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Abstract

Firms manufacturing highly innovative and complex products often rely on the expertise of their suppliers who provide critical components that enable core functionality of the products. During the product development stage there is often considerable uncertainty about component production cost, and it is of interest to both the manufacturer and the supplier to engage in a collaborative effort to reduce the expected unit cost as well as uncertainty around it. Despite the obvious benefits of cost reduction, however, the supplier may be reluctant to collaborate, as he wishes to guard against revealing his proprietary cost information. Building on the traditional frameworks of the newsvendor model and adverse selection, we investigate how information asymmetry and the structure of procurement contracts interact to influence the supply chain parties' incentives to collaborate. We consider a number of contracts based on price and quantity, and identify a simple contract, Expected Margin Commitment (EMC), that effectively promotes collaboration. The manufacturer prefers EMC if (a) collaboration leads to a large reduction in unit cost and/or (b) demand variability is low. Otherwise, a screening contract is preferred. We also find that, paradoxically, ex-post efforts to enhance supply chain efficiency may hinder ex-ante collaboration that precedes production.

1 Introduction

Many manufacturing firms rely on the expertise and the resources provided by their suppliers when they develop new products or upgrade existing products, and how well they manage these relationships critically impacts the product's success. For instance, it has been documented that the subcontracting structure of Japanese automobile manufacturers—in which suppliers actively participate in every development and production process—has been one of the key differentiators that enable their competitive advantage over U.S. manufacturers (McMillan 1990). With increasing sophistication and complexity of the products that accompany technology breakthroughs, the manufacturers and the suppliers need to collaborate more than ever in order to survive in the marketplace.

Examples of supply chain collaboration may be found in every stage of the product life cycle, ranging from such activities as co-branding initiatives to long-term strategic alliances (Rudzki 2004). However, given that approximately 80% of a product's cost is determined during product development (Blanchard 1978), it is no surprise that major collaborative efforts are made in an early product development stage. In particular, as a recent survey by Aberdeen Group (2006) reveals, firms identify cost reduction achieved during product development as one of the primary reasons for engaging in collaborative relationships. This view is supported by the following quote by an operations director from Copeland Corporation, an Ohio-based manufacturer of AC/heating equipment (Kinni 1996, p. 105):

> The only way we could reach the current state of manufacturing efficiency is through sharing and understanding both companies' processes... [Copeland's component supplier] Osco is a member of the New Product Team and is intimately involved in all aspects of the casting design and machining process. The best way to achieve the lowest-cost raw material and finished component is to leverage the design process by utilizing the supplier's expertise and achieving the lowest true cost for the component.

While firms strive to attain the highest level of efficiency through collaboration, it can be an elusive goal. Forming a successful collaborative relationship usually rests on two key factors: the inter-firm information structure and product characteristics. The former is crucial since it influences the firms' willingness to establish and sustain the relationship. Benefits of collaboration notwithstanding, the reality that each firm's ultimate goal is maximizing its own profitability. Firms are inherently opportunistic, implying that they are averse to sharing proprietary information (such as the cost structure) and will take advantage of the other's if they are presented with it. As an executive from an auto parts supplier put it, "if one doesn't say anything, all the savings are ours" (Anderson and Jap 2005). From these reports and other evidence, it is clear that information asymmetry exists even in collaborative relationships, and in fact, it plays a crucial role in shaping the firms' incentives to collaborate.

In addition, product characteristics such as the strategic importance of a procured component, modularity of component architecture, and uncertainty in production cost, quality, and delivery lead time also play big roles in determining successful outcome of collaboration (Pyke and Johnson 2003). In this paper we focus on the impact of uncertainty, both of demand and of the cost of producing a strategically important component. Unpredictable consumer demand is an especially important concern for the firms manufacturing innovative products with short life cycles, such as smartphones, whose fast pace of feature evolutions and shifting consumer tastes create a high level of inventory risks due to forecasting limitations and high rates of obsolescence. Uncertainty in the component cost arises as the supplier faces a multitude of production options early in the product development phase. For instance, the supplier may consider adopting untested technology in order to fulfill the manufacturer's requirement for the end product's functionality. In fact, reduction of uncertainty that accompanies new technology adoption is cited as one of the main reasons that firms collaborate (Handfield et al. 1999, Ragatz et al. 2002). Therefore, while innovations in product design and in production processes are necessary, they present a cost risk to the supplier and ultimately to the manufacturer, who bears a portion of the same risk when financial transactions are made.

The factors we have mentioned—uncertainties in demand and cost, information asymmetry, and incentives to collaborate—are all intricately related. As the supplier's initial uncertainty about the component cost stems in large part from imprecise product design requirements,[1] it is likely to be reduced by forging a close working relationship with the manufacturer during product development,

[1] During the product development stage, suppliers usually receive only rough estimates of design specification parameters from the OEMs (Nellore et al. 1999).

which would help understand each other's expectations and limitations better. As the product specification ambiguities clear up, the supplier is able to select technologies suitable for production. Additionally, such an increase in predictability is typically accompanied by reduction of expected unit cost, as evidenced by many studies including Handfield et al. (1999), who report in their survey of 49 manufacturers that collaboration reduced production costs by up to 30%.

However, despite the obvious benefits that collaborative cost reduction brings, it may not always be a good proposition for the supplier. As collaboration typically involves mutual information exchanges, the supplier unavoidably reveals some of his cost structure to the manufacturer (see Womack et al. 1991, p. 149). For example, the supplier may have to inform the manufacturer that he will use a particular material to build a component, but the price of the material may be known publicly. Hence, the supplier faces a dilemma: despite the benefits, is it worth participating in the collaborative effort and risk exposing a better estimate of his cost to the manufacturer? How does the choice of a procurement contract impact the supplier's and the manufacturer's incentives to collaborate? How do uncertainties in demand and cost impact collaboration decisions? These are the questions that we aim to answer.

In this paper we develop a stylized game-theoretic model that formalizes the process by which the manufacturer's and the supplier's voluntary contributions to collaborative efforts lead to cost reduction. Using this model, we find that both firms' incentives to collaborate critically depend on the procurement contracting strategy that the manufacturer employs. In addition, we identify demand variability as one of the important environmental factors that influence a successful outcome of collaboration. Specifically, we obtain the following insights from our analysis.

- Although the adverse selection literature points to the screening contract as the most efficient mechanism to deal with information asymmetry, in the setting that we consider, it may not be the optimal procurement contract to use since it hinders the supplier's ex-ante incentive to collaborate, thereby creating and aggravating a hold-up problem.

- Price commitment, which is frequently mentioned in the literature as an effective means to alleviate the negative consequences of the hold-up problem, does not promote collaboration in our setting. Instead, we show that committing to a fixed margin over the expected cost, which we call Expected Margin Commitment (EMC), is a better instrument in achieving the same goal.

- Demand variability is a key factor that determines which contracting strategy should be employed by the manufacturer. The manufacturer prefers EMC to the screening contract when (a) collaboration can potentially lead to a large reduction in the unit cost and/or (b) demand variability is low.

- Paradoxically, ex-post supply chain efficiency improvement—achieved through more accurate demand forecasting or lead time reduction—is in conflict with ex-ante collaboration; when efficiency improvement is so large that the supply chain turns into a make-to-order production system, neither party exerts collaborative efforts.

The rest of the paper is organized as follows. After a literature review in Section 2, in Section 3 we lay out the assumptions of the model and introduce notations used throughout the paper. Next, in Section 4, we present the analysis of the benchmark case in which the supply chain is assumed to be integrated. In the following two sections (Sections 5 and 6), we study how collaboration incentives are impacted by the procurement contracting strategies. Section 8 considers two extensions of the model. Finally, Section 9 summarizes the results and the insights.

2 Literature Review

The topic of supply chain collaboration has received much attention in the business press, but surprisingly few works exist in the academic literature, especially in the operations management (OM) area. Notable exceptions are the papers that investigate the benefits of Collaborative Planning, Forecasting and Replenishment (CPFR), including Aviv (2001, 2007). CPFR is mainly concerned with promoting information sharing and joint process improvement during production and fulfillment stages. While there are overlaps, our paper differs from the CPFR literature in that we study collaboration that occurs during the product development stage that precedes production. As indicated in many reports (e.g., Aberdeen Group 2006), such an early-stage collaboration is commonplace in many industries. In this paper we specifically focus on collaborative cost reduction, motivated by widespread practice of such initiatives (for example, Stallkamp 2005 details the supplier cost reduction program called SCORE at Chrysler). Roels et al. (2010) is one of the few OM papers that study the topic of collaboration, but their model is developed in the context of service provisioning, whereas ours applies to product development and manufacturing environments. Özer et al. (2010) conduct laboratory experiments to validate their hypotheses on "trust" in forecast information sharing, in part motivated by CPFR. Interestingly, they conclude that a continuum exists between absolute trust and no trust, just as we assume in our model regarding the collaboration level.

As we analyze the dynamics that occur during product development, this paper is related to the new product development (NPD) literature. For surveys of the literature, see Krishnan and Ulrich (2001) and Krishnan and Loch (2005). In this literature, however, the topic of inter-firm collaboration has not received much attention. The only exception, to the best of our knowledge, is Bhaskaran and Krishnan (2009), whose broad theme is similar to ours but they investigate a set of research questions quite different from ours. While they acknowledge that agency issues caused by opportunistic behaviors of the collaboration partners is a real challenge, they sidestep this discussion. In contrast, information asymmetry plays a central role in our paper. Moreover, one of the unique features of this paper is the interaction between collaborative cost reduction decisions and procurement contracting, the topic that is unaddressed in Bhaskaran and Krishnan (2009).

Supply chain contracting in the presence of information asymmetry, especially that of adverse selection, has become an established area of research in OM in recent years. Articles such as Ha (2001), Corbett (2001), and Corbett et al. (2004) are some of the representative works in this stream of research. Among them, Iyer et al. (2005) is quite related to this paper since they also consider the use of a screening contract in the context of product development. However, the features and the focuses of the two papers do not overlap much; whereas they study the issue of resource sharing under the complementary/substitutability assumptions in a static setting, we study how collaboration incentives are impacted by various types of procurement contracts (not just a screening contract) in a dynamic setting. More recently, several authors have investigated dynamic adverse selection problems arising in strategic sourcing, such as Li and Debo (2009) and Taylor and Plambeck (2007a,b). Although there are some similarities (for example, Taylor and Plambeck 2007a compare price-only and price-quantity contracts, as in this paper), these models differ from ours in many dimensions, including motivations, modeling approaches, and managerial insights.

Our model can also be viewed as a variant of the models that combine adverse selection and moral hazard, since, in our model, the supplier exerts a discretionary, non-contractible effort and subsequently possesses private information about his cost. There are a number of papers in the procurement contracting literature with a similar focus, including Laffont and Tirole (1986) and Baron and Besanko (1987). However, our model does not fit exactly into the traditional framework and therefore differs from these works because, in ours, the manufacturer is not represented as a "principal" in a strict sense. Instead, even though it is the manufacturer who devises the contract terms and offer them to the supplier, their relationship is more equal in the beginning when they engage in a simultaneous-move game in which they *both* decide how much efforts should be expended. In this respect, our model shares some similarities to the models that consider the principal-agent problems in teams (McAfee and McMillan 1991, Olsen 1993) and those that consider double moral hazard (Cooper and Ross 1985, Baiman et al. 2000). However, many unique features of our model—including the joint decisions in the presence of adverse selection and double moral hazard, operational considerations such as inventory risk, and the dynamics created by the interaction between demand and cost uncertainties—distinguish our model from the existing works.

One of the central elements of our model is the contract offer timing decision, which naturally brings up the hold-up problem (Klein et al. 1978) and the issue of evaluating operational flexibility vs. the value of commitment. In the OM literature, Taylor (2006) examines this issue in a setting where a manufacturer may offer a contract either before or after demand is realized to a retailer who possesses private information about demand. Despite some similarities, the results in Taylor (2006) and in this paper are driven by different dynamics; for example, in this paper, one of the important determinants of whether to commit to a contract term is the interaction between demand variability and cost uncertainty. The work that comes closest to ours in addressing the timing issue is Gilbert and Cvsa (2002). Our paper differs from theirs in many respects, however, especially in our focus on information asymmetry, the role of uncertainty originating not only from demand but also from cost, and the decisions driven by inventory risks, as captured by the newsvendor framework.

3 Model Assumptions

3.1 Basic Assumptions

We focus on the two stages that precede sales: product development occurs in Stage 1, and production occurs in Stage 2. A manufacturer ("she") designs and builds a highly innovative product, which has a short life span due to fast technological obsolescence but requires a long production lead time. As a result, inventory risk is a significant concern for the manufacturer, and she decides the product quantity in advance using the newsvendor logic.[2]. Because the manufacturer lacks in-house expertise to develop a key component, she outsources the task to a supplier ("he"), who possesses the necessary capability. We assume that each end product requires one unit of this component.

In Stage 1 the manufacturer and the supplier engage in collaborative component development. At the beginning, the supplier does not have sufficient knowledge on how to manufacture the component most efficiently, since it has to be custom-made for the end product that features novel functionalities. For example, the supplier would have to choose from a multitude of options on raw materials and parts, second-tier supplier selections, and competing ideas for the component architecture. Consequently, the unit cost c of producing a component is highly uncertain at the start of Stage 1. This uncertainty can be reduced by collaborating with the manufacturer, who guides the supplier to build the component that satisfies her functional requirements. However, the manufacturer can only provide a rough guidance since her requirements are incomplete; not fully understanding the fine details of component manufacturing (e.g, does the right technology exist that enables the desired functionality?), the manufacturer starts product design by leaving many questions open, hoping that they will be resolved as the development process unfolds. Therefore, the two parties learn of each other's expectations and limitations through collaboration, which typically involves multiple iterations of trial and error. (For simplicity, however, we do not explicitly model such a dynamic learning process; see Section 3.2.) In addition to uncertainty reduction, a higher level of collaboration lowers the expected unit production cost. Hence, collaboration brings an obvious benefit to the manufacturer, as both the expected unit cost and uncertainty around it are

[2] Lee and Whang (2002) motivates their newsvendor-based model using the examples of product categories that are similar to what we consider.

lowered as a result. In our model, we identify these changes in the unit cost as the main outcome of collaboration and specifically focus on them.

Stage 2 begins after component development is complete. Significant uncertainty about the unit cost still remains, but at the start of this stage, the supplier privately learns unit cost realization, which is not relayed to the manufacturer. At this point the manufacturer may offer a procurement contract to the supplier (more details on this later). Production and assembly start afterwards. We normalize the cost of acquiring other parts and assembling the end product to zero, since they do not play significant roles in our analysis. Since the production lead time is long, the manufacturer has to order production quantity q in advance, when demand uncertainty exists. In Section 8.1 we relax this make-to-stock production assumption and consider the make-to-order system. We assume that the end product is sold at the end of Stage 2 at a predetermined price r. Not only is the fixed price assumption in line with most other papers in the OM literature, it is consistent with practice. In the auto industry, for example, manufacturers typically set a target retail price first and then, working with the suppliers, figure out the ways to lower the cost below this target and be profitable (Womack et al. 1991, p. 148). For completeness, we relax the fixed price assumption in Section 8.2 as an extension of the model.

The manufacturer uses r as the basis of generating a forecast of the end product demand D, which is a random variable with the mean μ, pdf f, and cdf F. This distribution is common knowledge. We assume that F is defined on a nonnegative support with $F(0) = 0$, and that it exhibits an increasing generalized failure rate (IGFR) property, which is satisfied by many well-known distributions. The notations $\overline{F}(\cdot) \equiv 1 - F(\cdot)$ and $J(y) \equiv \int_0^y xf(x)dx$, which represents the incomplete mean of D, are used throughout the paper. For simplicity, we assume that unsold units are discarded after the end product becomes obsolete, i.e., we do not consider the secondary market. Introducing a salvage value for the product does not change the insights.

3.2 Collaboration Level and Unit Production Cost

To quantify the outcome of collaboration, we introduce the parameter $\theta \in [0, 1]$ that measures the extent to which the unit cost is reduced through collaboration. We refer to θ simply as the "collaboration level". At $\theta = 0$ the firms are completely disengaged ("arm's length relationship"), whereas $\theta = 1$ corresponds to the maximum level of collaboration that can be achieved. The collaboration level θ results from joint efforts made by the manufacturer and the supplier, respectively denoted as e_m and e_s. These efforts reflect the amount of investment, time, and resources that each firm puts in the collaborative process. To capture the idea that collaboration creates positive synergy between the two firms, we assume that e_m and e_s are complementary with respect to θ. To succinctly represent this relationship, we employ the Cobb-Douglas function with constant returns to scale: $\theta = e_m^{\alpha} e_s^{1-\alpha}$, where $0 < \alpha < 1$.[3] The exponents α and $1-\alpha$ are the elasticities of θ with respect to e_m and e_s. Complementarity is ensured since $\frac{\partial^2 \theta}{\partial e_m \partial e_s} > 0$. By construction, positive collaboration level ($\theta > 0$) is obtained if and only if both parties exert nonzero efforts.

Exerting an effort is costly to both the manufacturer and the supplier, and for simplicity, we assume that the disutility of effort is linear: $k_m e_m$ and $k_s e_s$. The disutility may include, among others, expenses incurred for communication, personnel exchanges, prototype testing, etc. We use the shorthand notation $K \equiv \left(\frac{k_m}{\alpha}\right)^{\alpha} \left(\frac{k_s}{1-\alpha}\right)^{1-\alpha}$ as this expression frequently appears in our analysis. It represents the composite cost-contribution ratio of exerting efforts. All functional forms introduced thus far are assumed to be common knowledge.

Reflecting our focus on unit cost reduction as the main outcome of collaboration, we define the relationship between θ and the unit cost c as follows. The conditional unit cost $c|\theta$ is a random variable defined on a finite support with the conditional cdf $G(\cdot|\theta)$ and the pdf $g(\cdot|\theta)$. Since the mapping $G^{-1}(z|\theta)$ uniquely identifies the unit cost realization for a fixed θ at the z^{th} quantile, $z \in [0, 1]$, we present our model in the transformed (θ, z)-space instead of the original (θ, c)-space, as doing so simplifies analysis. Throughout the paper we refer to $G^{-1}(\cdot|\theta)$ as the *unit cost function*. As it turns out, analysis becomes intractable when we combine the general distribution functions F and G. For this reason, we develop our model under the following simplifying assumptions on the unit cost distribution.[4]

[3] Constant returns to scale implies that an $x\%$ increase in both e_m and e_s results in the same percentage increase in θ. Although this is a somewhat strong assumption, we adopt it in order to simplify analysis. The same assumption is frequently found in the economics literature, especially since it offers intuitive interpretations (e.g., Varian 2003, p. 83). Note that Roels et al. (2010), like in our paper, employ the Cobb-Douglas function but they assume decreasing returns to scale, i.e., the function has a form $x^a y^b$ with $a + b < 1$. In our model, however, the objective functions in the optimization problems may not be unimodal if $a + b$ is sufficiently smaller than one, unnecessarily complicating the analysis. In our paper the distinction between constant vs. decreasing returns to scale is of small concern, since only the relative scale of θ matters and the main insights are not impacted by the exact shape of the functional form of θ, as long as it exhibits complementarity between e_m and e_s.

[4] Together, (i)-(iii) in Assumption 1 imply the more general conditions $\frac{\partial}{\partial \theta} E[c \,|\, \theta] = \frac{\partial}{\partial \theta} \int_0^1 G^{-1}(z \,|\, \theta) dz < 0$ and $\frac{\partial}{\partial \theta}[G^{-1}(z_2 \,|\, \theta) - G^{-1}(z_1 \,|\, \theta)] < 0$.

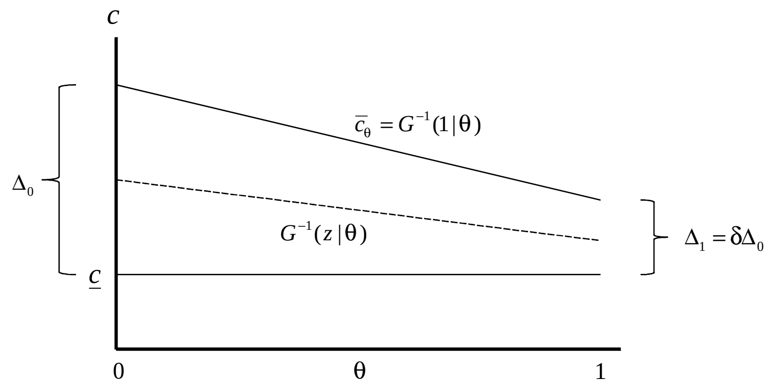

Figure 1: An example of a unit cost function satisfying Assumption 1.

Assumption 1 *(i) $c|\theta$ is uniformly distributed with a constant lower support bound $\underline{c}$ and an upper support bound $\bar{c}_\theta$, which varies with θ.*

(ii) $G^{-1}(z|\theta)$ decreases linearly in θ for all $z \in (0, 1]$.

(iii) $\delta \equiv \Delta_1/\Delta_0 < 1$, where $\Delta_\theta \equiv \bar{c}_\theta - \underline{c}$.

Although these assumptions are somewhat restrictive, they offer the essential features of the unit cost function we wish to capture. See Figure 1 for an illustration. Uniform distribution assumption in (i) is frequently employed in the models in which two or more random variables interact, as in ours (see, for example, Li and Debo 2008, Cachon and Swinney 2009; non-uniform distributions do not qualitatively change the insights but considerably complicate the analysis). Under this assumption, the expected unit cost at a given θ is equal to $E[c|\theta] = G^{-1}(1/2|\theta)$. Under the assumptions (ii) and (iii), both the mean unit cost and the *spread* $G^{-1}(z_2|\theta) - G^{-1}(z_1|\theta)$ for $0 \leq z_1 < z_2 \leq 1$, i.e., the gap between any two equiquantile curves, decrease in θ. This formalizes the idea that a higher level of collaboration leads to lower expectation and lower uncertainty of the unit cost. The quantity δ in (iii) represents the fractional residual unit cost at $\theta = 1$. Equivalently, $1 - \delta$ is the percentage of cost reduction that can be attained at full collaboration.

Among the assumptions stated above, perhaps the two most restrictive ones are that $G^{-1}(\cdot|\theta)$ decreases linearly and that the lower support bound is fixed to a constant. The former is in fact inconsequential because only the relative values of θ are of our interest; replacing the linear functions with nonlinear monotonic curves only changes the scale. The latter assumption is employed mainly for the purpose of simplifying the analysis (without it, tractability is lost). By having the lower bound fixed, we essentially assume that the supplier has a clear idea about the baseline unit cost $\underline{c}$ to build the component and that it is only the upside uncertainty that can be reduced through collaboration. Under these assumptions, we can express the unit cost function as

$$G^{-1}(z|\theta) = \underline{c} + \Delta_0 \left(1 - (1-\delta)\theta\right) z. \tag{1}$$

Information asymmetry emerges at the end of Stage 1, after collaboration is completed and θ is observed by both parties. At that point, the supplier privately learns the realized cost, or equivalently, the supplier's "type" $z|\theta$. This information is not relayed to the manufacturer, as the supplier keeps it to himself with the intention of using it to his advantage. The manufacturer continues to have only limited knowledge about the supplier's type, i.e., she knows the distribution of the unit cost at θ as specified in (1) but not the realized value.

Additionally, we make two technical assumptions on the range of parameter values in order to ensure the problem is well-behaved and to enable clean exposition by reducing the number of special cases that require separate discussions but of less import. First, we assume $\underline{c} + 2\Delta_0 < r$, which leads to positive order quantities in all cases we consider. Second, we restrict our attention to the case

$$K < r \int_0^1 \left[J\left(F^{-1}\left(1 - \frac{\underline{c} + \delta\Delta_0 z}{r}\right)\right) - J\left(F^{-1}\left(1 - \frac{\underline{c} + \Delta_0 z}{r}\right)\right)\right] dz. \tag{2}$$

This condition is satisfied when δ and the effort costs k_m and k_s are sufficiently small so that investing in cost reduction is attractive to them. Such a situation is conducive to the manufacturer and the supplier to engage in collaborative efforts since the unit cost can be significantly reduced with relatively small effort disutility.

3.3 Collaboration Effort Decisions and Contracting

As described above, the collaboration level θ is jointly determined in Stage 1 by the manufacturer's and the supplier's efforts. In practice, rarely do we observe these efforts being contracted upon. This is because neither party has a unilateral power to dictate the level of the other's effort, as each has to rely on the other's complementary expertise to develop the component. In contrast, as the designer and the producer of the end product who initiates the supply chain activities, the manufacturer has a greater influence over the procurement contract terms. Based on these observations, we model the game structure in the following stylized way. For the collaborative component development, we assume that the manufacturer and the supplier engage in a simultaneous-move game under which they decide their effort levels competitively, taking into account the costs and the mutual benefits they bring. For the component procurement, on the other hand, the manufacturer decides the terms of the trade and offers a take-it-or-leave-it contract to the supplier. Note that this leader-follower assumption does not give a complete leverage to the manufacturer since the supplier has an informational advantage, i.e., he keeps his realized unit cost private.

Motivated by the majority of procurement practices, we assume that the contract type is that of the price-quantity pair, (w, q). That is, the manufacturer specifies the unit price and the quantity of the component in a contract, making sure that the supplier will agree to the proposed terms. Depending on when the manufacturer offers the contract, the contract may or may not consist of a single price-quantity pair. If she offers the contract once at the beginning of Stage 2 (immediately before production starts), at which point the collaboration level θ is set and information asymmetry about the unit cost is in place, the optimal contract consists of a menu of price-quantity pairs $\{(w(z|\theta), q(z|\theta))\}$, for $0 \leq z \leq 1$ and $0 \leq \theta \leq 1$. Each pair in this screening contract maps to the supplier's realized type $z|\theta$. As is well known in the mechanism design literature, the manufacturer can structure the menu so that the supplier chooses the pair specifically designed for him, thereby truthfully revealing his type. Then the manufacturer can extract all of the supplier's surplus except for his *information rent*, which represents the inefficiency created by information asymmetry.

Although the practice of offering a procurement contract immediately before production starts is routinely observed, it is not the only option available to the manufacturer. In particular, she may decide to commit to a contract term in an early stage of the relationship, i.e., when they start to collaborate on component development. In Section 6 we investigate these commitment strategies in depth. Variants of these strategies are observed in practice. For instance, Japanese auto manufacturers and their suppliers agree on a payment amount based on the projected cost improvement that they expect to achieve through joint efforts (Womack et al. 1991). A similar practice was adopted by Chrysler as part of its pre-sourcing effort (Dyer 2000). Volume commitments are also

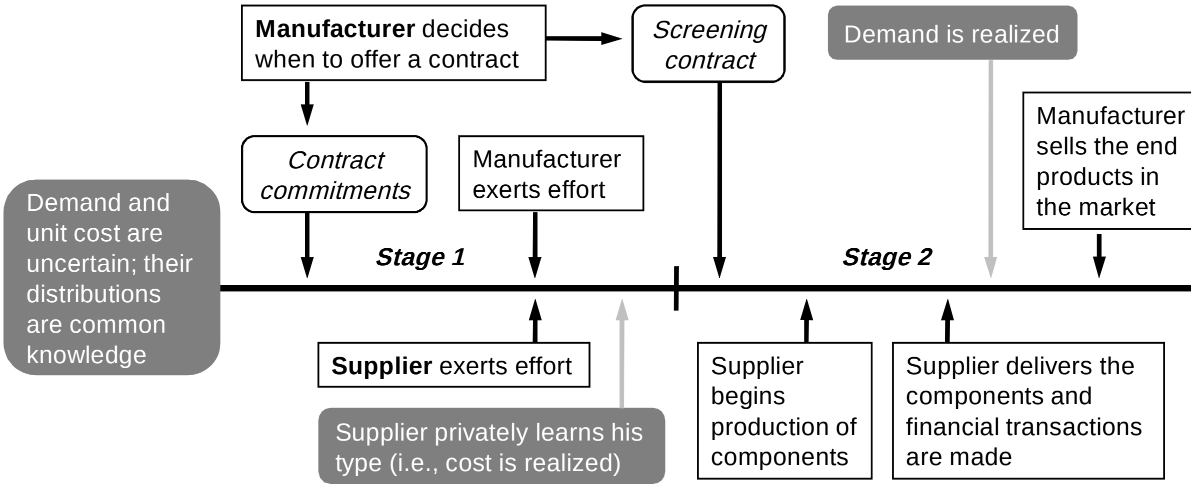

Figure 2: Sequence of Events.

frequently used as a way to improve supply chain relationships (Corbett et al. 1999).

The sequence of events is outlined in Figure 2. In summary, the manufacturer decides which contracting strategy to adopt before commencing collaborative component development. She may either commit to a contract term value at the outset, or delay offering a contract until after collaboration is completed. Once the strategy is set, in Stage 1, the manufacturer and the supplier simultaneously exert their collaborative cost reduction efforts e_m and e_s. There is still uncertainty remaining about the unit cost after the collaboration level $\theta = e_m^\alpha e_s^{1-\alpha}$ is determined. Afterwards, the supplier learns the true unit cost, but he keeps this information from the manufacturer. At this point the manufacturer may offer a contract term, depending on the strategy set in the beginning. At the end of Stage 2, the supplier manufactures and delivers the components in the quantity specified in the contract, and receives payment. The manufacturer in turn assembles the end products and sells them in the market.

4 Integrated Supply Chain

We first establish a benchmark under the assumption that the manufacturer and the supplier are integrated as a single firm. A manager of the integrated firm sets the optimal allocation of collaborative efforts between the "manufacturer" division and the "supplier" division as well as the production quantity. Since the unit cost is uncertain in the beginning, it is optimal for the manager to delay the quantity decision until after the cost is realized. Consistent with the assumption in the previous section, the collaboration level θ is already determined at this point. Thus, the integrated firm faces the problem

$$(\mathcal{B}) \qquad \max_{e_m, e_s} \quad \int_0^1 \left(rE[\min\{D, q(z|\theta)\}] - G^{-1}(z|\theta) q(z|\theta) \right) dz - k_m e_m - k_s e_s$$
$$\text{s.t.} \quad q(z|\theta) = \arg\max_q \left\{ rE[\min\{D, q\}] - G^{-1}(z|\theta) q \right\},$$

with the constraint $0 \leq \theta = e_m^\alpha e_s^{1-\alpha} \leq 1$. This is a stochastic program with recourse (Birge and Louveaux 1997). The optimal solutions, denoted by the superscript B (for "benchmark") are specified as follows. Note that, in the remainder of the paper, we mainly focus on the optimal efforts and the resulting collaboration level, the variables of our main interest, at the expense of suppressing the discussions of the optimal purchase price and quantity.

Proposition 1 *(First-best) The integrated firm chooses the efforts* $e_m^B = \left(\frac{\alpha}{k_m} \frac{k_s}{1-\alpha} \right)^{1-\alpha}$ *and* $e_s^B = \left(\frac{k_m}{\alpha} \frac{1-\alpha}{k_s} \right)^{\alpha}$*, resulting in* $\theta^B = 1$*.*

As expected, the integrated firm opts for the maximum collaboration level $\theta = 1$. The expected unit cost is lowest at this level, and therefore, the firm's expected profit is largest as its profit margin goes up and the inventory risk (measured in the overage cost) is reduced. The optimal allocation of efforts is also quite intuitive. Observe that the cost-contribution ratios $\frac{k_s}{1-\alpha}$ and $\frac{k_m}{\alpha}$ play key roles. The relative magnitude of these ratios is

$$\frac{e_s^B}{e_m^B} = \frac{k_m/\alpha}{k_s/(1-\alpha)}.$$

As the manufacturer's cost-contribution ratio $\frac{k_m}{\alpha}$ increases, more effort is allocated to the supplier, and vice versa. If the manufacturer and the supplier are symmetric, i.e., $k_m = k_s$ and $\alpha = 1/2$, the optimal efforts are identical: $e_m^B = e_s^B = 1$. Anchoring on these insights as a benchmark, we now consider what happens in a decentralized supply chain where information asymmetry exists and procurement contracting plays a key role.

5 Collaboration Under a Screening Contract

In a decentralized supply chain, the manufacturer specifies the unit price as well as the quantity in a procurement contract that she offers to the supplier. The main challenge for the manufacturer in this setting is how she structures the contract in the presence of information asymmetry; without perfect knowledge of the unit cost, her ability to offer the contract terms that are favorable to herself is limited. The contract theory points to the screening mechanism as the most efficient form of contracting in this situation. That is, the optimal contract consists of a menu of price-quantity pair, where each pair is tailored to a unit cost realization, or each supplier type.

In order for the manufacturer to implement the screening mechanism, she should offer the contract to the supplier after the latter privately learns his type. Under the sequence of events outlined in Section 3, therefore, the contract is offered at the start of Stage 2 after the collaborative cost reduction is completed and the final value of θ is known. Hence, the menu of contracts has the form $\{(w(z|\theta), q(z|\theta))\}$, where $w(z|\theta)$ and $q(z|\theta)$ are the price and the quantity designated for the supplier type z for a given value of θ. The optimal menu, denoted by the superscript $*$, is determined from the following optimization problem.

$$
\begin{aligned}
(\mathcal{S}_2) \qquad \max_{\{(w(z|\theta),q(z|\theta))\}} \quad & \int_0^1 \left(rE[\min\{D, q(z|\theta)\}] - w(z|\theta)q(z|\theta)\right) dz \\
\text{s.t.} \quad & \pi_s(z, z|\theta) \geq 0 \ , \ \forall z \in [0,1], && \text{(IR-S)} \\
& \pi_s(z, z|\theta) \geq \pi_s(z, \widehat{z}|\theta) \ , \ \forall z, \widehat{z} \in [0,1]. && \text{(IC-S)}
\end{aligned}
$$

This problem setup is standard in the literature (see Ha 2001 who formulate the problem similarly with the newsvendor objective, as in $(\mathcal{S}_2)$.) Here, $\pi_s(z, \widehat{z}|\theta) \equiv [w(\widehat{z}|\theta) - G^{-1}(z|\theta)]q(\widehat{z}|\theta)$ is the z-type supplier's Stage 2 profit when he accepts the price-quantity pair $(w(\widehat{z}\,|\theta), q(\widehat{z}\,|\theta))$ that is intended for the $\widehat{z}$-type supplier. The optimal screening mechanism rests on the revelation principle, which states that one can always design an optimal contract under which the supplier voluntarily chooses the price-quantity pair that is designated for him, effectively revealing his true type. This is reflected in the incentive compatibility constraint (IC-S) above. The participation constraint (IR-S) ensures that the resulting profit for the supplier is nonnegative regardless of the realized cost. The solution of $(\mathcal{S}_2)$ is as follows.

Lemma 1 *The optimal screening contract consists of a menu of price-quantity pairs* $\{(w^*(z|\theta), q^*(z|\theta))\}$ *where* $q^*(z|\theta) = F^{-1}\left(1 - \frac{1}{r}\left[\underline{c} + 2\Delta_0\left(1-(1-\delta)\theta\right)z\right]\right)$ *and* $w^*(z|\theta) = \underline{c} + \Delta_0\left(1-(1-\delta)\theta\right)\left(z + \frac{\int_z^1 q^*(x|\theta)dx}{q^*(z|\theta)}\right)$. *The Stage 2 expected profits of the manufacturer and the supplier are* $r\int_0^1 J(q^*(z|\theta))dz$ *and* $\Delta_0\left(1-(1-\delta)\theta\right)\int_0^1 zq^*(z|\theta)dz$*, respectively.*

Despite the truth-revealing nature of the optimal screening contract, the first-best cannot be achieved because the manufacturer's imperfect knowledge of the unit cost leaves the supplier with a positive information rent except for the highest-type supplier (i.e., $z = 1$). The supplier's expected profit in Lemma 1 represents the expected information rent over all possible realizations of z.

Anticipating these Stage 2 outcomes, the manufacturer and the supplier simultaneously decide the optimal effort levels e_m and e_s in Stage 1, resulting in the collaboration level $\theta = e_m^{\alpha} e_s^{1-\alpha}$. In doing so, they maximize their Stage 1 utilities $U_m(e_m|e_s) \equiv r\int_0^1 J(q^*(z|\theta))dz - k_m e_m$ and $U_s(e_s|e_m) \equiv \Delta_0\left(1-(1-\delta)\theta\right)\int_0^1 zq^*(z|\theta)dz - k_s e_s$. The equilibrium collaboration level of this game is specified in the next proposition. We use the superscript S (for "screening") to denote the equilibrium outcomes of this game.

Proposition 2 *(Equilibrium collaboration level under the screening contract) The Nash equilibrium of the effort game under the screening contract exists. Let* $\psi(\theta) \equiv -q^*(1|\theta) + \int_0^1 zq^*(z|\theta)dz$ *and*

$$\Psi(\theta) \equiv \begin{cases} \Delta_0\left(1-\delta\right)\left[2q^*(1|\theta) + 2\psi(\theta)\right]^{\alpha}\psi(\theta)^{1-\alpha} \geq 0 & \text{if} \quad \psi(\theta) \geq 0, \\ -\Delta_0\left(1-\delta\right)\left[2q^*(1|\theta) + 2\psi(\theta)\right]^{\alpha}\left[-\psi(\theta)\right]^{1-\alpha} < 0 & \text{if} \quad \psi(\theta) < 0. \end{cases}$$

If $\Psi(\theta) < K$ *for all* $\theta \in [0,1]$*, then* $\theta^S = 0$*. If* $\Psi(\theta) > K$ *for all* $\theta \in [0,1]$*, then* $\theta^S = 1$*. Otherwise,* $\theta^S \in [0,1]$ *is found from the equation* $\Psi(\theta) = K$*.*

While Proposition 2 identifies the equilibrium solution, the expressions there do not permit easy interpretations. In addition, an analytical proof of uniqueness of the equilibrium is not readily available, although it is confirmed by numerical examples. We overcome this difficulty by investigating special cases. Consider first a simple example, in which demand is uniformly distributed on a unit interval $[0,1]$, the manufacturer and the supplier are symmetric with respect to their effort costs and contributions, i.e., $k_m = k_s = k$ and $\alpha = 1/2$, and the maximum collaboration achieves the lowest possible unit cost and completely removes uncertainty around it, i.e., $\delta = 0$ at $\theta = 1$.

Then the equilibrium collaboration level in Proposition 2 can be succinctly expressed as

$$\theta^S = \left(1 - \tfrac{3}{16\Delta_0}\left(3(r-\underline{c}) - \sqrt{(r-\underline{c})^2 - \left(\tfrac{8rk}{\Delta_0}\right)^2}\right)\right)^+, \tag{3}$$

where $(\cdot)^+ \equiv \max\{0, \cdot\}$. Notice that θ^S decreases in k, the effort cost. The interpretation is straightforward; higher effort cost makes it more expensive for the manufacturer and the supplier to exert efforts, and therefore, the resulting collaboration level is lower. It also implies that the value of θ^S cannot be greater than the value attained in the limit $k \to 0$, i.e., when the efforts can be made costlessly. Hence, θ^S is bounded above by $\widehat{\theta}^S \equiv \lim_{k\to 0}\theta^S$, where $\widehat{\theta}^S = \left(1 - \frac{3(r-\underline{c})}{8\Delta_0}\right)^+$. Recall that we have assumed $\underline{c} + 2\Delta_0 < r$ (otherwise, a negative quantity may arise). Applying this condition, we find: $\widehat{\theta}^S < \frac{1}{4}$. Consequently, the maximum collaboration level $\theta = 1$ is never achieved in this example. This is in stark contrast to the result in Proposition 1, where we found that $\theta = 1$ is the only outcome when the supply chain was assumed to be integrated.

Such a contrast is driven in part by the strong assumption $\delta = 0$. However, the key insight is invariant to the parameter values: the equilibrium collaboration level in a decentralized supply chain tends to be lower than the maximum level $\theta = 1$. This is true even if $\delta > 0$, demand distribution is non-uniform, and the manufacturer and the supplier have asymmetric effort costs and contributions. The following result confirms this.

Corollary 1 *Let $\widehat{y}$ be the unique root of the function*

$$\widetilde{\psi}(y) \equiv -y\left(\overline{F}(y) - \frac{\underline{c}}{r}\right)^2 + \int_y^{F^{-1}(1-\underline{c}/r)} \left(\overline{F}(x) - \frac{\underline{c}}{r}\right) x f(x)dx.$$

In the limit $K \to 0$, the equilibrium collaboration level θ^S approaches $\widehat{\theta}^S = \min\left\{\left(\frac{\underline{c}+2\Delta_0 - r\overline{F}(\widehat{y})}{2\Delta_0(1-\delta)}\right)^+, 1\right\}$. Moreover, $\theta^S \le \widehat{\theta}^S$ for $K > 0$.

According to the corollary, the upper bound $\widehat{\theta}^S$ of the equilibrium collaboration level can take any value between 0 and 1, depending on the parameter values and the shape of the demand distribution F (we investigate this further in Section 7). In addition, as we found above in the uniform distribution example, $\widehat{\theta}^S < 1$ if $\delta = 0$ (this is easily verified). These observations provide strong evidence that the equilibrium collaboration level is generally lower than the first-best level

$\theta = 1$. Provided that both the expectation and uncertainty of the unit cost is smallest at $\theta = 1$, it is obvious that the manufacturer and the supplier make suboptimal decisions with regard to their collaborative effort contributions, as they lead to $\theta < 1$; they forego an opportunity to generate an extra surplus in the supply chain which they could have shared.

As we alluded in the Introduction, this deviation from the first-best arises because the manufacturer's attempt to minimize the impact of her informational disadvantage backfires. Namely, the supplier is reluctant to contribute her share of collaborative effort for fear of being *held up* by the manufacturer. To be more specific, consider the chain of events after the supplier increases his share of collaborative effort. Higher effort e_s leads to a higher collaboration level θ, which corresponds to a lower mean and uncertainty of the unit cost, as specified by Assumption 1. While smaller average unit cost benefits the supplier, smaller uncertainty does not. Recall that the supplier's expected profit consists of his information rent. With lower uncertainty about the unit cost, the supplier's informational advantage is eroded, and as a response, the manufacturer is able to structure the screening contract so that she can extract the supplier's surplus more effectively. Therefore, collaboration is a double-edged sword for the supplier—on one hand, it will increase his profitability as it brings a lower expected unit cost, but on the other hand, he has to guard against ceding his informational advantage to the opportunistic manufacturer. This tradeoff restrains the supplier from fully collaborating.

Interestingly, Corollary 1 indicates that $\theta^S < 1$ may emerge even if either party can exert his/her effort costlessly, i.e., $k_m = 0$ or $k_s = 0$. For example, even if the manufacturer contributes an infinite amount of resources since it costs her nothing to do so (i.e., $k_m = 0$), under some circumstances, especially if the residual cost uncertainty δ is small, her unbounded effort alone is not sufficient to bring the collaboration level to $\theta = 1$. This extreme case scenario again points to the supplier's unwillingness to collaborate as the reason for the suboptimal outcome. We generalize this insight in the next proposition, which compares the allocation of equilibrium efforts e_m^S and e_s^S with that under the first-best.

Proposition 3 *(Comparison of effort allocations) If* $0 < \theta^S < 1$, *(i)* $e_s^S < e_s^B$ *and (ii)* $e_s^S/e_m^S < \frac{1}{2}e_s^B/e_m^B$.

In the proposition we focus on the cases that result in $\theta^S < 1$, not $\theta^S = 1$, since the former allows a fair comparison of effort allocations. (If $\theta^S = 1$, the allocation may be skewed by having a corner solution on one effort but not on the other.) Part (i) of the proposition makes it clear that the incentive dynamic described above leads to a lower equilibrium effort for the supplier, despite the manufacturer's best attempt to compensate for the supplier's reluctance by increasing her share of contribution. In addition, part (ii) says that the supplier's share of effort relative to the manufacturer's, i.e., e_s/e_m, is smaller when the supply chain is decentralized and a screening contract is offered for procurement. As an illustration, assume that the manufacturer and the supplier are symmetric with respect to their effort cost-contribution ratios, i.e., $\frac{k_m}{\alpha} = \frac{k_s}{1-\alpha}$. Then the efforts are evenly allocated under the first-best ($e_s^B/e_m^B = 1$), whereas under the screening contract, the supplier's effort is less than a half of the manufacturer's ($e_s^S/e_m^S < \frac{1}{2}$).

In sum, while the screening mechanism used for procurement enables the manufacturer to effectively deal with information asymmetry, it creates a hold-up problem for the supplier. As a result, the supplier has a low incentive to contribute to the collaborative cost reduction effort that precedes procurement. This dynamic suggests that procurement decisions are not to be made independently of the collaborative effort decisions during product development. The question is then, what types of procurement contract promote collaboration?

6 Collaboration Under Contract Term Commitments

In the previous section we identified the hold-up problem as the source of inefficient collaboration outcome. A remedy commonly suggested in the literature to resolve this problem is price commitment, under which the manufacturer commits to a price before costly investments are made. Motivated by this, we investigate if contractual commitments, including price commitment, are effective in alleviating inefficiency in our setting as well.

6.1 Price and Quantity Commitments

As we demonstrated in the previous section, the screening mechanism equips the manufacturer with an imperfect but an effective way to deal with information asymmetry but at the expense of discouraging the supplier from collaborating on the joint cost reduction effort. The hold-up problem cannot be avoided as long as the manufacturer makes use of a screening contract, since it should be offered after the unit cost uncertainty is resolved to the supplier—a point in time when collaboration is already completed. This reasoning suggests that abandoning the screening mechanism, and in doing so, breaking up the price-quantity pair in the contract and offering one or both before collaboration starts, may convince the supplier to collaborate more. By committing to a contract term, the manufacturer is able to convey to the supplier that she will not act as opportunistically as she would have with a screening contract.

Since a procurement contract specifies price and quantity, there can be three types of the commitments: price commitment, quantity commitment, and price-quantity commitment. Of the three, price commitment has received most attention in the literature, but we investigate all three (a) for completeness and (b) to illustrate distinct effects of committing to a price and/or a quantity. The disadvantage of contract term commitment is obvious. The manufacturer would have to leave a larger portion of the rent to the supplier, since, without the price and the quantity being offered simultaneously in pairs, a truth-revealing mechanism cannot be implemented. Therefore, instituting the screening mechanism vs. the commitment strategy can be viewed as a tradeoff between (potentially) incentivizing the supplier to collaborate more and extracting more rents from him.

To see how the commitment strategy works, consider price commitment. At the beginning of Stage 1 the manufacturer offers a price w to the supplier. At this point in time no information asymmetry exists, since the unit cost is yet to be realized and both the manufacturer and the supplier know only its distribution. Next, each party exerts an effort simultaneously, resulting in the equilibrium collaboration level θ which determines the mean unit cost. The uncertainty in the unit cost is resolved afterwards, and subsequently the manufacturer offers to the supplier a quantity q.[5] Quantity commitment and price-quantity commitment follow similar sequences of events.

With price commitment, reduced unit cost uncertainty no longer represents a risk to the supplier since the manufacturer lacks a device (i.e., pricing) to take advantage of the reduction later. Therefore, intuition guides us to believe that price commitment will eliminate the hold-up problem and induce the supplier to exert more collaborative effort, potentially leading to full collaboration. As the following proposition reveals, however, this reasoning tells only a half of the story.

[5] A combination of w and a menu of quantities, i.e., $\{q(z|\theta)\}$, is insufficient to implement the truth-revealing screening mechanism since at least two contract terms are needed in a menu to satisfy both the individual rationality constraint and the incentive compatiability constraint. If such a contract were offered, the supplier would always choose the same quantity in the menu $\{q(z|\theta)\}$ that maximizes his profit regardless of his type.

Proposition 4 *Under all three contract commitments, i.e., price, quantity, and price-quantity commitments, neither party exerts collaborative effort in equilibrium:* $e_m = e_s = \theta = 0$.

As the proposition asserts, none of the commitment strategies results in full collaboration. In fact, a complete opposite happens: in equilibrium, neither party exerts effort, and therefore, the collaboration level is at the lowest level, $\theta = 0$. This unexpected conclusion is driven by the fact that collaborative cost reduction needs inputs from both the manufacturer and the supplier. Under price commitment, it is true that the supplier is more incentivized to exert effort than he would have been if he were subject to a screening contract. However, the manufacturer is not; with her payment price w fixed at a constant, she does not receive any benefit of collaborative cost reduction since her profit margin $r - w$ is fixed and her quantity is effectively fixed, too, as the latter is based on the constant underage cost $r - w$ and the constant overage cost w. Since exerting an effort incurs disutility but does not bring any profit increase, the manufacturer does not contribute, i.e., she sets $e_m = 0$. As a response the supplier sets $e_s = 0$, too, since collaboration requires mutual efforts; no synergy can be created with only one party's effort.

Quantity commitment also fails to bring positive efforts, but for a different reason. In this case the hold-up problem is again the culprit. The optimal price w that the manufacturer sets in Stage 2 is lower if the unit cost uncertainty smaller, implying that the supplier's profit margin goes down with higher θ. Since the quantity q is fixed, it also means that the supplier's profit (margin times the quantity) is highest at $\theta = 0$. Hence, the supplier refuses to collaborate and sets $e_s = 0$, and as a response, it is optimal for the manufacturer to set $e_m = 0$, too. Therefore, not all commitments alleviate the hold-up problem; with quantity commitment, the problem is actually exacerbated. The same result is obtained for price-quantity commitment by a similar reasoning.

Therefore, committing to either or both contract terms at the outset of the relationship does not promote collaboration—quite to the contrary, it stifles collaboration. This is because, while collaboration requires both parties' efforts, the commitment strategies we described above incentivize only either one or neither. Under price commitment, it is the manufacturer who refuses to put in effort. On the other hand, under quantity commitment, it is the supplier, and under price-quantity commitment, it is both. In order for both to be motivated, then, a middle ground should be reached on which the manufacturer can internalize the benefit of cost reduction and at the same time the supplier is not concerned about being held up. In the next subsection we propose a simple contracting scheme that achieves this goal.

6.2 Expected Margin Commitment

Under expected margin commitment (EMC), the manufacturer commits to pay a constant margin v above the expected unit cost $\int_0^1 G^{-1}(z|\theta)\,dz$, no matter what collaboration level θ results from their mutual efforts. EMC is similar to but different from price commitment, since, while commitment is made on price, the price (which is equal to $w(\theta) = v + \int_0^1 G^{-1}(z|\theta)\,dz$) is not fixed—it decreases with θ. This is appealing to both the manufacturer and the supplier. The manufacturer receives the benefit of cost reduction since her margin $r - w(\theta)$ improves while the inventory risk (represented by the overage cost $w(\theta)$) becomes smaller. From the supplier's perspective, EMC encourages exerting an effort since the order quantity increases with θ (which can be verified from the proposition below) while his expected profit margin is protected, as it is equal to the constant value v. Unlike under the screening contract, he does not have to trade off a lower unit cost with a lower payment. Hence, EMC has a potential to neutralize the hold-up problem. Taking the two together, we see that collaboration becomes attractive to both parties under EMC.

However, this does not necessarily imply that the manufacturer always prefers EMC, since it does not enable her to extract rents from the supplier as efficiently as she could have with a screening contract. We consider this tradeoff further in the next section. First, let us characterize the equilibrium collaboration level under EMC. We use the superscript M to denote the equilibrium outcomes under EMC.

Proposition 5 *(Equilibrium collaboration level under expected margin commitment) The Nash equilibrium of the collaborative effort game under EMC exists. Let* $q^\dagger(\theta) \equiv F^{-1}\left(1 - \frac{1}{r}\left[v + \underline{c} + \frac{\Delta_0}{2}\left(1 - (1-\delta)\theta\right)\right]\right)$ *and* $\Gamma(\theta) \equiv \frac{1}{2}\Delta_0(1-\delta)\left(q^\dagger(\theta)\right)^\alpha \left(\frac{v}{rf(q^\dagger(\theta))}\right)^{1-\alpha}$. *If* $\Gamma(\theta) < K$ *for all* $\theta \in [0,1]$*, then* $\theta^M = 0$. *If* $\Gamma(\theta) > K$ *for all* $\theta \in [0,1]$*, then* $\theta^M = 1$. *Otherwise,* θ^M *is found from the equation* $\Gamma(\theta) = K$.

Note that this proposition is incomplete since it does not specify the optimal value of v, which involves analytical difficulty. However, it is intuitive that the optimal value of v should be determined from the binding participation constraint, i.e., the manufacturer should choose the minimum margin for the supplier that ensures his participation in the trade. This is consistent with the equilibrium result in the screening contract case, and indeed, it is what we observe from numerical experiments whenever K is sufficiently small. With the binding constraint the optimal value of v is equal to $v^M = \frac{\Delta_0}{2}\left(1-(1-\delta)\theta^M\right)$.[6] In the subsequent analyses we assume this is true, except for the next result which does not rely on this assumption.

Corollary 2 *$\theta^M = 1$ in the limit $K \to 0$.*

That is, the equilibrium collaboration level under EMC always approaches its upper bound when the effort costs are negligible. This is in contrast to the analogous result in Corollary 1 for the screening contract case, where we found that the upper bound $\widehat{\theta}^S$ may be less than one depending on parameter values. Hence, Corollary 2 provides evidence that EMC tends to bring a higher collaboration level than the screening contract does, as we suspected.

As we mentioned above, however, the manufacturer may not always prefer EMC to the screening contract despite the former's ability to promote collaboration, because it requires her to leave a larger fraction of surplus to the supplier. We investigate this tradeoff in the next section, with a goal of identifying the conditions under which one contracting approach dominates the other.

7 Optimal Contracting Strategies

In this section we compare the performances of the two contracting strategies we studied in the previous sections, namely, the screening contract and EMC, from the manufacturer's perspective. We focus on the role of demand variability, an important product characteristic that drive many procurement decisions in practice. In our setting, demand variability not only influences the terms of procurement contracts (i.e., price and quantity), but also the supply chain parties' incentives to collaborate on cost reduction. We elaborate on this below.

The first hint at how demand variability impacts the collaboration level comes from Corollary 1, which specifies the upper bound $\widehat{\theta}^S$ of the equilibrium collaboration level under the screening contract. As we found there, the shape of the demand distribution F determines whether $\widehat{\theta}^S$ is equal to zero, one, or a value in between. To make this observation more concrete, let us assume

[6] This assumes the ex-post participation constraint $\pi_s(z|\theta^M) \geq 0$, $\forall z \in [0,1]$, which is consistent with the assumption in the screening contract case. With this, we rule out the possibility that the supplier walks away from the trade if his realized cost is too high.

that demand is normally distributed and see how $\widehat{\theta}^S$ varies with the standard deviation σ. The result of this sensitivity analysis is summarized in the next proposition.

Proposition 6 *Suppose that demand is normally distributed with the mean μ and the standard deviation σ. Then $\frac{\partial \widehat{\theta}^s}{\partial \sigma} > 0$ for $0 < \widehat{\theta}^S < 1$.*

That is, the upper bound of the equilibrium collaboration level under the screening contract increases with demand variability. This finding hints that a similar statement can be made about the collaboration level for a general case, i.e., $\frac{\partial \theta^s}{\partial \sigma} > 0$ is likely as well. Indeed, this is confirmed by numerical examples. On the surface, this sounds intuitive—more uncertainty brings higher level of collaboration. After all, many studies in the literature tout supply chain collaboration as an important strategic tool to minimize the negative consequences of demand variability. For example, Lee et al. (2004) identifies the collaborative demand forecast sharing as one of the four strategies for mitigating the bullwhip effect. However, this naïve intuition does not apply to our setting, since in our model demand information is symmetric; demand forecast sharing is a built-in assumption in our model.

Instead, the sensitivity result in Proposition 6 arises from a subtle interaction between demand variability and collaborative cost reduction. The reasoning is as follows. Larger demand variability brings a higher demand-supply mismatch risk to the manufacturer, and this prompts her to find a way to compensate for the expected loss. An obvious remedy is to recoup her loss by lowering the payment to the supplier and extract more surplus from him. However, the manufacturer's ability to do so is limited by the supplier's unit cost; the higher the unit cost, the smaller the amount of surplus that the manufacturer can take away from the supplier. Hence, it is optimal for the manufacturer to restructure the terms of the screening contract so that the supplier finds it more appealing to put in his share of collaborative effort, lowering the unit cost in the process and thus creating more surplus that the manufacturer can extract from him. The net effect is higher collaboration level. Therefore, a higher collaboration level results from the manufacturer's self-interested motive, rather than from a social planner-like goal of creating mutual benefits.

Combining this observation that high demand variability fosters collaboration under the screening contract with that from Corollary 2, namely that the supply chain parties tend to collaborate more readily under EMC, we infer that the difference in θ between the screening contract and EMC

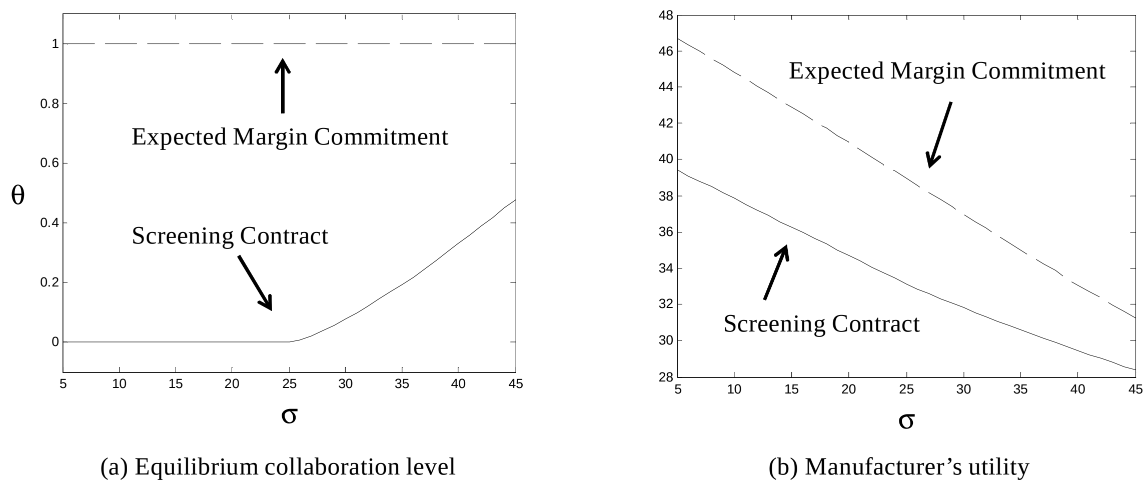

Figure 3: In this example, $\delta = 0.8$, $r = 1$, $\underline{c} = 0.19$, $\Delta_0 = 0.4$, $\alpha = 0.5$, and $k_m = k_s = 0.12$. Demand is normally distributed with the mean 100.

is larger when demand variability is low, while the opposite is true when demand variability is high. An example in Figure 3(a) supports this hypothesis. In this example, $\theta^M = 1$ is always attained in equilibrium under EMC while θ^S steadily increases with σ under the screening contract. However, as Figure 4(a) illustrates, this is not a universal result; there are situations where $\theta^M = \theta^S = 0$ if σ is sufficiently small and $\theta^M = \theta^S = 1$ if σ is sufficiently large. The difference between these two examples is the degree of cost reduction that can be attained via collaboration; $\delta = 0.8$ in Figure 3, i.e., 20% reduction is achieved by full collaboration, whereas $\delta = 0.95$ in Figure 4, i.e., 5% reduction is achieved.

From these examples and the extensive numerical experiments we have conducted, we conclude that the manufacturer prefers EMC to the screening contract when the following conditions are met: (a) a large percentage of cost reduction (small δ) can be achieved through collaboration and/or (b) demand variability is low. This is illustrated in Figure 3(b), which shows that EMC dominates the screening contract especially when demand variability is small. On the other hand, if the degree of achievable cost reduction is relatively small and demand variability is large, then the screening contract becomes more attractive to the manufacturer; see Figure 4(b) that shows the screening contract dominating EMC for large values of σ.[7]

[7] In Figure 4(b) it is also observed that the screening contract dominates EMC for very small σ. This happens because $\theta^M = \theta^S = 0$ in that region; collaboration is too costly under both contracts (see Figure 4(a)). Since the

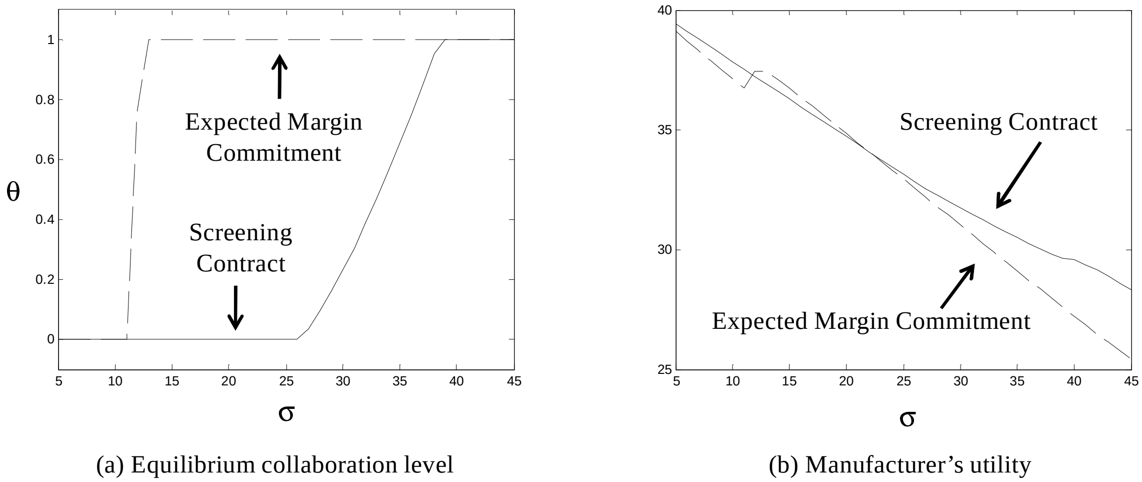

Figure 4: In this example, $\delta = 0.95$. Other parameter values are the same as those in Figure 3.

8 Extensions

8.1 Collaboration in a Make-to-Order Production System

Thus far, we have based our analysis on the assumption that production lead time is long and therefore the manufacturer has to procure the component well before demand is realized. While this assumption is quite reasonable for many product categories that we used as a motivation, there are situations where the manufacturer is able to operate in a make-to-order production system. This is possible when the total lead time of productions and assemblies is relatively short and the customers' willingness-to-wait is large. The benefit of having such a system is clear: since the manufacturer does not have to position the products before demands arrive, supply matches demand perfectly, and the inventory risk is eliminated. On the other hand, what is the impact of having a make-to-order system on collaborative cost reduction? The next proposition answers this.

Proposition 7 *(Collaboration in a make-to-order production system) The optimal collaboration level is $\theta = 1$ if the supply chain is integrated. In a decentralized supply chain, the manufacturer and the supplier choose $e_m = 0$ and $e_s = 0$ under both non-commitment and EMC, leading to the equilibrium collaboration level $\theta = 0$. Furthermore, the manufacturer is indifferent between the two*

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screening contract enables the manufacturer to extract the supplier's surplus more effectively, given the same value of θ, the manufacturer's profit is higher when she uses the screening contract.

contract choices.

Notice that, in the proposition, we used the term "non-commitment" in place of "screening contract". This is because the screening mechanism cannot be implemented when there is no demand-supply mismatch; since the order quantity is determined after demand is realized, it is optimal to set $q = D$ regardless of the supplier type, and hence, the optimal price-quantity pairs cannot be tailored for each supplier type.

Given our observation from the previous section that θ^S increases with demand variability (Proposition 6 and the subsequent discussions), it is not unexpected that $\theta = 0$ emerges in equilibrium under non-commitment, as the supply exactly matches the demand in a make-to-order production system and this is equivalent to having zero variability in a make-to-stock system. However, it is not immediately clear why the same should be true under EMC; as we found earlier, EMC is effective in incentivizing the supplier to exert a collaborative effort, often leading to $\theta = 1$. This surprising result in fact arises because the make-to-order system acts as a quantity commitment. With the expected margin fixed to a constant under EMC and the expected volume also equal to a constant $E[q] = E[D] = \mu$, exerting a collaborative effort only incurs the effort disutility without affecting the supplier's expected profit, and hence, it is optimal for him to set $e_s = 0$. Consequently, $\theta = 0$ regardless of the value of e_m, and as a response, the manufacturer also sets $e_m = 0$. In addition, as the proposition states, the distinction between non-commitment and EMC disappears as the screening mechanism cannot be implemented and both lead to $\theta = 0$.

This finding suggests that an ex-post improvement of supply chain efficiency may bring an unintended consequence: it hinders ex-ante collaboration. One of the main goals of supply chain management is mitigating the impact of demand-supply mismatch, which can be achieved by investing in technologies and resources to improve forecasting accuracy and reducing production lead times. Transforming a supply chain into a make-to-order system is a consummate outcome of such efforts, and the literature touts many benefits associated with it. Our analysis identifies one caveat of these arguments, namely, that the supply chain members' incentives to collaborate are lowered when they anticipate that the supply chain will operate in the most efficient manner, i.e., when demand-supply mismatch is eliminated. Interestingly, the supply chain members end up in this

Prisoner's Dilemma-like situation regardless of procurement contract options.[8] Although better matching between supply and demand through enhanced forecasting and lead time reduction will contribute to a profit increase, it comes at the expense of discouraging the supply chain members from exerting collaborative efforts during product development. As a result, they may not be able to receive the full benefit of efficiency improvement.

8.2 Retail Pricing

As we mentioned in Section 3.1, it is a common practice that cost reduction efforts are made after a target retail price is set. However, depending on the presence of competing products in the market and consumers' sensitivity to price, the manufacturer may consider optimally choosing the retail price r after the cost reduction initiative during product development is complete. In this subsection we relax the fixed retail price assumption and investigate the impact of having an endogenously determined price on the collaboration level.

To this end, assume a linear additive demand curve $D = \beta_0 - \beta_1 r + \epsilon$, where ϵ is the stochastic part of the demand that is independent of the retail price r. We modify the sequence of events such that the manufacturer determines the optimal r at the start of Stage 2, i.e., immediately after collaboration is complete. As is well-known in the OM literature (e.g., Petruzzi and Dada 1999), the problem of simultaneous price and quantity decisions in the newsvendor framework does not lend itself to an amenable analysis. Hence, we conduct numerical experiments to gain insights.

We focus on the role of consumers' price sensitivity, represented by the parameter β_1; the larger β_1, the higher the sensitivity. An example illustrated in Figure A.1 (in Appendix A) reveals that the collaboration level θ tends to increase with β_1, especially under the screening contract. The reason behind this result is qualitatively similar to that of the demand variability result that we discussed in Section 7. With an increasing price sensitivity of the consumers, the manufacturer has to lower the price, which in turn leads to smaller production quantity (as the underage cost becomes smaller). The net outcome is a lower expected profit, and to compensate for the loss, the manufacturer structures the screening contract so that it is palatable for the supplier to collaborate more and create a larger surplus to extract from. In addition, as supported by the example, EMC

[8] It can be shown that other forms of commitments that were discussed in Section 6.1, i.e., price commitment, quantity commitment, and price-quantity commtiment, also fail to result in $\theta > 0$.

tends to promote collaboration better than the screening contract does. Therefore, we conclude that the insights obtained from the earlier analysis remain quite robust even under endogenous retail pricing, which enriches the model and adds another dimension to our discussion.

9 Conclusion

In this paper we study how supply chain members' incentives to collaborate during product development is impacted by information asymmetry and procurement contracting strategies. Despite a high level of interests among the practitioners of supplier management and strategic sourcing, the topic of collaboration has received relatively little attention in the OM literature. We aim to fill this gap by focusing on one of the most important aspects of collaboration, namely, firms' desire to balance the benefit of collaboration with the need to protect their proprietary information. To this end, we develop a game-theoretic model that captures the incentive dynamics that arise when a manufacturer and a supplier exert collaborative efforts to reduce the unit cost of a critical component during product development, but at the same time, the supplier is unwilling to fully share his private cost information. We find that the manufacturer's choice of a procurement contracting strategy critically impacts the supplier's and the manufacturer's incentives to collaborate. In addition, we identify demand variability as one of the important environmental variables that influence the collaborative outcome.

We start our analysis by considering a screening contract, which is known to be the optimal mechanism to employ when an agent (the supplier) possesses private information. A screening contract may appeal to the manufacturer since it is effective in extracting a large fraction of the supplier's surplus ex-post. However, knowing that the manufacturer's ability to do so is bounded by uncertainty in the unit cost, the supplier is reluctant to contribute a large amount of effort to the joint cost reduction initiative since collaboration leads to a better estimate of the cost range, thereby eroding his informational advantage. In other words, the supplier's desire to protect private information about his cost structure lowers his incentive to collaborate and reduces the effectiveness of the screening contract.

To resolve this hold-up problem and convince the supplier to collaborate, the manufacturer may commit to a contract term before collaboration starts. However, not all commitments work. In particular, the frequently-cited price commitment fails to incentivize either party to collaborate. This happens because, while price commitment does resolve the hold-up problem for the supplier, it leaves the manufacturer with no share of the cost reduction benefit; since the manufacturer does not collaborate, neither does the supplier, as no synergy is created without the efforts by both parties. As an alternative, we propose Expected Margin Commitment (EMC), under which the supplier is guaranteed to earn a fixed margin above the expected unit cost. Our analysis shows that this form of commitment is indeed quite effective in promoting collaboration, and it dominates the screening contract approach in many situations, especially when: (a) a large degree of cost reduction can be attained through collaboration and/or (b) demand variability is relatively small.

As an extension of the model, we also investigate the nature of collaboration incentives in a make-to-order production system. The make-to-order system represents a high level of production efficiency and is achieved by forecasting accuracy improvement and lead time reduction. Surprisingly, such ex-post efficiency improvement is tempered by the ex-ante inefficiency: neither party is willing to collaborate on cost reduction during product development, and hence, production has to proceed with a high unit cost. EMC and other commitments do not alleviate this problem, unlike in a make-to-stock system. Therefore, we conclude that ex-post production efficiency improvement may not represent the full efficiency gain when it depends on the outcome of the ex-ante collaborative efforts. We also find that the main insights remain intact even if the manufacturer were allowed to optimally determine the retail price after collaborative cost reduction is completed.

The insights obtained from our analysis are to be understood in the context the model assumptions. Relaxing some of these assumptions and including other real-world considerations into the model will undoubtedly enrich the managerial insights and present an opportunity to test the robustness of our findings. For example, in this paper we focus on unit cost reduction as the outcome of collaboration, based on many industry reports that identifies cost reduction as the most important reason that the firms establish collaborative relationships. Of course, there are other benefits of collaboration. They include, among others, reduction of product time-to-market (Bhaskaran and Krishnan 2009) and improvement of supplier reliability (Wang et al. 2009). Although this paper focuses on one aspect, a more complete picture of the incentive dynamics where collaboration plays a key role will emerge once the impacts of these and other factors are better understood in future researches.

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Appendix

A Figures

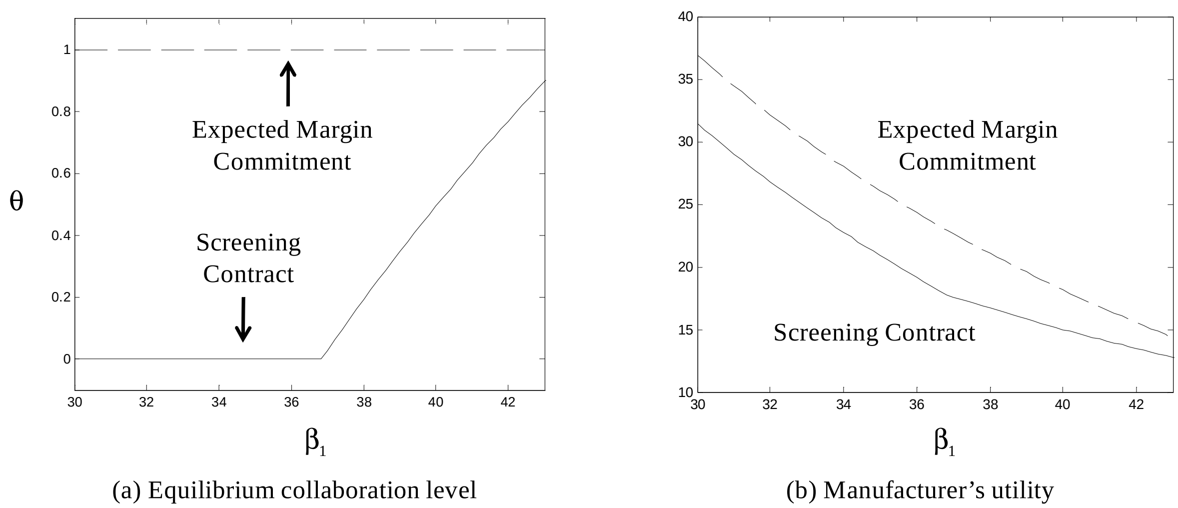

Figure A.1: Equilibrium collaboration levels and the manufacturer's utilities with retail pricing. A linear addditive demand curve $D = \beta_0 - \beta_1 r + \epsilon$ is assumed. In this example, ϵ is assumed to be normally distributed with $\mu = 50$ and $\sigma = 30$, along with $\beta_0 = 50$. The rest of the parameters have the same values as those of Figure 3 (except that r is a endogenously determined).

B Auxiliary Results

Lemma B.1 *The following properties hold for* $q^*(z|\theta) = F^{-1}\left(1 - \frac{1}{r}\left[\underline{c} + 2\Delta_0\left(1-(1-\delta)\theta\right)z\right]\right)$ *defined in Lemma 1.*

(i) $\frac{\partial}{\partial\theta} q^*(z|\theta) > 0$, $\forall z \in (0, 1]$,

(ii) $\frac{\partial}{\partial\theta} \int_0^1 zq^*(z|\theta)dz = \frac{1-\delta}{1-(1-\delta)\theta}\left(-q^*(1|\theta) + 2\int_0^1 zq^*(z|\theta)dz\right)$,

(iii) $\int_0^1 zq^*(z|\theta)dz > \frac{1}{2}q^*(1|\theta)$.

Proof. (i) is verified by inspecting the expression of $q^*(z|\theta)$. To prove (ii), note that

$$\frac{\partial q^*(z|\theta)}{\partial\theta} = -\frac{1-\delta}{1-(1-\delta)\theta} z \frac{\partial q^*(z|\theta)}{\partial z}.$$

Using this and by Leibniz's rule and integration by parts,

$$\begin{aligned}
\frac{\partial}{\partial\theta}\int_0^1 zq^*(z|\theta)dz &= \int_0^1 z\frac{\partial q^*(z|\theta)}{\partial\theta}dz = -\frac{1-\delta}{1-(1-\delta)\theta}\int_0^1 z^2\frac{\partial q^*(z|\theta)}{\partial z}dz \\
&= -\frac{1-\delta}{1-(1-\delta)\theta}\left(z^2 q^*(z|\theta)\big|_{z=0}^{z=1} - 2\int_0^1 zq^*(z|\theta)dz\right) \\
&= \frac{1-\delta}{1-(1-\delta)\theta}\left(-q^*(1|\theta) + 2\int_0^1 zq^*(z|\theta)dz\right).
\end{aligned}$$

(iii) immediately follows by combining (i) and (ii). ■

Lemma B.2 *Let $\psi(\theta) \equiv -q^*(1|\theta) + \int_0^1 zq^*(z|\theta)dz$, where $q^*(z|\theta)$ is defined in Lemma 1. The root of $\psi(\theta)$, denoted as $\widehat{\theta}$, exists in the interval $\left(-\frac{r-\underline{c}-2\Delta_0}{2\Delta_0(1-\delta)}, \frac{1}{1-\delta}\right)$ and is unique. Moreover, $\psi(\theta) > 0$ for $\theta < \widehat{\theta}$ and $\psi(\theta) < 0$ for $\theta > \widehat{\theta}$.*

Proof. Inverting $q^*(z|\theta) = F^{-1}\left(1 - \frac{1}{r}\left[\underline{c} + 2\Delta_0\left(1-(1-\delta)\theta\right)z\right]\right)$ yields

$$z = \frac{r\overline{F}(q) - \underline{c}}{2\Delta_0\left(1-(1-\delta)\theta\right)} \text{ and } dz = \frac{-rf(q)}{2\Delta_0\left(1-(1-\delta)\theta\right)}dq.$$

Then

$$\int_0^1 zq^*(z|\theta)dz = \frac{r^2}{4\Delta_0^2\left(1-(1-\delta)\theta\right)^2}\int_{q^*(1|\theta)}^{q^*(0|\theta)}\left(\overline{F}(q) - \frac{\underline{c}}{r}\right)qf(q)dq.$$

Noting that $q^*(0|\theta) = F^{-1}\left(1-\underline{c}/r\right)$ and $2\Delta_0\left(1-(1-\delta)\theta\right) = r\overline{F}\left(q^*(1|\theta)\right) - \underline{c}$, we can rewrite this relation with the change of variables $q \to x$ and $q^*(1|\theta) \to y$ as

$$\int_0^1 zq^*(z|\theta)dz = \frac{1}{\left(\overline{F}(y) - \underline{c}/r\right)^2}\int_y^{F^{-1}(1-\underline{c}/r)}\left(\overline{F}(x) - \frac{\underline{c}}{r}\right)xf(x)dx.$$

Then $\psi(\theta)$ can be rewritten as $\widetilde{\psi}(y)/\left(\overline{F}(y) - \underline{c}/r\right)^2$, where

$$\widetilde{\psi}(y) \equiv -y\left(\overline{F}(y) - \frac{\underline{c}}{r}\right)^2 + \int_y^{F^{-1}(1-\underline{c}/r)}\left(\overline{F}(x) - \frac{\underline{c}}{r}\right)xf(x)dx. \tag{4}$$

Hence, $\psi(\theta)$ and $\widetilde{\psi}(y)$ have the same sign, and therefore, our goal of showing that there exists $\widehat{\theta}$ such that $\psi(\theta) > 0$ for $\theta < \widehat{\theta}$ and $\psi(\theta) < 0$ for $\theta > \widehat{\theta}$ is achieved by showing that there exists $\widehat{y}$ such that $\widetilde{\psi}(y) > 0$ for $y < \widehat{y}$ and $\widetilde{\psi}(y) < 0$ for $y > \widehat{y}$. Note that the lower and upper bounds of y that are defined for $\widetilde{\psi}(y)$, i.e., 0 and $F^{-1}(1-\underline{c}/r)$, correspond to $\theta = -\frac{r-\underline{c}-2\Delta_0}{2\Delta_0(1-\delta)}$ and $\theta = \frac{1}{1-\delta}$, which are obtained from the relation $y = q^*(1|\theta) = F^{-1}\left(1-\frac{1}{r}\left[\underline{c}+2\Delta_0\left(1-(1-\delta)\theta\right)\right]\right)$. Taking a derivative, $\widetilde{\psi}'(y) = -\eta_1(y)\eta_2(y)$, where $\eta_1(y) \equiv \overline{F}(y) - yf(y) - \underline{c}/r$ and $\eta_2(y) \equiv \overline{F}(y) - \underline{c}/r$. Let y_1 and y_2 be the roots of $\eta_1(y)$ and $\eta_2(y)$, respectively. Note that $y_2 = F^{-1}(1-\underline{c}/r)$ is equal to the upper bound of y. Since F has the IGFR property, $\overline{F}(y) - yf(y) < \overline{F}(y)$ that appears in $\eta_1(y)$ is decreasing and, as a result, $y_1 < y_2$, if y_1 exists. The existence is confirmed by continuity of $\eta_1(y)$ along with $\eta_1(0) = 1-\underline{c}/r > 0$ and $\lim_{y\to y_2}\eta_1(y) = -y_2 f(y_2) < 0$. Moreover, y_1 is unique, as proved in Theorem 1 of Lariviere and Porteus (2001). We therefore conclude that there is a unique $y_1 < y_2$ such that $\eta_1(y) > 0$ for $0 \le y < y_1$, $\eta_1(y_1) = 0$, and $\eta_1(y) < 0$ for $y_1 < y \le y_2$. This in turn implies $\widetilde{\psi}'(y) > 0$ for $y_1 < y < y_2$. In addition, observe that: (i) $\widetilde{\psi}(0) = \int_0^{y_2}(\overline{F}(x) - \underline{c}/r)xf(x)dx > 0$, (ii) $\widetilde{\psi}'(0) = -(1-\underline{c}/r)^2 < 0$, (iii) $\lim_{y\to y_2}\widetilde{\psi}(y) = 0$, and (iv) $\lim'_{y\to y_2}\widetilde{\psi}(y) = 0$. Summarizing, $\widetilde{\psi}(y)$ initially (at $y=0$) starts from a positive value with a negative slope, flattens out at y_1, increases as y goes from y_1 to y_2, converging to zero. This implies that there is a unique $\widehat{y} \in (0, y_1)$ such that $\widetilde{\psi}(y) > 0$ for $0 \le y < \widehat{y}$, $\widetilde{\psi}(\widehat{y}) = 0$, and $\widetilde{\psi}(y) < 0$ for $y > \widehat{y}$, the result we set out to prove. ■

C Proofs of the Main Results

Proof of Proposition 1. Note that the restriction $0 \le \theta = e_m^\alpha e_s^{1-\alpha} \le 1$ limits the range of e_m from 0 to $\overline{e}_m \equiv e_s^{-\frac{1-\alpha}{\alpha}}$ and, similarly, e_s may vary between 0 and $\overline{e}_s \equiv e_m^{-\frac{\alpha}{1-\alpha}}$. Both upper bounds are reached if and only if $\theta = 1$. For a fixed θ and a realized value of z, the firm optimally chooses the quantity $q(z|\theta) = F^{-1}\left(1-\frac{1}{r}G^{-1}(z|\theta)\right) = F^{-1}\left(1-\frac{1}{r}\left(\underline{c}+\Delta_0\left(1-(1-\delta)\theta\right)z\right)\right)$, where we used the relation (1). Substituting this, the objective function in (B) becomes $U(e_m, e_s) = r\int_0^1 J(q(z|\theta))dz - k_m e_m - k_s e_s$. Differentiating this with respect to e_m and e_s yields

$$\begin{aligned}\frac{\partial U}{\partial e_m} &= \Delta_0(1-\delta)\left(\int_0^1 zq(z|\theta)dz\right)\alpha\left(\frac{e_s}{e_m}\right)^{1-\alpha} - k_m,\\ \frac{\partial U}{\partial e_s} &= \Delta_0(1-\delta)\left(\int_0^1 zq(z|\theta)dz\right)(1-\alpha)\left(\frac{e_m}{e_s}\right)^{\alpha} - k_s.\end{aligned}$$

Consider $\frac{\partial U}{\partial e_m}$. If $e_s = 0$, it is optimal to choose $e_m = 0$ since $\frac{\partial U}{\partial e_m} = -k_m < 0$ for all $e_m \ge 0$. If $e_s > 0$, on the other hand, $\lim_{e_m\to 0}\frac{\partial U}{\partial e_m} = \infty$, implying that the maximum occurs either at an interior point that satisfies the first-order condition $\frac{\partial U}{\partial e_m} = 0$ or at the corner, i.e., $e_m = \overline{e}_m$. A similar analysis with respect to e_s shows that the maximum occurs either at an interior point that satisfies $\frac{\partial U}{\partial e_s} = 0$ or at $e_s = \overline{e}_s$ as long as $e_m > 0$. Otherwise, $e_s = 0$. Hence, possible optimal outcomes are characterized by: (i) $e_m = e_s = \theta = 0$, (ii) $\frac{\partial U}{\partial e_m} = 0$ and $\frac{\partial U}{\partial e_s} = 0$ with $0 < \theta \leq 1$, (iii) $\left.\frac{\partial U}{\partial e_m}\right|_{e_s=\overline{e}_s} = 0$ and $\left.\frac{\partial U}{\partial e_s}\right|_{e_s=\overline{e}_s} > 0$ with $\theta = 1$, (iv) $\left.\frac{\partial U}{\partial e_s}\right|_{e_m=\overline{e}_m} = 0$ and $\left.\frac{\partial U}{\partial e_m}\right|_{e_m=\overline{e}_m} > 0$ with $\theta = 1$. We show first that (i) is never optimal and then among the rest, (ii) with $\theta = 1$ dominates (iii) and (iv). Consider (ii). Combining the first-order conditions $\frac{\partial U}{\partial e_m} = 0$ and $\frac{\partial U}{\partial e_s} = 0$ with $\theta = e_m^{\alpha} e_s^{1-\alpha}$ allows us to rewrite the firm's utility as a function of θ: $U(\theta) = r \int_0^1 J(q(z|\theta))dz - K\theta$. Differentiating this, $U'(\theta) = \Delta_0(1-\delta) \int_0^1 zq(z|\theta)dz - K$ and $U''(\theta) = \Delta_0(1-\delta) \int_0^1 z\frac{\partial q(z|\theta)}{\partial \theta}dz > 0$, where we used Leibniz's rule. Since $U(\theta)$ is convex and $U(0) < U(1)$ according to (2), it is optimal to choose $\theta = 1$. Hence, (i) is eliminated. Since $\theta = 1$ is optimal, using the relation $1 = e_m^{\alpha} e_s^{1-\alpha}$, we can rewrite the firm's utility as a function of e_s only: $U(\overline{e}_m, e_s) = r \int_0^1 J(q(z|1))dz - k_m e_s^{-\frac{1-\alpha}{\alpha}} - k_s e_s$. Therefore, maximizing U with the constraint $\theta = 1$ is equivalent to finding e_s that minimizes the total effort cost $k_m e_s^{-\frac{1-\alpha}{\alpha}} + k_s e_s$. The solution is $e_s^* = \left(\frac{k_m}{\alpha}\frac{1-\alpha}{k_s}\right)^{\alpha}$. Substituting this in $e_m = \overline{e}_m = e_s^{-\frac{1-\alpha}{\alpha}}$ yields $e_m^* = \left(\frac{\alpha}{k_m}\frac{k_s}{1-\alpha}\right)^{1-\alpha}$. We now show that e_m^* and e_s^* are obtained from the first-order conditions specified in (ii). From $\frac{\partial U}{\partial e_m} = 0$ and $\frac{\partial U}{\partial e_s} = 0$ with $\theta = 1$, we get $e_m = \Delta_0 (1-\delta) \frac{\alpha}{k_m} \int_0^1 zq(z|1)dz$ and $e_s = \Delta_0 (1-\delta) \frac{1-\alpha}{k_s} \int_0^1 zq(z|1)dz$. Substituting them in $1 = e_m^{\alpha} e_s^{1-\alpha}$ yields $\Delta_0 (1-\delta) \int_0^1 zq(z|1) = K$, and therefore, $e_m = \frac{\alpha}{k_m}K = e_m^*$ and $e_s = \frac{1-\alpha}{k_s}K = e_s^*$. This confirms that the optimal values e_m^* are e_s^* result from the first-order conditions $\frac{\partial U}{\partial e_m} = 0$ and $\frac{\partial U}{\partial e_s} = 0$ with $\theta = 1$, thereby eliminating (iii) and (iv) as possible optimal outcomes. ■

Proof of Lemma 1. The proof is analogous to the ones found in the analyses of the standard adverse selection models. See Ha (2001) and Bolton and Dewatripont (2005). The expressions in the lemma are derived based on Assumption 1. ■

Proof of Proposition 2. Note that the restriction $0 \leq \theta = e_m^{\alpha} e_s^{1-\alpha} \leq 1$ limits the range of e_m from 0 to $\overline{e}_m \equiv e_s^{-\frac{1-\alpha}{\alpha}}$ and, similarly, e_s from 0 to $\overline{e}_s \equiv e_m^{-\frac{\alpha}{1-\alpha}}$. Both upper bounds are reached if and only if $\theta = 1$. Differentiating the manufacturer's and the supplier's utilities $U_m(e_m|e_s) =$

$r\int_0^1 J(q^*(z|\theta))dz - k_m e_m$ and $U_s(e_s|e_m) = \Delta_0 (1-(1-\delta)\theta)\int_0^1 zq^*(z|\theta)dz - k_s e_s$,

$$\begin{aligned} \frac{\partial U_m}{\partial e_m} &= 2\Delta_0(1-\delta)\alpha\left(\frac{e_s}{e_m}\right)^{1-\alpha}[q^*(1|\theta)+\psi(\theta)] - k_m, \\ \frac{\partial U_s}{\partial e_s} &= \Delta_0(1-\delta)(1-\alpha)\left(\frac{e_m}{e_s}\right)^{\alpha}\psi(\theta) - k_s, \end{aligned}$$

where we used part (ii) of Lemma B.1 in the second equation. Let $\widehat{\theta}$ be the root of $\psi(\theta)$. We proved in Lemma B.2 that $\psi(\theta) > 0$ for $\theta < \widehat{\theta}$ and $\psi(\theta) < 0$ for $\theta > \widehat{\theta}$. Suppose $\widehat{\theta} \le 0$. Then $\psi(\theta) \le 0$ for all $\theta \in [0,1]$. From the expression above, we see that this implies $\frac{\partial U_s}{\partial e_s} < 0$ for all $e_s \in [0, \overline{e}_s]$, and therefore, the supplier chooses $e_s = 0$. This in turn implies $\frac{\partial U_m}{\partial e_m} = -k_m < 0$ for all $e_m \in [0, \overline{e}_m]$, and therefore, the manufacturer chooses $e_m = 0$. Hence, $e_m = e_s = \theta = 0$ is the equilibrium outcome if $\psi(\theta) \le 0$, and therefore $\Psi(\theta) \le 0$, for all $\theta \in [0,1]$. This is consistent with the statement in the proposition for the case $\Psi(\theta) \le K$. Next, suppose $0 < \widehat{\theta} < 1$. Then, according to Lemma B.2, $\psi(\theta) \ge 0$ for $\theta \in [0, \widehat{\theta}]$ and $\psi(\theta) < 0$ for $\theta \in (\widehat{\theta}, 1]$. Let $\widehat{e}_m \equiv \left(\widehat{\theta} e_s^{-(1-\alpha)}\right)^{\frac{1}{\alpha}} < \overline{e}_m$ and $\widehat{e}_s \equiv \left(\widehat{\theta} e_m^{-\alpha}\right)^{\frac{1}{1-\alpha}} < \overline{e}_s$. In the interval $[0, \widehat{\theta}]$, e_m varies between 0 and $\widehat{e}_m$ while e_s varies between 0 and $\widehat{e}_s$. Similarly, $e_m \in (\widehat{e}_m, \overline{e}_m]$ and $e_s \in (\widehat{e}_s, \overline{e}_s]$ in the interval $(\widehat{\theta}, 1]$. Consider $\theta \in (\widehat{\theta}, 1]$. Since $\psi(\theta) < 0$ in this interval, $\frac{\partial U_s}{\partial e_s} < 0$, which implies that the optimal value of e_s does not exist in $(\widehat{e}_s, \overline{e}_s]$; it has to be in $[0, \widehat{e}_s]$. In other words, an equilibrium, if it exists, should result in $\theta \in [0, \widehat{\theta}]$. Therefore, a search for an equilibrium in $\theta \in [0,1]$ is reduced to a search in $\theta \in [0, \widehat{\theta}]$, in which $\psi(\theta) \ge 0$ and hence $\Psi(\theta) \ge 0$. Define $a \equiv \left(\Delta_0(1-\delta)\psi(\theta)\frac{1-\alpha}{k_s}\right)^{\frac{1}{\alpha}}$ and $b \equiv \left(\frac{1}{2\Delta_0(1-\delta)}\frac{1}{q^*(1|\theta)+\psi(\theta)}\frac{k_m}{\alpha}\right)^{\frac{1}{1-\alpha}}$. We consider the three cases stated in the proposition in turn.

(i) Suppose $\Psi(\theta) < K$ for all $\theta \in [0,1]$. Then $\Psi(\theta) < K$ for all $\theta \in [0, \widehat{\theta}]$. This inequality can be rewritten as $a < b$. From the expressions of $\frac{\partial U_m}{\partial e_m}$ and $\frac{\partial U_s}{\partial e_s}$ we derived above, we find that (a) $\frac{\partial U_m}{\partial e_m} < 0$ and $\frac{\partial U_s}{\partial e_s} \ge 0$ if $\frac{e_s}{e_m} \le a$, (b) $\frac{\partial U_m}{\partial e_m} < 0$ and $\frac{\partial U_s}{\partial e_s} < 0$ if $a < \frac{e_s}{e_m} < b$, (c) $\frac{\partial U_m}{\partial e_m} \ge 0$ and $\frac{\partial U_s}{\partial e_s} < 0$ if $\frac{e_s}{e_m} \ge b$. In each defined interval of $\frac{e_s}{e_m}$, it is optimal for either the manufacturer or the supplier to decrease his/her effort as much as possible since his/her utility is monotonically decreasing. Since we encompass all possible range of $\frac{e_s}{e_m}$ defined under $e_m \in [0, \widehat{e}_m]$ and $e_s \in [0, \widehat{e}_s]$ (which are together equivalent to $\theta \in [0, \widehat{\theta}]$), it implies that one of the two parties chooses a zero effort at the optimum. This in turn implies that the other party chooses zero effort as well, since $\frac{\partial U_m}{\partial e_m} < 0$ for all $e_m \in [0, \widehat{e}_m]$ if $e_s = 0$ and $\frac{\partial U_s}{\partial e_s} < 0$

for all $e_s \in [0, \widehat{e}_s]$ if $e_m = 0$. Hence, $e_m = e_s = 0$ in equilibrium, and as a result, $\theta = 0$ in equilibrium if $\Psi(\theta) < K$ for all $\theta \in [0, \widehat{\theta}]$.

(ii) The case $\Psi(\theta) > K$ for all $\theta \in [0, 1]$ is not permitted under the assumption $0 < \widehat{\theta} < 1$, since $\psi(\theta) < 0$ and hence $\Psi(\theta) < 0$ for $\theta \in (\widehat{\theta}, 1]$. We consider this case below when we assume $\widehat{\theta} \geq 1$.

(iii) The only remaining possibility is $\min_{0\leq\theta\leq\widehat{\theta}} \{\Psi(\theta)\} \leq K \leq \max_{0\leq\theta\leq\widehat{\theta}} \{\Psi(\theta)\}$. Since $\Psi(\theta)$ is continuous in $\theta \in [0, \widehat{\theta}]$, the solution of $\Psi(\theta) = K$ exists. The same equation is obtained by combining the first-order conditions $\frac{\partial U_m}{\partial e_m} = 0$ and $\frac{\partial U_s}{\partial e_s} = 0$ with $\theta = e_m^{\alpha} e_s^{1-\alpha}$. This system of three equations also yield the expressions $e_m(\theta) = 2\Delta_0 (1-\delta) \frac{\alpha}{k_m} \theta \left[q^*(1|\theta) + \psi(\theta)\right]$ and $e_s(\theta) = \Delta_0 (1-\delta) \frac{1-\alpha}{k_s} \theta\psi(\theta)$, from which the equilibrium effort levels are identified once the optimal θ is found from the optimality condition $\Psi(\theta) = K$. Since the solution exists, the equilibrium also exists.

Finally, suppose $\widehat{\theta} \geq 1$. Then by Lemma B.2, $\psi(\theta) \geq 0$ for all $\theta \in [0, 1]$. We consider the three cases stated in the proposition as we did for $0 < \widehat{\theta} < 1$. Cases (i) and (iii) proceed similarly as above, with $\widehat{e}_m \to \overline{e}_s$, $\widehat{e}_s \to \overline{e}_s$, and $\widehat{\theta} \to 1$. Hence, we only consider case (ii):

(ii) Suppose $\Psi(\theta) > K$ for all $\theta \in [0, 1]$. This can be rewritten as $b < a$. Then (a) $\frac{\partial U_m}{\partial e_m} \leq 0$ and $\frac{\partial U_s}{\partial e_s} > 0$ if $\frac{e_s}{e_m} \leq b$, (b) $\frac{\partial U_m}{\partial e_m} > 0$ and $\frac{\partial U_s}{\partial e_s} > 0$ if $b < \frac{e_s}{e_m} < a$, and (c) $\frac{\partial U_m}{\partial e_m} > 0$ and $\frac{\partial U_s}{\partial e_s} \leq 0$ if $\frac{e_s}{e_m} \geq a$. In each case it is optimal for either party to increase his/her effort as much as possible since his/her utility is monotonically increasing. This leads to the corner solution, i.e., either $e_m = \overline{e}_m$ or $e_s = \overline{e}_s$, at which $\theta = 1$. From the inequalities in (a)-(c) it is clear that the equilibrium is reached when the utility of the other party is maximized, i.e., when either $\left.\frac{\partial U_m}{\partial e_m}\right|_{e_s=\overline{e}_s} = 0$ or $\left.\frac{\partial U_s}{\partial e_s}\right|_{e_m=\overline{e}_m} = 0$. If $e_m = \overline{e}_m$, then $\left.\frac{\partial U_s}{\partial e_s}\right|_{e_m=\overline{e}_m} = 0$, which is equivalent to $\left.\frac{e_s}{e_m}\right|_{e_m=\overline{e}_m} = a$. From this we get $e_s = \Delta_0 (1-\delta) \frac{1-\alpha}{k_s} \psi(1)$ and $e_m = \overline{e}_m = e_s^{-\frac{1-\alpha}{\alpha}} = \left(\Delta_0 (1-\delta) \frac{1-\alpha}{k_s} \psi(1)\right)^{-\frac{1-\alpha}{\alpha}}$. Similarly, if $e_s = \overline{e}_s$, $e_m = 2\Delta_0 (1-\delta) \frac{\alpha}{k_m} \left[q^*(1|1) + \psi(1)\right]$ and $e_s = \overline{e}_s = e_m^{-\frac{\alpha}{1-\alpha}} = \left(2\Delta_0 (1-\delta) \frac{\alpha}{k_m} \left[q^*(1|1) + \psi(1)\right]\right)^{-\frac{\alpha}{1-\alpha}}$.

We have exhausted all possibilities, and the conclusion is summarized in the proposition. ■

Proof of Corollary 1. For expositional clarity we only consider the case in which the optimality condition $\Psi(\theta) = K$ in Proposition 2 has a solution in $\theta \in [0,1]$. The statements in the corollary for the other cases can be verified but we omit it here. In the limit $K \to 0$, $\Psi(\theta) = K$ is reduced to $\psi(\theta) = 0$. In the proof of Lemma B.2 we showed that $\psi(\theta) = 0$ can be rewritten as $\widetilde{\psi}(y) = 0$, which as a unique solution $\widehat{y}$, with the change of variables $y = F^{-1}\left(1 - \frac{1}{r}\left[\underline{c} + 2\Delta_0\left(1-(1-\delta)\theta\right)\right]\right)$, or equivalently, $\theta = \frac{\underline{c}+2\Delta_0 - r\overline{F}(y)}{2\Delta_0(1-\delta)}$. These are the expressions found in the corollary. Moreover, with the same change of variables, the optimality condition $\Psi(\theta) = K$ can be written as

$$\widetilde{\Psi}(y) \equiv \frac{\Delta_0\left(1-\delta\right)\left(2y\left(\overline{F}(y) - \underline{c}/r\right)^2 + 2\widetilde{\psi}(y)\right)^{\alpha}\widetilde{\psi}(y)^{1-\alpha}}{\left(\overline{F}(y) - \underline{c}/r\right)^2} = K,$$

given that $\widetilde{\psi}(y) > 0$, which is a necessary condition for having a solution of this equation since $\widetilde{\Psi}(y) \le 0 < K$ otherwise. In Lemma B.2 we showed that $\widetilde{\psi}(y) > 0$ if and only if $0 \le y < \widehat{y}$. Hence, the solution of $\widetilde{\Psi}(y) = K$ should satisfy $y < \widehat{y}$, which in turn implies that the solution of $\Psi(\theta) = K$ satisfies $\theta < \widehat{\theta} = \frac{\underline{c}+2\Delta_0 - r\overline{F}(\widehat{y})}{2\Delta_0(1-\delta)}$ since $\psi(\theta)$ and $\widetilde{\psi}(y)$ have the same sign (as proved in the same lemma) and therefore so do $\Psi(\theta)$ and $\widetilde{\Psi}(y)$. ■

Proof of Proposition 3. From Proposition 2, we see that $\theta^S \in (0,1)$ is determined from the equation $\Psi(\theta) = K$, which implies $\psi(\theta^S) > 0$ since $K > 0$. Note that, from Proposition 1, $e_s^B = \left(\frac{k_m}{\alpha}\frac{1-\alpha}{k_s}\right)^{\alpha}$ and $\frac{e_s^B}{e_m^B} = \frac{k_m}{\alpha}\frac{1-\alpha}{k_s}$. It was shown in the proof of Proposition 2 that $e_m^S = 2\Delta_0\left(1-\delta\right)\frac{\alpha}{k_m}\theta^S\left[q^*(1|\theta^S) + \psi(\theta^S)\right]$ and $e_s^S = \Delta_0\left(1-\delta\right)\frac{1-\alpha}{k_s}\theta^S\psi(\theta^S)$ if $0 < \theta^S < 1$. Then

$$\begin{aligned} e_s^S &= \Delta_0\left(1-\delta\right)\frac{1-\alpha}{k_s}\theta^S\psi(\theta^S) < \Delta_0\left(1-\delta\right)\frac{1-\alpha}{k_s}\theta^S 2^{\alpha}\left[q^*(1|\theta^S) + \psi(\theta^S)\right]^{\alpha}\psi(\theta^S)^{1-\alpha} \\ &= \frac{1-\alpha}{k_s}\theta^S\Psi(\theta^S) = \theta^S\frac{1-\alpha}{k_s}K = \theta^S\left(\frac{k_m}{\alpha}\frac{1-\alpha}{k_s}\right)^{\alpha} = \theta^S e_s^B < e_s^B. \end{aligned}$$

Also,

$$\frac{e_s^S}{e_m^S} = \frac{1}{2}\left(\frac{k_m}{\alpha}\frac{1-\alpha}{k_s}\right)\frac{\psi(\theta^S)}{q^*(1|\theta^S) + \psi(\theta^S)} < \frac{1}{2}\left(\frac{k_m}{\alpha}\frac{1-\alpha}{k_s}\right) = \frac{1}{2}\frac{e_s^B}{e_m^B}.$$

■

Proof of Proposition 4.

(i) Under price commitment, the events unfold as follows: (1) the manufacturer commits to w, (2) the manufacturer and the supplier decide e_m and e_s simultaneously, and (3) the manufacturer offers q. In the last step, the manufacturer chooses $q(w) = F^{-1}\left(1 - \frac{w}{r}\right)$ to maximize her profit $rE[\min\{D, q\}] - wq$. Anticipating this, the supplier chooses e_s for a given value of e_m to maximize his utility $\int_0^1 (w - G^{-1}(z|\theta))q(w)dz - k_s e_s = \left(w - \underline{c} - \frac{\Delta_0}{2}\left(1 - (1-\delta)\theta\right)\right) q(w) - k_s e_s$. It is straightforward to show that this function is concave and is maximized at $e_s = \left(\frac{\Delta_0(1-\delta)}{2} \frac{1-\alpha}{k_s} q(w)\right)^{\frac{1}{\alpha}} e_m$. At the same time, the manufacturer chooses e_m to maximize her expected profit $rE[\min\{D, q(w)\}] - wq(w) - k_m e_m = rJ(q(w)) - k_m e_m$. The solution is $e_m = 0$, and therefore, $e_s = 0$ and $\theta = 0$ in equilibrium.

(ii) Under quantity commitment, the sequence of events is: (1) the manufacturer commits to the quantity q, (2) the manufacturer and the supplier decide the efforts e_m and e_s simultaneously, and (3) the manufacturer offers the price w. At the time of the price offer, the manufacturer faces the problem $\max_w rE[\min\{D, q\}] - wq$ subject to the participation constraint $(w - G^{-1}(z|\theta))q \geq 0$, $\forall z \in [0, 1]$. The solution is $w = G^{-1}(1|\theta) = \underline{c} + \Delta_0 \left(1 - (1-\delta)\theta\right)$, i.e., the manufacturer chooses a price that leaves zero profit to the supplier with the highest cost. Anticipating this pricing, the supplier chooses his effort e_s for a given value of e_m to maximize his utility $\int_0^1 (w - G^{-1}(z|\theta))qdz - k_s e_s = \frac{\Delta_0}{2}\left(1 - (1-\delta)\theta\right) q - k_s e_s$. This function is decreasing in e_s, and therefore, the supplier chooses $e_s = 0$. At the same time, the manufacturer chooses her effort e_m to maximize her utility $rE[\min\{D, q\}] - wq - k_m e_m = rE[\min\{D, q\}] - [\underline{c} + \Delta_0 \left(1 - (1-\delta)\theta\right)] q - k_m e_m$. It is straightforward to show that this function is concave and maximized at $e_m = \left(\Delta_0(1-\delta)\frac{\alpha}{k_m}\right)^{\frac{1}{1-\alpha}} e_s$. From this expression we see that it is optimal for the manufacturer to choose $e_m = 0$ since the supplier chooses $e_s = 0$, and as a result, $\theta = 0$.

(iii) Under price-quantity commitment, the manufacturer offers w and q, and then the manufacturer and the supplier decide e_m and e_s simultaneously. The supplier chooses e_s that maximizes his utility $\int_0^1 (w - G^{-1}(z|\theta))qdz - k_s e_s = \left(w - \underline{c} - \frac{\Delta_0}{2}\left(1 - (1-\delta)\theta\right)\right) q - k_s e_s$. The solution is $e_s = \left(\frac{\Delta_0}{2k_s}(1-\delta)(1-\alpha)q(w)\right)^{\frac{1}{\alpha}} e_m$. At the same time, the manufacturer chooses e_m to maximize her utility $rE[\min\{D, q\}] - wq - k_m e_m$. The solution is $e_m = 0$, and therefore, $e_s = 0$ and $\theta = 0$ in equilibrium.

$\blacksquare$

Proof of Proposition 5. Under the expected margin commitment, (1) the manufacturer commits to the margin v and the payment function $w(\theta) = v + \int_0^1 G^{-1}(z|\theta)\, dz = v + \underline{c} + \frac{\Delta_0}{2}(1-(1-\delta)\theta)$, (2) the manufacturer and the supplier decide e_m and e_s simultaneously to determine θ, and finally (3) the manufacturer offers the quantity q. In the last step, for a realized value of θ, the manufacturer chooses $q^\dagger(\theta) = F^{-1}\left(1 - \frac{w(\theta)}{r}\right)$ to maximize her expected Stage 2 profit $rE[\min\{D, q\}] - w(\theta)q$. Anticipating this, the manufacturer chooses e_m to maximize her Stage 1 utility $U_m(e_m|e_s) = rE[\min\{D, q^\dagger(\theta)\}] - w(\theta)q^\dagger(\theta) - k_m e_m = rJ(q^\dagger(\theta)) - k_m e_m$, while the supplier chooses e_s to maximize his Stage 1 utility $U_s(e_s|e_m) = \int_0^1 (w(\theta) - G^{-1}(z|\theta))q^\dagger(\theta) dz - k_s e_s = vq^\dagger(\theta) - k_s e_s$. Differentiating,

$$\begin{aligned}
\frac{\partial U_m}{\partial e_m} &= \frac{\Delta_0(1-\delta)}{2} q^\dagger(\theta)\alpha \left(\frac{e_s}{e_m}\right)^{1-\alpha} - k_m, \\
\frac{\partial U_s}{\partial e_s} &= \frac{v\Delta_0(1-\delta)}{2rf(q^\dagger(\theta))}(1-\alpha)\left(\frac{e_m}{e_s}\right)^{\alpha} - k_s.
\end{aligned}$$

The optimality condition $\Gamma(\theta) = K$ for θ is obtained by combining the first-order conditions $\frac{\partial U_m}{\partial e_m} = 0$ and $\frac{\partial U_s}{\partial e_s} = 0$ with $\theta = e_m^\alpha e_s^{1-\alpha}$ yields the optimality condition $\Gamma(\theta) = K$ for θ as well as the equilibrium efforts $e_m(\theta) = \frac{\Delta_0(1-\delta)}{2}\frac{\alpha}{k_m}\theta q^\dagger(\theta)$ and $e_s(\theta) = \frac{v\Delta_0(1-\delta)}{2rf(q^\dagger(\theta))}\frac{1-\alpha}{k_s}\theta$. The rest of the proof, including the cases $\Gamma(\theta) < K$ and $\Gamma(\theta) > K$, is similar to that of Proposition 2 and is omitted. ■

Proof of Proposition 6. For notational convenience, we drop the superscript S. Let Φ and ϕ be the cdf and the pdf of the standard normal distribution. Then, if $0 < \widehat{\theta} < 1$, $\widetilde{\psi}(\widehat{y}) = 0$ and $\widehat{\theta}$ defined in Corollary 1 can be written as

$$\begin{aligned}
\widetilde{\psi}(y) &= -\widehat{y}\left(\overline{\Phi}\left(\frac{\widehat{y}-\mu}{\sigma}\right) - \frac{\underline{c}}{r}\right)^2 + \int_{\frac{\widehat{y}-\mu}{\sigma}}^{\Phi^{-1}(1-\underline{c}/r)} \left(\overline{\Phi}(\zeta) - \frac{\underline{c}}{r}\right)(\mu+\sigma\zeta)\phi(\zeta)\, d\zeta = 0, && (5) \\
\widehat{\theta} &= \frac{\underline{c} + 2\Delta_0 - r\overline{\Phi}\left(\frac{\widehat{y}-\mu}{\sigma}\right)}{2\Delta_0(1-\delta)}, && (6)
\end{aligned}$$

where we have let $\zeta = \frac{x-\mu}{\sigma}$ in (5). Implicit differentiation of (5) with respect to σ yields

$$\begin{aligned} 0 &= -\left(\frac{\partial \widehat{y}}{\partial \sigma}\right)\left(\overline{\Phi}\left(\frac{\widehat{y}-\mu}{\sigma}\right)-\frac{\underline{c}}{r}\right)^2+\widehat{y}\left(\frac{\partial \widehat{y}}{\partial \sigma}-\frac{\widehat{y}-\mu}{\sigma}\right)\frac{1}{\sigma}\phi\left(\frac{\widehat{y}-\mu}{\sigma}\right)\left(\overline{\Phi}\left(\frac{\widehat{y}-\mu}{\sigma}\right)-\frac{\underline{c}}{r}\right) \\ &\quad +\int_{\frac{\widehat{y}-\mu}{\sigma}}^{\Phi^{-1}(1-\underline{c}/r)}\left(\overline{\Phi}\left(\zeta\right)-\frac{\underline{c}}{r}\right)\zeta\phi\left(\zeta\right)d\zeta \\ &= -\left(\frac{\partial \widehat{y}}{\partial \sigma}-\frac{\widehat{y}-\mu}{\sigma}\right)\left(\overline{\Phi}\left(\frac{\widehat{y}-\mu}{\sigma}\right)-\frac{\underline{c}}{r}\right)\left(\overline{\Phi}\left(\frac{\widehat{y}-\mu}{\sigma}\right)-\frac{\underline{c}}{r}-\frac{\widehat{y}}{\sigma}\phi\left(\frac{\widehat{y}-\mu}{\sigma}\right)\right) \\ &\quad -\frac{\widehat{y}-\mu}{\sigma}\left(\overline{\Phi}\left(\frac{\widehat{y}-\mu}{\sigma}\right)-\frac{\underline{c}}{r}\right)^2+\int_{\frac{\widehat{y}-\mu}{\sigma}}^{\Phi^{-1}(1-\underline{c}/r)}\left(\overline{\Phi}\left(\zeta\right)-\frac{\underline{c}}{r}\right)\zeta\phi\left(\zeta\right)d\zeta. \end{aligned}$$

Rearranging (5), the last integral can be expressed as

$$\int_{\frac{\widehat{y}-\mu}{\sigma}}^{\Phi^{-1}(1-\underline{c}/r)}\left(\overline{\Phi}\left(\zeta\right)-\frac{\underline{c}}{r}\right)\zeta\phi\left(\zeta\right)d\zeta=\frac{\widehat{y}}{\sigma}\left(\overline{\Phi}\left(\frac{\widehat{y}-\mu}{\sigma}\right)-\frac{\underline{c}}{r}\right)^2-\frac{\mu}{\sigma}\int_{\frac{\widehat{y}-\mu}{\sigma}}^{\Phi^{-1}(1-\underline{c}/r)}\left(\overline{\Phi}\left(\zeta\right)-\frac{\underline{c}}{r}\right)\phi\left(\zeta\right)d\zeta.$$

Substituting this,

$$\begin{aligned} 0 &= -\left(\frac{\partial \widehat{y}}{\partial \sigma}-\frac{\widehat{y}-\mu}{\sigma}\right)\left(\overline{\Phi}\left(\frac{\widehat{y}-\mu}{\sigma}\right)-\frac{\underline{c}}{r}\right)\left(\overline{\Phi}\left(\frac{\widehat{y}-\mu}{\sigma}\right)-\frac{\underline{c}}{r}-\frac{\widehat{y}}{\sigma}\phi\left(\frac{\widehat{y}-\mu}{\sigma}\right)\right) \\ &\quad +\frac{\mu}{\sigma}\left[\left(\overline{\Phi}\left(\frac{\widehat{y}-\mu}{\sigma}\right)-\frac{\underline{c}}{r}\right)^2-\int_{\frac{\widehat{y}-\mu}{\sigma}}^{\Phi^{-1}(1-\underline{c}/r)}\left(\overline{\Phi}\left(\zeta\right)-\frac{\underline{c}}{r}\right)\phi\left(\zeta\right)d\zeta\right]. \end{aligned}$$

The following can be shown by integration by parts:

$$\int_a^b \phi\left(\zeta\right)\Phi\left(\zeta\right)d\zeta=\frac{1}{2}\left(\Phi\left(b\right)^2-\Phi\left(a\right)^2\right).$$

Using this relation and after a few steps of algebra,

$$\int_{\frac{\widehat{y}-\mu}{\sigma}}^{\Phi^{-1}(1-\underline{c}/r)}\left(\overline{\Phi}\left(\zeta\right)-\frac{\underline{c}}{r}\right)\phi\left(\zeta\right)d\zeta=\frac{1}{2}\left(\overline{\Phi}\left(\frac{\widehat{y}-\mu}{\sigma}\right)-\frac{\underline{c}}{r}\right)^2.$$

Substituting this back into the above equality, we get

$$\frac{\partial \widehat{y}}{\partial \sigma}-\frac{\widehat{y}-\mu}{\sigma}=\frac{\mu}{2\sigma}\frac{\eta_2(\widehat{y})}{\eta_1(\widehat{y})}, \tag{7}$$

where $\eta_1(y) \equiv \overline{F}(y) - yf(y) - \frac{\underline{c}}{r} = \overline{\Phi}\left(\frac{y-\mu}{\sigma}\right) - \frac{y}{\sigma}\phi\left(\frac{y-\mu}{\sigma}\right) - \frac{\underline{c}}{r}$ and $\eta_2(y) \equiv \overline{F}(y) - \frac{\underline{c}}{r} = \overline{\Phi}\left(\frac{y-\mu}{\sigma}\right) - \frac{\underline{c}}{r}$. Recall from the proof of Proposition 2 that $\widehat{y} < y_1$, where y_1 is the unique solution of $\eta_1(y) = 0$ such that $\eta_1(y) > 0$ for $y < y_1$. Hence, $\eta_1(\widehat{y}) > 0$. It is also shown in the same proof that $\widehat{y} < y_2$, where y_2 solves $\eta_2(y) = 0$. Since $\eta_2(y)$ is a decreasing function, $\eta_2(\widehat{y}) > 0$. In sum, we have $\eta_1(\widehat{y}) > 0$ and $\eta_2(\widehat{y}) > 0$. Using these results and differentiating (6),

$$\frac{\partial\widehat{\theta}}{\partial\sigma} = \frac{r}{2\Delta_0(1-\delta)}\left(\frac{\partial\widehat{y}}{\partial\sigma} - \frac{\widehat{y}-\mu}{\sigma}\right)\frac{1}{\sigma}\phi\left(\frac{\widehat{y}-\mu}{\sigma}\right) = \frac{r}{2\Delta_0(1-\delta)}\frac{\mu}{2\sigma^2}\frac{\eta_2(\widehat{y})}{\eta_1(\widehat{y})}\phi\left(\frac{\widehat{y}-\mu}{\sigma}\right) > 0,$$

where we used (7). ■

Proof of Proposition 7. It is straightforward to show that $\theta = 1$ is optimal if the supply chain is integrated. Suppose that, in a decentralized supply chain, the manufacturer does not commit to a contract term in the beginning and instead offers a screening contract $\{(w(z|\theta), q(z|\theta))\}$ after collaboration is completed. In a make-to-order environment, this contract is offered after the manufacturer observes the realized demand D. Hence, at the time she devises the contract terms, the manufacturer's profit function is $\int_0^1 (r\min\{D, q(z|\theta)\} - w(z|\theta)q(z|\theta))\,dz$, which is free of expectation. The optimization problem is the same as $(\mathcal{S}_2)$ except for this modified objective. Following the standard adverse selection proof steps, it can be shown that the problem reduces to

$$\max_{q(z\,|\,\theta)} \int_0^1 [r\min\{D, q(z|\theta)\} - (\underline{c} + 2\Delta_0\,(1-(1-\delta)\theta)\,z)\,q(z|\theta)]\,dz.$$

It is easy to see that the objective function of this problem peaks at $q(z|\theta) = D$ for each value of z and any θ. Substituting this back into the objective and taking an expectation, we can show that the manufacturer's Stage 1 utility is equal to $U_m(e_m|e_s) = \mu\,[r - \underline{c} - \Delta_0\,(1-(1-\delta)\theta)] - k_m e_m$. Similarly, the supplier's utility is $U_s(e_s|e_m) = \frac{\mu\Delta_0}{2}(1-(1-\delta)\theta) - k_s e_s$, which is decreasing in θ, and hence, decreasing in e_s for any fixed e_m. This implies that the supplier sets $e_s = 0$, and as a result, $\theta = 0$ in equilibrium regardless of the manufacturer's choice of e_m. With $\theta = 0$ the manufacturer's utility is decreasing in e_m, so she chooses $e_m = 0$. The resulting utility is $U_m(0|0) = \mu(r - \underline{c} - \Delta_0)$. Next, consider EMC. With the constant margin v the payment function is $w(\theta) = v + \underline{c} + \frac{\Delta_0}{2}(1-(1-\delta)\theta)$, and as before, it is optimal to set $q = D$ regardless of θ. Then the Stage 1 utilities of the manufacturer and the supplier are, respectively, $U_m(e_m|e_s) = \mu\left[r - v - \underline{c} - \frac{\Delta_0}{2}(1-(1-\delta)\theta)\right] - k_m e_m$ and $U_s(e_s|e_m) = v\mu - k_s e_s$. Since $U_s(e_s|e_m)$ is decreasing in e_s, the supplier chooses $e_s = 0$; hence, $\theta = 0$ in equilibrium. It follows that the manufacturer chooses $e_m = 0$ and the resulting utilities are $U_m(0|0) = \mu\left[r - v - \underline{c} - \frac{\Delta_0}{2}\right]$ and $U_s(0|0) = v\mu$. At $\theta = 0$, the optimal v that ensures the participation of all supplier types is $v = \frac{\Delta_0}{2}$. Hence, $U_m(0|0) = \mu(r - \underline{c} - \Delta_0)$, which is identical to the value we derived under non-commitment. ■

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