low})$, we have $\hat{\theta} = G^{-1}(B^G)$ and $B - K(\hat{\theta}) \geq B^G$, indicating that $\partial U_E / \partial B^G = 0$ at $B^G = \Delta$. When B^G is in the range between $G(v_{low})$ and $G(v_{high})$, we have $\hat{\theta}_{high} = G^{-1}(B^G)$ and $B - K(\hat{\theta}_{high}) \geq B^G$, indicating that $\partial U_E / \partial B^G = 0$ at $B^G = \Delta$. When B^G is in the range between $G(v_{high})$ and G_*, we still have $B - K(\hat{\theta}_{high}) \geq B^G$ and thus $\hat{\theta} = K^{-1}(B - B^G)$ or $\hat{\theta} = v_{high}$, which indicates that $\partial U_E / \partial B^G \leq 0$. When B^G goes beyond G_*, we have $\hat{\theta} = K^{-1}(B - B^G)$ or $\hat{\theta} = v_{low}$, which indicates that $\partial U_E / \partial B^G \leq 0$. As a result, in Scenario (iii), the optimal $B^G = \min\{G_*, \Delta\}$. In sum, the optimal $B^G = \min\{G_*, \Delta\}$. Accordingly, $\hat{\theta} = K^{-1}(B - B^G)$ or $\hat{\theta} = v_{high}$.

We then check the optimal B and P. Given $B^G(B, P, \hat{\gamma}) = \min\{G_*, \Delta\}$, the manufacturer's problem becomes:

$$\max_{P,B} U_E = -B + D\beta(R - \varphi) + \hat{\gamma}\left[B - K(\hat{\theta}) - B^G(B, P, \hat{\gamma})\right] + \left[D\bar{R} + \hat{\gamma}P - P\right]\hat{\theta}.$$

We note that, if $G_* > \Delta$, then $B^G = \Delta$ and $\hat{\theta} = \hat{\theta}_{high}$; in this case, it is optimal for the manufacturer to reduce B as much as possible because B^G and $\hat{\theta}$ do not depend on B. Therefore, in equilibrium, it must be $G_* \leq \Delta$ and $B^G(B, P, \hat{\gamma}) = G_*$. Hence, B^G is independent of P. Now, we suppose $G_* < v_{high}$. Accordingly, we should have $K^{-1}(B - B^G) = \hat{\theta}_{high} < v_{high}$ and it is optimal to reduce P as much as possible because $\hat{\theta}$ is independent of P. Therefore, in equilibrium, $\hat{\theta} = v_{high} = G^{-1}(G_*) = K^{-1}(K_*)$.

Accordingly, we can express both P and B as a function of $\hat{\theta}$, the target PTS. We note that fair valuation requires that $\hat{\gamma}P\hat{\theta} = B$, from which we can obtain the required equity share:

$$\hat{\gamma} = \frac{3(a+b) - \sqrt{9a^2 + 10ab + b^2}}{4b},$$

which is independent of $\hat{\theta}$. As a result, the manufacturer's problem is equivalent to:

$$\max_{\hat{\theta}} U_E = -\frac{a+b}{ab}\hat{\theta}^2 + D\beta\,(R-\varphi) + \left[D\bar{R} - \left(\frac{2-2\hat{\gamma}}{a} + \frac{2}{b}\right)\hat{\theta}\right]\hat{\theta},$$

subject to $U_E^N \geq 0$. Applying the first-order condition, we obtain the optimal PTS:

$$\hat{\theta} = \frac{DR - D\beta\,(R-\varphi)}{\frac{6-4\hat{\gamma}}{a} + \frac{6}{b}}.$$

We next consider a loan investment.

We note that $B - S - K(\theta) < B + r$. Thus, the new supplier's problem can be written as:

$$\max_{\theta,S} U_L^N = \theta\,[P - K(\theta) - r] + (1-\theta)\,S - G(\theta).$$

It is clear that $\partial U_L^N/\partial S = 1-\theta > 0$, and thus we must have $S = \min\left\{B^G, B - K(\theta)\right\}$ in equilibrium. We apply the first-order condition with respect to θ and obtain:

$$0 = \frac{\partial U_L^N}{\partial \theta} = \begin{cases} P - B - r - 2\theta/a - 2\theta/b, & \text{if } B^G > B - K(\theta); \\ P - B^G - r - 3\theta^2/a - 2\theta/b, & \text{if } B^G \leq B - K(\theta). \end{cases}$$

We denote that:

$$\delta_{high} = \frac{1}{3}\left[\sqrt{\frac{a^2}{b^2} + 3a\,(P - B^G - r)} - \frac{a}{b}\right] \text{ and } \delta_{low} = \frac{P-B-r}{2/a+2/b},$$

as the values of θ that solve the two equations, and define:

$$\hat{\theta}_{low} \equiv \min\left\{\delta_{low}, \bar{\theta}\left(B, B^G\right)\right\} \text{ and } \hat{\theta}_{high} \equiv \min\left\{\delta_{high}, \bar{\theta}\left(B, B^G\right)\right\}.$$

We can easily show that when $B^G \leq B - K\left(\hat{\theta}\right)$, $\hat{\theta}_{high} \geq \hat{\theta}_{low}$. Accordingly, we know that (1) $\hat{\theta} = \hat{\theta}_{high}$ if $B^G < B - K\left(\hat{\theta}_{high}\right)$, (2) $\hat{\theta} = \hat{\theta}_{low}$ if $B^G > B - K\left(\hat{\theta}_{low}\right)$, and (3) $\hat{\theta} = K^{-1}\left(B - B^G\right)$ otherwise.

Next, we look at the manufacturer's problem by substituting $\hat{S}$ and $\hat{\theta}$ in U_L:

$$U_L = -B + \beta\,(R-\varphi)\,D + \left(1-\hat{\theta}\right)\left[B - K\left(\hat{\theta}\right) - B^G\right]^+ + \left[D\bar{R} - P + B + r\right]\hat{\theta}.$$

We check the optimal B^G by considering the following three scenarios that are mutually exclusive and collectively exhaustive: (i) $G^{-1}(G_*) \leq \min\{\delta_{low}, \delta_{high}\}$; (ii) $\delta_{low} < G^{-1}(G_*) \leq \delta_{high}$; and (iii) $G^{-1}(G_*) > \max\{\delta_{low}, \delta_{high}\}$.

In Scenario (i), $\hat{\theta} = \bar{\theta}$. When B^G is in the range between 0 and G_*, we have $\hat{\theta} = G^{-1}(B^G) \leq G^{-1}(G_*) = K^{-1}(K_*)$ and thus $B - K(\hat{\theta}) \geq B - K_* = G_* \geq B^G$. Hence, the first order condition with respect to B^G leads to:

$$\frac{\partial U_L}{\partial B^G} = \frac{b}{2\hat{\theta}}(D\bar{R} - P + r) + \left(1 + \frac{b}{a}\right)\left(\frac{3}{2}\hat{\theta} - 1\right) = 0;$$

We denote the solution of B^G as Θ, in which:

$$\Theta = \frac{1}{b}\left(\frac{1}{3} - \frac{1}{3}\sqrt{1 - \frac{3(D\bar{R} - P + r)}{1/a + 1/b}}\right)^2.$$

When B^G goes beyond G_*, we have $\hat{\theta} = G^{-1}(G_*) = K^{-1}(K_*)$ and $S = B - K(\hat{\theta}) < B^G$, which indicates that $\partial U_L / \partial B^G = 0$. As a result, in Scenario (i), we have the optimal $B^G = \min\{G_*, \Theta\}$ if $3(D\bar{R} - P + r) < 1/a + 1/b$, and $B^G = G_*$ if otherwise. In Scenario (ii), when B^G is in the range between 0 and G_*, we have the same result as in Scenario (i). When B^G goes beyond G_*, we have $\hat{\theta} = K^{-1}(B - B^G)$ or $\hat{\theta} = [P - B - r]/[2/a + 2/b]$, indicating that $\partial U_L / \partial B^G \leq 0$, and thus in Scenario (ii) the optimal B^G is the same as that in Scenario (i). Similarly, in Scenario (iii), we obtain the same result by following a similar logic.

We then check the optimal B and P, after normalizing $\hat{r} = 0$. Note that, given $B^G(B, P, \hat{r}) = \min\{G_*, \Theta\}$ (suppose Θ exists), $\hat{\theta} \leq \bar{\theta} \leq G^{-1}(G_*)$ and thus $B^G \leq B - K(\hat{\theta})$. Accordingly, $\hat{\theta} = \hat{\theta}_{high}$ or $K^{-1}(B - B^G)$. Thus, the manufacturer's problem becomes:

$$\max_{P,B} U_L = \beta(R - \varphi)D - (1 - \hat{\theta})\left[K(\hat{\theta}) + B^G\right] + [D\bar{R} - P + \hat{r}]\hat{\theta}.$$

Now suppose Θ exists and $G_* > \Theta$. Accordingly, $B^G = \Theta < G_* \leq B - K(\hat{\theta}_{high})$ and $\hat{\theta} = \hat{\theta}_{high}$. In this case, B does not matter. In addition, suppose $G^{-1}(\Theta) < \delta_{high}$; it is then easy to verify that U_L is decreasing in P and thus $G^{-1}(\Theta) \geq \delta_{high}$ and $\hat{\theta} = \delta_{high} = G^{-1}(B^G)$ (otherwise $\hat{\theta}$ does not depend on B^G and it is optimal to reduce B^G). This contradicts the result of $B^G(B, P, \hat{r}) = \min\{G_*, \Theta\}$ unless $B^G = G_* = G(\delta_{high})$. As a result, we can express both P and B as a function of $\hat{\theta}$, the target PTS. As a result, the manufacturer's problem is equivalent to:

$$\max_{\hat{\theta}} U_L = \beta (R-\varphi) D - \left(1-\hat{\theta}\right) \left[\frac{\hat{\theta}^2}{a} + \frac{\hat{\theta}^2}{b}\right] + \left[D\bar{R} - \frac{3\hat{\theta}^2}{a} - \frac{\hat{\theta}^2}{b} - \frac{2\hat{\theta}}{b}\right] \hat{\theta},$$

subject to $U_L^N \geq \Pi_0^N$. Applying the first-order condition, we obtain:

$$\hat{\theta} = \frac{1}{6}\sqrt{\left(1+\frac{3a}{b}\right)^2 + 6aD\bar{R}} - \frac{1}{6}\left(1+\frac{3a}{b}\right) = \frac{D\bar{R}}{\sqrt{\left(\frac{1}{a}+\frac{3}{b}\right)^2 + \frac{6D\bar{R}}{a}} + \left(\frac{1}{a}+\frac{3}{b}\right)},$$

and accordingly, we have:

$$\hat{P} - \hat{r} = \left(\frac{3}{a}+\frac{1}{b}\right)\hat{\theta}^2 + \frac{2}{b}\hat{\theta}. \blacksquare$$

References

Bhaskaran SR, Krishnan V (2009) Effort, Revenue, and Cost Sharing Mechanisms for Collaborative New Product Development. *Management Science* 55(7):1152–1169.

Blake M (2017) Intel Cuts Stake in ASML to below 5 Percent. Reuters December 1 2017. https://www.reuters.com/article/us-asml-holding-intel-stake/intel-cuts-stake-in-asml-to-below-5-percent-idUSKBN1DV42G.

Bullis K (2014) Why Apple Failed to Make Sapphire iPhones. *MIT Technology Review* (November 25), https://www.technologyreview.com/s/532636/why-apple-failed-to-make-sapphire-iphones/.

Dilger DE (2013) Apple Signs $578M Sapphire Deal with GT Advanced Technology. *Appleinsider* (November 04), http://appleinsider.com/articles/13/11/04/apple-signs-578m-sapphire-deal-with-gt-advanced-technology/.

King I, Rahn C (2012) Intel Investing $4.1 Billion in ASML to Speed Production. Bloomberg July 17 2012. https://www.bloomberg.com/news/articles/2012-07-09/intel-agrees-to-buy-10-stake-in-asml-for-about-2-1-billion.

Koch R (1998) *The 80/20 Principle: the Secret of Achieving More with Less.* New York: Doubleday.

Roels G (2014) Optimal Design of Coproductive Services: Interaction and Work Allocation. *Manufacturing & Service Operations Management* 16(4):578–594.

Scarf HE (1982) The Computation of Equilibrium Prices: An Exposition. Arrow KJ, Intriligator MD, eds. *Handbook of Mathematical Economics II*: 1007–1061. North-Holland Publishing Co., Amsterdam.

Wakabayashi D (2014) New iPhone: A Sapphire Screen and a Higher Cost. *The Wall Street Journal* (August 14), http://www.wsj.com/articles/new-iphone-a-sapphire-screen-and-a-higher-cost-1408042296/.