STRATEGIC INVESTMENT IN A BUDGET-CONSTRAINED FIRM'S R&D: WHY, WHEN, AND HOW

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ABSTRACT

We model a bilateral monopolistic supply chain in which a supplier's sales are linked with a manufacturer's costly R&D. The manufacturer has a limited budget for R&D. The supplier can influence the manufacturer's R&D spending by setting the wholesale price and/or providing strategic investment in R&D. We find that if the budget is common information to the supplier, the manufacturer's profit can decrease as its budget increases. The manufacturer has great incentives to hide the R&D budget. To overcome this information distortion, we develop a simple and implementable threshold policy based on mechanism design. Moreover, the separating equilibrium can be obtained with fewer structural assumptions about the supplier's prior belief about the budget.

Keywords: Cost Reduction, R&D, Budget Constrained, Asymmetric Information

1. INTRODUCTION

It is commonly perceived that a firm can finance costly R&D through financial intermediaries such as angel investors, venture capital, or banks if the R&D is commercially interesting enough. Nevertheless, the reality is that large as well as small firms have difficulty in financing R&D for various reasons, credit history being one. When a loan is considered, financial institutions examine the borrowers' credit history. Small firms tend to have a weak or insufficient credit history that limits the available loan amount. Despite overcoming the credit history issue, a firm might face a serious concern—asymmetric evaluation of an R&D project by the firm and investors. Himmelberg and Petersen (1994) empirically show that, compared to a large firm, a small firm's R&D is more constrained by its internal cash flow because of the financial investors' lack of expertise or knowledge to evaluate R&D. Moreover, Carpenter and Petersen (2002) advocate that the growth of small firms is constrained by internal financing.

One may think that large or established firms are free from the aforementioned problems and can finance as they desire. A recent anecdote tells us that this is not always true. Nokia's credit rating dropped from A in 2010 to BB+ (junk status) by Fitch in April 2012 (Thomas 2012). One of the major factors considered while evaluating Nokia's credit was current and future sales. Nokia has been losing its market share in the cell phone market, including both cheap feature phone and expensive smartphone markets. Thus, very few banks are willing to lend money to Nokia. A large firm can also have a difficult time financing when its sales and credit rating declines.

An exogenous macroeconomic crisis may be another reason for limited financing. We have seen how major financial intermediaries behaved during the recent financial crisis. Regardless of governments' stimulus policies, banks failed to finance or lend conservatively. Holmstrom and Tirole (1997) study how firms become capital constrained when financial institutions have limited capital.

It is noteworthy that some firms exert efforts to solve partner firms' financial problems in order to prevent the reduction of their own profits. An example of this assistance is when Intel established a $300 million fund in August 2011 to invest in its manufacturing partners' R&D related to the Ultrabook. The Ultrabook is a newly defined laptop by Intel that shares similarities with Apple's MacBook Air. Although several very thin and powerful but pricey notebooks are present in the market, MacBook Air has experienced far better sales owing to its physical characteristics and suitable pricing. In order to sell a similar laptop to Windows users, other notebook OEMs must offer a competitive or better quality product to consumers for a lower price. The quality of a computer is mostly determined by its CPU and operating system, controlled by Intel and Microsoft respectively. As a result, the OEMs can only choose product price as its competitive weapon. However, it is well known that an OEM’s margin is very thin. A vast amount of money is invested in advance for R&D, installation or reconfiguration of a production line, restructuring of supply chain, etc. In order to make a proper investment, adequate margins are needed. Intel decided to expend on the upfront investment instead of providing more margins, that is, it lowered its CPU price for OEMs (Wingfield 2012).

Microsoft and Nokia's deal in March 2011 is another example. In this deal, Microsoft had to invest $1 billion in Nokia to support Nokia's R&D and to promote Nokia's Windows-based cell phone. In return, Nokia was expected to pay royalties to Microsoft whenever a Windows-based phone is sold (Bass 2011). Both examples have a few similarities. The notebook OEMs and Nokia’s R&D were financially assisted, which led to the assisting firms receiving the most benefit. The second similarity is that the OEMs and Nokia, considered downstream firms or manufacturers, were assisted by an upstream firm or a supplier. The third and most interesting similarity was the simple method of support: upfront investment and wholesale price (or royalty).

In this paper, we construct a stylized model to reproduce the above observations and understand when, why, and how an upstream firm would invest in a downstream firm's R&D. We analyze a bilateral monopolistic supply chain in which a supplier's sales are linked with a manufacturer's costly R&D for cost reduction. We assume that the supplier is not financially constrained but the manufacturer is. The supplier can have an influence on the manufacturer's R&D spending by adjusting its price and/or subsidizing R&D.

We explain the reason for engaging in strategic investment by showing why the price-only mechanism is inadequate. When the manufacturer is very capital constrained, the supplier can receive more benefits by strategically investing in the downstream firm's R&D. However, it is quite interesting to see that the manufacturer's profit can actually decrease as its budget increases when the budget is known to the supplier. Therefore, the manufacturer has a great incentive to hide its budget, as it is usually the case. It is more surprising that this incentive becomes larger when the investment is available.

To overcome this information distortion, we investigate the amount that must be invested through a properly designed investment and price contract. We find a threshold of budget in our contract, that is, “when to invest,” under which the supplier should take advantage of strategic investment in addition to the wholesale price. If the budget is above the threshold, the supplier is not required to use the sophisticated mechanism any more. It can not only separate the manufacturer but also achieve the first best case using only the wholesale price.

The contribution of our work is twofold. First, we explain why a supplier would invest in a manufacturer's R&D. Conventional wisdom might state that if the manufacturer does not have enough money for R&D, which is critical for the supplier, the supplier must expend its own money in the R&D. Furthermore, we propose another reason for the strategic investment, which is to eliminate the manufacturer’s information distortion incentives regarding its R&D budget. In addition, we find that suppliers’ support is only effective when the manufacturer is in great financial danger. Second, our study contributes to procurement literature related to asymmetric information. To the best of our knowledge, this article is the first to treat R&D budget as asymmetric information. Moreover, we show that the role of hidden information is different from the conventional adverse selection problems. The resulting equilibrium is different despite the prior belief regarding asymmetric information. This could be considered a special case of adverse selection but cannot be neglected since the budget is kept secret in reality.

2. LITERATURE REVIEW

Our paper is a multidisciplinary work related to operations, marketing, and economics. Cost reduction has been a popular topic in operations literature. Prior research by Porteus (1986), Fine (1986), and Fine and Porteus (1989) examine cost reduction in one firm. As operations in supply chain gains more interest, the focus has shifted to motivating other firms' cost reduction activities or investments indirectly or directly. While a procurement contract is an indirect method, direct methods include a procurement contract as well as supporting complementary or supplementary resources.

Bernstein and Kok (2009) analyze how to induce upstream firms' cost reduction investment through a proper contract from the downstream firm's perspective. They extend Fine and Porteus (1989) under a supply chain setting. Gilbert and Cvsa (2003) consider a similar problem but from the upstream firm's perspective.

Zhu et al. (2007) analyze a supply chain in which the buyer can invest in the supplier's quality improvement effort under full information and deterministic demand. In case of direct support, issues related to asymmetric information naturally arise. Iyer et al. (2005) take into account adverse selection in a supply chain. They assume that a manufacturer is not aware of a supplier's R&D capability and suggest a screening contract to the manufacturer. They also differentiate between screening contracts according to whether they offer complementary or supplementary assistance to suppliers. Kim and Netessine (2012) examine collaborations—which are complementary—for the supplier's cost reduction and design an optimal contract under adverse selection and moral hazard. Instead of developing a new mechanism, Lee and Yang (2012) concentrate on when to invest—which is supplementary—in the supplier's R&D under moral hazard with respect to the market circumstances such as demand uncertainty and time sensitivity in a bilateral monopoly. In their model, the manufacturer can avoid the supplier's moral hazard by not supporting R&D. As a result, the manufacturer has to pay the R&D premium at the procurement stage. Our approach is different because we model forward support (or push) instead of backward support (or pull), and we consider other information as asymmetric and provide different managerial insights as well.

Although some literature on backward support exists, few papers examine forward support for cost reduction. Harhoff (1996) and Gilbert and Cvsa (2003) study what the supplier should do to enhance buyers' demand. Harhoff (1996) presents that the supplier can benefit from knowledge spillover to buyers from its own R&D, since buyers can save R&D investment and still gain benefits from the spillover. Gilbert and Cvsa (2003) focus on the supplier's pricing strategy to induce the downstream firm's R&D. While both papers provide information on indirect mechanisms under complete information, we analyze a model with a direct financial aid. This aid is observed under incomplete information, which is closer to reality.

Extensive marketing literature analyzes demand-enhancing activities or promotions. Blattberg et al. (1995) provide a substantial review of promotions. Cooperative demand enhancing, such as cooperative advertising or side allowances for promotions, can be viewed as forward support in our classification. Kim and Staelin (1999) provide one of the earliest analyses that show why suppliers would provide allowances to retailers while acknowledging that retailers can pocket some of the allowances. They find that identical retailers do not pocket the allowances but transfer them to consumers. Similarly, identical suppliers have to spend money on retailers' marketing activity. Thus, entire suppliers' allowances are used to marketing activities in equilibrium. (See He et al. (2009) and the references therein for the game theoretical extensions of Kim and Staelin (1999)) The key difference between cost reduction and promotions is that asymmetric information can play a critical role in their outcomes. If retailers have private information about promotion capability or budget, suppliers can promote directly by hiring specialized promotion companies; the same cannot be done for cost reduction. Therefore, our paper differs from demand-enhancing literature pertaining to marketing.

Table 1 Demand Enhancing Activities in Supply Chain for Operations and Marketing

Direction	Paper	Monetary Support	Asymmetric Information
Backward (Pull)	Bernstein and Kok (2009)		
	Iyer et al. (2005)	✓	✓
	Zhu et al. (2007)	✓	
	Kim and Netessine (2012)		✓
	Lee (2012)	✓	✓
Forward (Push)	Harhoff (1996)		
	Gilbert and Cvsa (2003)		
	Kim and Staelin (1999)	✓	
	He et al. (2009)	✓	
	Ours	✓	✓

Among research works on asymmetric information, our study is more closely related to adverse selection than moral hazard. Many adverse selection works concerning operations, including Zhang (2010), Zhang et al. (2010), and Taylor and Xiao (2009) and the references therein, regard cost, inventory, and demand as private information. We assume that the manufacturer's budget for R&D is private. We study information that has not been previously studied, and we prove that the role of information is different. For example, according to previous studies, information on cost, inventory, and demand has a direct effect on the objective function, usually in terms of coefficients. The purpose of an optimal mechanism is only to reveal the private information. However, the budget plays a critical role in a constraint that indirectly influences the objective function. Hence, the optimal mechanism in this paper requires an additional incentive condition besides well-known incentive compatibility (IC) and individual rationality (IR).

Recently, research on operations in a capital-constrained firm was conducted. Buzacott and Zhang (2004) and Xu and Birge (2004) study inventory decisions when bank financing is available. While the former focuses on secured loans, the latter considers non-secured loans and costly bankruptcy. Kouvelis and Zhao (2008) extend the literature by incorporating a rich supplier who, in addition to banks, can finance the capital-constrained newsvendor under costly bankruptcy. Meanwhile, Boyabatli and Toktay (2011) model capacity investment and technology choices for a budget-constrained firm. Nonetheless, research on cost reduction R&D investment and procurement in a budget-constrained firm is inadequate. To the best of our knowledge, this paper is the first to investigate how to induce a budget-constrained firm's R&D with asymmetric information. We rely on the nature of R&D financing and exogenous macroeconomic shock to assume a capital-constrained firm, similar to Hall (1992), Himmelberg and Petersen (1994), Holmstrom and Tirole (1997) and Erel et al. (2012).

3. MODEL

Considering a bilateral supply chain with one supplier (S) and one manufacturer (M), S sells its products to M at the wholesale price w. M faces a linear demand such as $p = b - aq$ where a is the price sensitivity of the product, b is an exogenously given intercept, and p and q represent the retail price and the quantity.

Suppose M has an R&D project that can reduce M's processing or manufacturing cost. Let x be the amount of cost reduction from the R&D of which cost is increasing and convex. For ease of exposition, we assume the R&D cost is $-\alpha x^2 / 2$. This quadratic cost assumption is generally used in literature (Gilbert and Cvsa 2003, Lauga and Ofek 2009, and Chayet et al. 2011). Moreover, a general convex increasing function does not change most results. In our model, the R&D project is implemented before the procurement, which can cause a “hold-up” problem. Suppose that M makes an R&D investment decision before the procurement contract is signed. At the contracting stage, M's investment is already sunken and S can take advantage of it to gain more profits. Anticipating this, M becomes reluctant to invest. To solve this issue, S should commit some margin to M ex-ante. See Che and Sokovics (2008) and Gilbert and Cvsa (2003) for more details.

We assume that M may not be able to finance the R&D sufficiently because of its size, credit history, financial crisis, declining sales, asymmetric evaluation of financial investors, etc. This is empirically supported by Hall (1992), Himmelberg and Petersen (1994), Hall (2002) and Erel et al. (2012). As a result, a rich S may be willing to invest in a poor M's R&D like the recent strategic investments of Microsoft and Intel. The budget for R&D may consist of its internal cash and some loans at a different financing cost. We start our analysis assuming that no loan is available to M but disregard this assumption later. It is shown that the availability of loan does not change any managerial implications.

3.1. Why Not Price? w Only Under Complete Information

To determine the role of the budget, we begin with the wholesale price-only contract. Assume that M has only $\alpha B^2/2$ as the R&D budget. For the analytical convenience, we use the maximum attainable cost reduction B instead of the budget. S is the Stackelberg leader who determines w, and M is the follower who determines $x \le B$ and q. We use backward induction. First, we solve M's issue at the ordering stage. For some w and x,

$$\begin{aligned} \max_q \pi_M(q \mid w, x) &= (p - w + x)q \\ &= (b - aq - w + x)q \end{aligned}$$

The first order condition gives us the unique solution.

$$q^*(x, w) = \frac{b + x - w}{2a}$$

At the R&D stage, M's problem is as follows.

$$\begin{aligned} \pi_M(x \mid w) &= -\frac{1}{2}\alpha x^2 + \pi_M(q^*(x, w)) \\ &= -\frac{1}{2}\alpha x^2 + \frac{(b - w + x)^2}{4a} \end{aligned}$$

Let $x_1(w)$ be the solution of the first order condition.

$$x_1(w) = \frac{b - w}{2a\alpha - 1}$$

Proposition 1. If $2a\alpha - 1 > 0$, then $\pi_M^*(x \mid w)$ is concave and $x_1(w)$ is the unique maximizer. However, if M has a limited budget, $\alpha B^2/2$, then M’s optimal investment decision is $x^* = \min(B, x_1(w))$.

The concavity condition implies that the investment cost coefficient is sufficiently high or the demand is sensitive enough to its price. We will assume $2a\alpha - 1 > 0$ henceforth. Knowing Proposition 1, S's profit function can be written as follows:

$$\begin{aligned} &\pi_S(w) = w?q \;\; w \;\; x^* \\ &\text{s.t.} \\ &x^* = \min(B, x_1(w)) \end{aligned}$$

Let us solve this in two different cases according to x^*, namely, $B < x_1(w)$ and $B \geq x_1(w)$. Firstly, assume $B < x_1(w)$. For a given B, S's decision becomes simple.

$$\pi_S(w) = \frac{1}{2a} w(b - w + B)$$

The profit function is concave and the first order condition gives us the unique solution. We denote $w_1 = (b+B)/2$ as the optimal solution. Let us check when $B < x_1(w)$ holds.

$$B < x_1(\frac{b+B}{2})$$
$$\equiv B < \frac{b}{4a\alpha - 1} = B_\theta$$

Proposition 2. If $B < B_\theta = \dfrac{b}{4a\alpha - 1}$ then, $w_1 = \dfrac{b+B}{2}$ and $x^* = B$ are the optimal solutions. The profits are

$$\pi_S^* = \frac{(b+B)^2}{8a}$$
$$\pi_M^* = \frac{1}{16a}(-(8a\alpha - 1)B^2 + 2bB + b^2)$$

While w and π_S^* increases in B, π_M^* increases in $B \in [0, \dfrac{b}{8a\alpha - 1}]$ and then decreases.

We should emphasize that there are regions in which π_M^* decreases. This indicates that M's profit declines as it can afford more R&D in these regions. The intuition is as follows. When B is zero, the game becomes a simple bilateral monopoly and $w = B/2$. When B is small, S knows that M will invest B even at $w = (b+B)/2$, since M's marginal gain from the investment is more than the marginal loss from the increased wholesale price. S becomes better off owing to R&D and the higher price. Thus, both firms' profits increase. As B becomes larger, M's marginal benefit from R&D decreases and becomes less than the marginal loss from the increasing wholesale price at some point, $b/(8a\alpha - 1)$. Although M's profit decreases, M invests its entire budget since S is aware of the budget and takes advantage of this by setting $w = (b+B)/2$. Therefore, M's condition worsens when B is moderate. If the budget is not common, the information distortion incentive, that is, understating its budget, can arise. This is somewhat surprising considering that moral hazard is the major issue when investing money. For instance, if M understates the budget, S will set the price so that M can expend all it reports. M can gain some private benefits by using the left of the budget, which is referred to as moral hazard. Proposition 2 shows that the information asymmetry can be problematic, not because of moral hazard (hidden action) but because of adverse selection (hidden information). If there were moral hazard in M, it would only exacerbate the incentive problem. This issue will be later discussed in this paper.

Secondly, when $B \geq x_1(w)$. If $B > x_1(w)$, the budget constraint disappears. We can obtain the solutions by substituting $x^* = x_1(w)$ into $\pi_S(w)$. Let us denote $B_u = x^*$ as the optimal improvement when M is financially unconstrained, that is, $x^* = B_u, \forall B \geq B_u$. Otherwise, the only remaining case is $B = x_1(w)$, the binding case. Let us define w_2 such that $B = x_1(w_2)$.

Proposition 3. There exists $B_u = \dfrac{b}{4a\alpha - 2}$. If $B_\theta \leq B < B_u$, then $w^* = b - (2a\alpha - 1)B$ and $x^* = B$. While w decreases in B, both π_M^* and π_S^* increase in B. The profits are

$$\pi_S^* = \alpha bB - (2a\alpha - 1)B^2$$
$$\pi_M^* = \frac{1}{2}\alpha(2a\alpha - 1)B^2$$

If $B_u \leq B$, the unconstrained case, $w^* = b/2$ and $x^* = B_u$. The profits are

$$\pi_S^* = \frac{\alpha b^2}{4(2a\alpha - 1)}$$
$$\pi_M^* = \frac{\alpha b^2}{8(2a\alpha - 1)}$$

Corollary 1. w^*, π_S^*, and π_M^* are continuous in B.

Notice that S can induce M to invest its entire budget in two different ways. The first one, Proposition 2, is to set w_1 at which M wants to invest $x_1(w_1) > B$ but cannot help but to invest B. Proposition 3 is to set w_2 at which $x_1(w_2) = B$. The rationale behind this is that S can set either a high or a low price. If S knows that M will expend a fixed amount of money regardless of the wholesale price, then S would set the high price. However, if M's investment depends on S's price, S cannot simply charge a high price. Instead, S determines a price that induces M to invest at a maximum. Due to S's pricing strategy and the decreasing marginal return from investment, M's profit increases, decreases, and then increases again in its budget.

We examine how the R&D budget is related to the profits of both firms through the wholesale price-only contract that generates the information distortion incentive. Many other contracts perform better than the price-only contract. However, we will focus on the upfront payment (strategic investment) and the wholesale price contract, a two-part tariff, among them because it is one of the efficient contracts, and it is also observed from real cases.

3.2. First Best Case: (w, I) Under Complete Information

We consider a contract specified by (w, I) where w represents the wholesale price and I represents the upfront investment from S to M. While M is capital constrained for R&D, S is not since it has a sufficient amount of cash, like Intel and Microsoft. Although the investment can be considered free money because of the zero interest rate, it actually is not since S can gain return on investment through the procurement contract, w.

The sequence of events is similar to the previous example. The only differences are that S determines (w, I) at the outset, and M's investment decision is constrained by the increased budget, the original budget plus I.

It is convenient to define x_S as the improvement level desired by S. x_S and I are interchangeable since $I = \alpha(x_S^2 - B^2)/2$, which implies that S will invest only the difference between M's budget and S's target. S should solve the following problem with respect to w and x_S.

$$\begin{aligned}\max_{w,x_S} \pi_S(w, x_S) &= wq(w, x^*) - I \\ &= \frac{1}{2a}(b - w + x^*) - \frac{1}{2}\alpha(x_S^2 - B^2) \\ s.t.& \\ x^* &= \min(x_S, x_1(w))\end{aligned}$$

The constraint changes from $\min(B, x_1(w))$ to $\min(x_S, x_1(w))$ since S only considers investing when its desired level is greater than M’s. As we showed previously, it is better for S to make M utilize the amount M can spend. Hence, S’s problem becomes

$$\max_{w,x_S} \pi_S(w, x_S) = \frac{1}{2a}w(b - w + x_S) - \frac{1}{2}\alpha(x_S^2 - B^2)$$

Proposition 4. Let us denote $B^{FB} = \dfrac{b}{4a\alpha - 1}$. Under the complete information assumption, the optimal contract is

$$(w^{FB}, x_S^{FB}) = \begin{cases} \left(\dfrac{2a\alpha b}{4a\alpha - 1}, B^{FB}\right) & \text{if } B \le B^{FB} \\ (b - (2a\alpha - 1)B, B) & \text{if } B^{FB} < B \le B_u \end{cases}$$

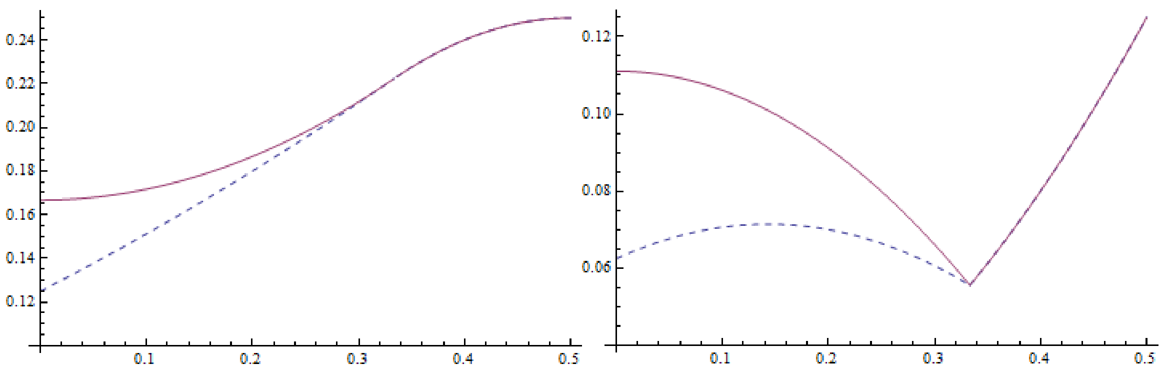
The profits are

$$\pi_S^{FB} = \begin{cases} \dfrac{\alpha b^2}{2(4a\alpha - 1)} + \dfrac{B^2}{2} & \text{if } B \le B^{FB} \\ \alpha b B - \alpha(2a\alpha - 1)B^2 & \text{if } B^{FB} < B \le B_u \end{cases}$$

$$\pi_M^{FB} = \begin{cases} \dfrac{a\alpha^2 b^2}{(4a\alpha-1)^2} - \dfrac{\alpha B^2}{2} & \text{if } B \le B^{FB} \\ \dfrac{1}{2}\alpha(2a\alpha-1)B^2 & \text{if } B^{FB} < B \le B_u \end{cases}$$

It is straightforward to see π_S^{FB} is increasing in $B \in [0, B_u]$. However, π_M^{FB} is monotonically and concavely decreasing in $B \le B^{FB}$ and convexly increasing afterward in $B \in (B^{FB}, B_u]$. We should note that if $B^{FB} < B$ then S does not need to consider any financial support since M can invest more than S. As a result, (w, x_S) is reduced to w only. If $B < B^{FB}$, then S uses (w, x_S), and both firms' profits are improved from those with w only. Figure 1 depicts the results well. A dashed line represents w only and a thick line represents (w, x_S).

Figure 1. Profits of S and M under Complete Information with w only and (w, x_S)



(a) $\pi_S^{FB}(w, x_S)$ and $\pi_S^{FB}(w)$ (b) $\pi_M^{FB}(w, x_S)$ and $\pi_M^{FB}(w)$

As we can see from the figures, the incentive for information distortion is larger when using (w, x_S) than using w only. In w only, M may want to understate its budget at a positive level instead of zero. In (w, x_S), M may report zero if it wants. We should note that this is entailed by S's financial support, x_S or I. Although S's financial support can increase S's own profit, unless used properly, the support aggravates the asymmetric information incentive.

4. ASYMMETRIC INFORMATION ABOUT THE BUDGET

According to the revelation principle by Myerson (1979), there is an optimal mechanism where the asymmetric information is truthfully reported in the exchange of information rent.

4.1. Second Best Case: (w, x_S) under hidden information

We assume that M's budget is only known to M. M can either understate or overstate its budget, but the investment is assumed to be observed. Therefore, M would not overstate. We can construct a truth-revealing optimal mechanism (w, x_S), which satisfies incentive compatibility (IC) and individual rationality (IR) according to the revelation principle by Myerson.

The decision sequence is the same as the first best case. S proposes a menu of contracts, $(w(\cdot), x_S(?))$, based on a prior belief c.d.f. $F(\cdot)$ and p.d.f. $f(\cdot)$ about M's budget whose support is $[0, B_u]$. We do not place any restrictions on F, unlike previous adverse selection papers (Iyer et al. 2005, Taylor and Xiao 2009 and Zhang 2010).

M reveals its true budget, B, by choosing a specific contract term, $(w(B), x_S(B))$. Then, S invests $\alpha(x_S(B)^2 - B^2)/2$ and M expends $\alpha x(B)^2/2$ and achieves x of cost reduction (or margin improvement) where $x \le x_S(B)$. M procures from S, and profits are realized.

We can conjecture that, similar to the first best case, the optimal mechanism consists of two parts. Let B_2 be a budget under which (w, x_S) is used and over which only w is used. Then, S's problem is formulated as follows:

$$
\begin{aligned}
\max_{w,x_S} E[\pi_S(w, x_S \mid B)] &= E[w(B)q - I(B)] \\
&= \int_0^{B_2} \left(\frac{1}{2a} w(B)(b - w + x^*) - \frac{1}{2}\alpha(x_S(B)^2 - B^2) \right) f(B)\,dB \\
&+ \int_{B_2}^{B_u} (\alpha b B - (2a\alpha - 1)B^2) f(B)\,dB \\
s.t.& \\
&(x^*, B) = \arg\max_{x \le x_S, \hat{B} \le B} \pi_M(x, \hat{B} \mid B) \\
&\max_{x \le x_S, \hat{B} \le B} \pi_M(x, \hat{B} \mid B) \ge 0
\end{aligned}
$$

, where $\pi_M(x, \hat{B} \mid B)$ is the M's profit when M reports $\hat{B}$ instead of B as its budget, and x is set as the R&D level.

It is worthwhile to discuss the structure of the problem since our model is different from a conventional adverse selection problem. First, the agent's type (θ) is directly related to its utility in general. $u(q, \theta) = q\theta$ is an example where q is the agent's decision. As the type (θ) changes, the utility changes although the decision is the same. However, in our model, an agent's type (Budget, B) is indirectly related with its utility (profit) because it plays a critical role in a constraint rather than in utility. Consequently, as the type (B) changes, the agent's utility (M's profit) will not change as long as the agent's decision is not affected, that is, the budget constraint is not binding. Second, the type (θ) is endogenous because the principal can influence by strategic investment. This is possible because we assume fully substitutable resources to be supported. Third, the agent is tempted to either overstate or understate in conventional problems. In our model, M can increase its profit with an intermediate budget by both understating and overstating the budget. So M is tempted by both incentives and countervailing incentives (Lewis and Sappington 1989), although overstating cannot be executed because the investment is observed.

Before analyzing an optimal mechanism, we can consider what will happen under a truth-revealing optimal mechanism. First, B is truthfully revealed. Second, $\pi_M(x_S(B), B \mid B)$ must be non-decreasing to eliminate the information distortion incentive. Therefore, under such an optimal mechanism, M reports its original type (B) and expends as much as it can ($\alpha x_S(B)^2/2$), as desired by S.

$$\pi_M^*(B) = \pi_M(B \mid B, w(B), x_S(B)) \qquad \text{Report } B$$

$$= -\frac{1}{2}\alpha B^2 + \frac{1}{4a}(b - w(B) + x_S(B))^2$$

$$\frac{\partial \pi_M^*(B)}{\partial B} = -\alpha B + \frac{1}{2a}(b - w(B) + x(B))(-w'(B) + x'(B)) \geq 0 \qquad (IC)$$

4.2. Analysis

Assume that there exists B_2 such that $B_2 \in [0, B_u]$. If there is an optimal policy where $B < B_2$, then the strategic investment with the wholesale price, (w, x_S), is used. If $B \geq B_2$, then w contract is selected. Let π_S^s and π_S^w be the S's profit when (w, x_S) and w only are used respectively.

M's profits under (w, x_S) and w only must be equal at B_2 since π_M^* should be continuous at B_2. Moreover, it is best for S to make $\pi_M^* = K, \forall B < B_2$.

$$K = -\frac{1}{2}\alpha B^2 + \frac{1}{4a}(b - w(B) + x_S(B))^2$$

$$w(B) = b + x_S(B) - 2\sqrt{aK + \frac{1}{2}a\alpha B^2} \qquad (1)$$

When S invests in M, S maximizes its profit under (1).

$$\pi_S^s(w(B), x(B)) = \frac{1}{2a}w(b - w(B) + x_S(B)) - \frac{1}{2}\alpha(x_S(B)^2 - B^2)$$

$$= \frac{1}{a}w(B)\sqrt{aK + \frac{1}{2}a\alpha B^2} - \frac{1}{2}\alpha(x_S(B)^2 - B^2)$$

Since $dw/dx = 1$ from (1), the first order condition, $d\pi_S(w(B), x(B))/dx$, gives us the following.

$$x_S^*(K \mid B) = \frac{1}{\alpha\sqrt{a}}\sqrt{K + \frac{1}{2}\alpha B^2} \qquad (2)$$

Substituting (2) into (1), we can obtain $w^*(K \mid B)$. Then $\pi_S^{s*}(K,B) = \pi_S^{s*}(w^*(K \mid B), x_S^*(K \mid B))$. M's profit under the price-only contract is equal to K at B_2. According to Proposition 4,

$$K = \pi_M^{FB} = \frac{1}{2}\alpha(2a\alpha - 1)B_2^2$$
$$B_2(K) = \sqrt{\frac{2K}{\alpha(2a\alpha - 1)}}$$

Now, S needs to optimally determine K.

$$\max_K E[\pi(K)] = \int_0^{B_2(K)} \pi_S^{s*}(K,B) f(B)\, dB + \int_{B_2(K)}^{B_u} \pi_S^{w*}(B) f(B)\, dB$$
$$\begin{aligned} \frac{dE[\pi(K)]}{dK} &= B_2'(K)\pi_S^{s*}(K, B_2(K)) + \int_0^{B_2(K)} \frac{\partial \pi_S^{s*}(K,B)}{\partial K} f(B)\, dB - B_2'(K)\pi_S^{w*}(B_2) \\ &= \int_0^{B_2(K)} \frac{\partial \pi_S^{s*}(K,B)}{\partial K} f(B)\, dB \\ &= 0 \end{aligned}$$

The second step in the first order condition is due to the fact that M's profits become equal at B_2 when it receives investments and when it does not.

Proposition 5. If B is unknown to S and is believed to be in $[0, B_u]$, S proposes the following optimal contract to M:

$$(w, x_S) = \begin{cases} (w^*(B), x_S^*(B)) & if\ B < B_2^* \\ (b - (2a\alpha - 1)B, 0) & if\ B_2^* \le B \end{cases}$$

, where $K^*, B_2^*, w^*(B)$ and $x_S^*(B)$ can be obtained by solving the following, respectively.

$$0 = \int_0^{B_2(K^*)} \frac{\partial \pi_S^{s*}(K^*,B)}{\partial K} f(B)\, dB$$
$$B_2^* = \sqrt{\frac{2K^*}{\alpha(2a\alpha - 1)}}$$
$$x_S^*(B) = \frac{1}{\alpha\sqrt{a}}\sqrt{K^* + \frac{1}{2}\alpha B^2}$$
$$w^*(B) = b + x_S^*(B) - 2\sqrt{aK^* + \frac{1}{2}a\alpha B^2}$$

Proof. Remember that we conjecture that $B_2 \in [0, B_u]$. Let us prove that the conjecture is true in equilibrium. $B_2 \geq 0$ if and only if $K^* \geq 0$. $B_2 \leq B_u$ if and only if $K^* \leq \frac{\alpha b^2}{8(2a\alpha - 1)} = \pi_M^{FB}(B_u)$.
Thus, we need to show that $K^* \in [0, \pi_M^{FB}]$. Let us first check the existence of K^*. Note that

$$\frac{\partial \pi_S^{s*}(K^*, B)}{\partial K} = \frac{1 - 4a\alpha}{2a\alpha} + \frac{b}{\sqrt{2a(2K + \alpha B^2)}} \tag{3}$$

$$\frac{\partial^2 \pi_S^{s*}(K^*, B)}{\partial K \partial B} < 0 \tag{4}$$

For K^* to exist, $\partial \pi_S^{s*}(K^*, 0) / \partial K > 0$ and $\partial \pi_S^{s*}(K^*, B_2(K^*)) / \partial K < 0$ since (4) implies (3) decreases. After performing some algebra, we can obtain the following inequalities:

$$0 < \frac{\alpha b^2 (2a\alpha - 1)}{2(4a\alpha - 1)^2} < K^* < \frac{a\alpha^2 b^2}{(4a\alpha - 1)^2} < \pi_M^{FB}(B_u)$$

□

Corollary 2. While $x^*(B)$ increases in B, $w^*(B)$ decreases in B.

Proposition 5 means that S strategically invests only when $B < B_2^*$, similar to the complete information case. Otherwise, S can achieve the first best profits by proposing the price-only contract in Proposition 4. Loosely speaking, when M is wealthy enough, private information will not provide any incentives. M is indifferent concerning sharing information credibly or hiding the information. From Corollary 2, there is the separating equilibrium in the second best case that contrasts to the pooling and separating equilibrium in the first best case. M's profit decreases in the pooling aspect of equilibrium in the first best case. This creates the information distortion incentives. The second best approach is to mitigate these incentives, which separates M with respect to its budget to make M's profit become non-decreasing. The corollary is somewhat intuitive because S proposes better conditions as M can afford more R&D.

It is necessary to mention that there are no assumptions on the prior belief distribution, $F(\cdot)$, and a separating equilibrium can still be obtained. This is because the private information in our model is reported before the agent's objective function is completely determined, which is not the case in conventional problems. Suppose that the utility of the agent of type θ misrepresenting his type as $\hat{\theta}$ is $u(q, \hat{\theta} \mid \theta) = q(\hat{\theta})\theta - t(\hat{\theta})$. The incentive compatibility conditions are

$$u(q, \hat{\theta} \mid \theta) \leq u^*(q, \theta)$$
$$u(q, \theta \mid \hat{\theta}) \leq u^*(q, \hat{\theta})$$

From the above conditions,

$$q(\hat{\theta})(\theta - \hat{\theta}) \leq u^*(q, \theta) - u^*(q, \hat{\theta}) \leq q(\theta)(\theta - \hat{\theta})$$

Dividing it by $\theta-\hat{\theta}$ and taking limit,

$$u^*(q,\theta_1)=u(\theta_0)+\int_{\theta_0}^{\bar{\theta}} q(\theta)\, f(\theta)\, d\theta$$

In our model, however, once M reports its budget then the margin is set. The profit function is determined by whether or not the budget is truly reported, that is, $u(q,\hat{\theta}\,|\,\theta)=u(q,\hat{\theta}\,|\,\hat{\theta})$. Therefore, we cannot use the above procedures, and the prior belief does not have a significant role in our model.

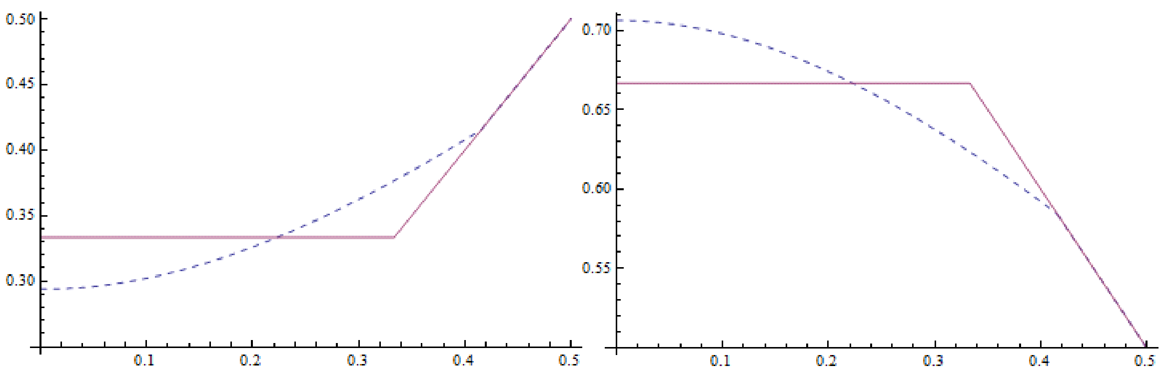
4.3. Example

For a special case when $a=1, \alpha=1$ and $b=1$ and uniformly distributed $f(\cdot)$, we can obtain the following closed form solutions.

$$K^*=\frac{1}{36}(\log(3-2\sqrt{2}))^2$$
$$x^*(B)=\frac{1}{6}\sqrt{18B^2+(\log(3-2\sqrt{2}))^2}$$
$$w^*(B)=1-\frac{1}{6}\sqrt{18B^2+(\log(3-2\sqrt{2}))^2}$$

Figure 2 and Figure 3 illustrate the exemplary results. A dashed line represents asymmetric information, and a regular line, symmetric information.

Figure 2. w and x Comparison under Symmetric and Asymmetric Information

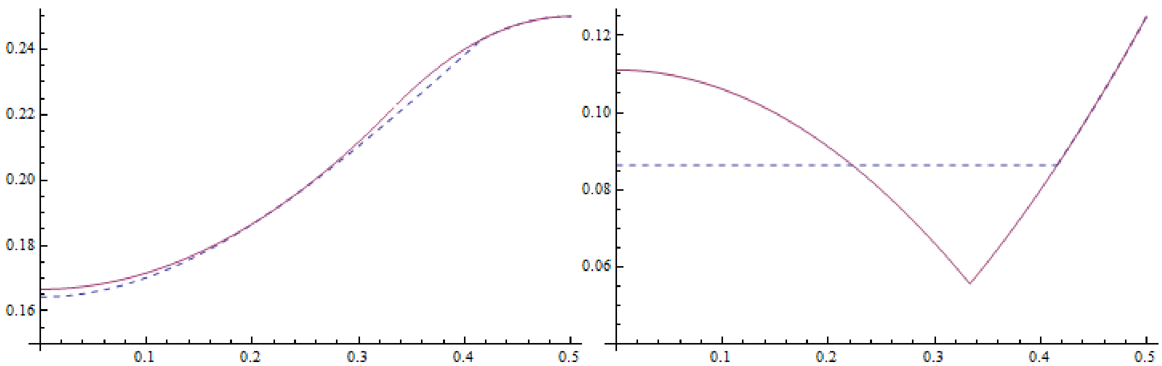


(a) w (b) x_S

If the budget is common information, S implements a pooling contract when it invests, but proposes a separating contract when it does not. When the budget becomes hidden information, S suggests a separating contract regardless of the investment decision. We can split Figure 2 and Figure 3 into three regions with the same standard. The first region is where the dashed line in Figure 2 (a) is above the regular line. S proposes the dashed line to prevent M from understating its budget by penalizing M with a higher price and less investments. The second region is where the dashed line is below the regular line. S offers a lower price and more investments to reward

M's stronger financial status. The third region is where the two lines coincide. Since M has more capital to spend than S would invest, S needs not consider the strategic investment. Instead, S utilizes the price-only contract and can achieve the first best case outcome under asymmetric information. As a result, Figure 3 depicts $\pi_M^{FB} > \pi_M^{SB}$ in the first region, $\pi_M^{FB} < \pi_M^{SB}$ in the second, and $\pi_M^{FB} = \pi_M^{SB}$ in the last.

Figure 3. Profit Comparisons of S and M under Symmetric and Asymmetric Information



(a) $\pi_S^{FB}(w, x_S)$ and $\pi_S^{SB}(w, x_S)$ (b) $\pi_M^{FB}(w, x_s)$ and $\pi_M^{SB}(w, x_S)$

5. EXTENSIONS

To provide the sharpest focus on the limited budget, the preceding analysis excluded external financing and assumed the quadratic investment function. We make these two assumptions to understand how critical they are.

5.1. When External Financing Is Available

Suppose that M has access to external financing (‘Bank’ for short). Assume that M has $\alpha C_I^2 / 2$ of internal cash and finances only when the desired investment is more than its internal cash due to the financing cost $r > 0$. M's investment decision is as follows:

$$\pi_M(x \mid w) = -\frac{1}{2}\alpha x^2 + \frac{1}{4a}(b - w + x)^2$$

$$s.t.$$

$$\frac{1}{2}\alpha x^2 \le \frac{1}{2}\alpha(C_I^2 + (1+r)C_B^2)$$

, where $\alpha C_B^2 / 2$ the amount M borrows from the bank. Let us first consider an unlimited credit line case. The budget constraint simply disappears, but the investment cost becomes expensive because $r > 0$. As long as M can finance optimal amount, S's decision is not affected in Section 3, $w = b/2$.

Suppose that M has a limited credit line that is independent of S's involvement. One may argue that S's involvement, such as in the MS-Nokia deal (Bass 2011), could affect M's credit line (Nokia's credit line or rating). However, a firm's credit line is determined by various factors, and such news may not be the major determinant, as witnessed in Thomas (2012). Assume $\alpha C_B^2 / 2$ is the maximum amount that M can borrow at the interest rate r. The right hand side of the constraint becomes a maximum investment that M can make, that is, the investment budget.

$$\frac{1}{2}\alpha B^2 \equiv \frac{1}{2}\alpha(C_I^2 + (1+r)C_B^2)$$

Thus, whether M can access to external financing alters neither the analysis nor the managerial insights.

5.2. General Investment Function

It is decreasing and then increasing profit function of M in R&D budget known to S that creates incentives to reveal false information. We show in this section that the same characteristics are preserved with a general convex investment function.

Assume the budget is common information. Let $c(x)$ be a general R&D convex cost function for x amount of cost reduction. Since the R&D spending by M is assumed to be verifiable, S only needs to consider M’s order quantity corresponding to the wholesale price and any strategic investments. Both firms’ profit functions are as follows:

$$\pi_S(w, x_S) = wq(w, x_S) - (c(x_S) - c(B)) \qquad (5)$$
$$\pi_M(q \mid w, x_s) = -c(x_S) + (p - w + x_S)q + (c(x_S) - c(B)) \qquad (6)$$

Since $p = b - wa$, $q^*(w, x) = (b - w + x_S)/2a$. For (5) to be joint concave, $2c''(x) > 1$ which implies that $c(x)$ is convexly increasing fast enough. Assume the cost reduction technology is so expensive. The following first order conditions characterize w^* and x_S^* which are independent of M’s budget.

$$\frac{\partial \pi_S}{\partial w} = b + x_S - 2w = 0 \qquad (7)$$
$$\frac{\partial \pi_S}{\partial x_S} = \frac{b + x_S}{4a} - c'(x_S) = 0 \qquad (8)$$

If $B \le x_S^*$, S invests $c(x_S^*) - c(B)$ to M so that M can expend $c(x_S)$ in R&D. M’s profit is written as follows:

$$\pi_M^*(B) = -c(B) + \frac{1}{4a}(b - w + x_S^*)^2$$

where the second term is constant in B. M’s profit concavely decreases in $B \le x_S^*$.

If $B > x_S^*$, then M has more budget than S would like to invest. S only needs to set w considering M's investment and ordering decisions.

$$\pi_M(q, x \mid w) = -c(x) + (p - w + x)q \tag{9}$$

$$\pi'_M(x) = -c'(x) + \frac{1}{2a}(b - w + x) \tag{10}$$

$$\pi''_M(x) = -c''(x) + \frac{1}{2a} \tag{11}$$

Assume (11)<0. (9) is concave and (10) provides the optimal x for some w when M does not have the budget constraint. Let $x_1(w)$ be the solution of (10). The optimal decision with the budget constraint is $x^* = \min(x_1(w), B)$. Notice that S does not set w such that $x_1(w) > B$ if $B > x_S^*$. To encourage investments in R&D, S should give more margins to M, that is, a low w. However, if $x_1(w) > B$, M cannot invest $x_1(w)$ owing to the budget constraint. In addition, S may not be able to induce M to invest infinite amount of money. There may exist x_U at which the unconstrained M is maximized. Therefore, S sets $w(B) = b + B - 2ac'(B)$ such that $x_1(w) = B$ if $x_S^* < B \le x_U$. The resulting M's profit increases in $x_S^* < B \le x_U$.

$$\pi_M^*(B) = -c(B) + ac'(B)^2$$
$$\pi_M^*(B)' = c'(B)(-1 + 2ac''(B)) > 0$$

We complete the analysis by characterizing x_U. We can obtain x_U by solving (6) and (5) sequentially without any constraints. Since x is a function of w, S's optimal decision is a solution of the following first order condition:

$$\frac{\partial \pi_S(w)}{\partial w} = \frac{1}{2a}(b + x + (-2 + x'(w))w)$$
$$w^* = \frac{b + x(w)}{2 - x'(w)}$$

Since $x(w)$ satisfies (10), we can obtain x_U by substituting w^* into (10).

$$x_U = \frac{c'(x_U)(4ac''(x_U) - 1)}{c''(x_U)} - b$$

And the resulting $w_U = w^*(x_U)$ is

$$w_U = \frac{c'(x_U)}{c''(x_U)}(2ac''(x_U) - 1)$$

We verify that M's profit function decreases and then increases in B.

6. DISCUSSION

Regardless of the size of the firms, they can face a constrained budget for some costly R&D because of the asymmetric evaluation of financial intermediaries, exogenous economic crisis, declining sales and credit ratings, etc. It is observed that supply chain partners such as Intel and Microsoft actively invest in downstream firms' R&D to resolve this, and this is one of the motivations for our study.

We construct a bilateral monopolistic supply chain where the manufacturer (M) is financially constrained for cost reduction R&D and the supplier (S) is not. The R&D is beneficial to not only M but also S since the more M invests in R&D, the more M increases its margin. M also orders more from S. First, we show that S's strategic investment when M has a financial disadvantage can improve both firms' profits. The issue is that it also creates great incentives for the manufacturer to distort the financial status. This is because S's optimal policy when the budget is known is to pool M, if investment is necessary. The policy also induces M to invest the entire budget, the sum of M's initial budget and S's investment. M worsens as the budget increases, since the margin is the same whereas the budget is spent. Thus, M has incentives to lie. This explains why the budget is often treated as top secret and emphasizes the need to research a carefully designed contract. To the best of our knowledge, this paper is the first to treat the budget as hidden information in the supply chain. Moreover, we find that the role of hidden information is very different from other information. The objective function of the agent is determined once the information is reported, which tends to be set before reporting in general. As a result, the prior belief distribution of the principal (S) does not play a significant role in our model. We still can draw the separating equilibrium that contrasts to the symmetric information case as well as the previous literature. The optimal policy in asymmetric information suggests that investment is necessary only when M is severely constrained, which resembles the first best case. The two policies differ because the former separates M and advises that a strategic investment is needed for a less constrained M to mitigate information asymmetry.

This paper is not only descriptive but also prescriptive about strategic investment in a supply chain partner's R&D. Although it is intuitive that a supplier is willing to invest in the manufacturer's R&D when it is deficient in R&D, the time to invest and the amount to invest are ambiguous if the R&D budget is hidden. We provide analytical solutions to each so that the suppliers can be free from the manufacturer's adverse selection.

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