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Collaborative Cost Reduction and Component Procurement Under Information Asymmetry

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During development of an innovative product there is often considerable uncertainty about component production cost, and it is of interest for both the manufacturer and the supplier to engage in a collaborative effort to reduce this uncertainty and lower the expected cost. Despite the obvious benefits this brings, the supplier may be reluctant to collaborate as he fears revealing his proprietary cost information. We investigate how information asymmetry and procurement contracting strategies interact to influence the supply chain parties' incentives to collaborate. We consider a number of procurement contracting strategies, and identify a simple strategy, expected margin commitment (EMC), that effectively promotes collaboration. The manufacturer prefers EMC if collaboration leads to a large reduction in unit cost and/or demand variability is low. Otherwise, a screening contract based on price and quantity is preferred. We also find that, paradoxically, ex post efforts to enhance supply chain efficiency may hinder ex ante collaboration that precedes production.

Key words: procurement; contracting; product development; asymmetric information; collaboration
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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—was one of the key differentiators that enabled their competitive advantage over U.S. manufacturers (McMillan 1990). With increasing sophistication and complexity of the products that accompany technology breakthroughs, the manufacturers and suppliers need to collaborate more than ever 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 air conditioning/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.

Although firms strive to attain the highest level of efficiency through collaboration, it can be an elusive goal. Forming a successful collaborative relationship rests on two key factors: the interfirm information structure and product characteristics. The former is crucial because it influences the firms' willingness to establish and sustain the relationship. Benefits of collaboration notwithstanding, the reality is 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, p. 77). 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 a 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 significant inventory risks because of 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 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, although 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, 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, a better cost predictability is typically accompanied by reduction of the expected unit cost, which then lowers the component procurement cost for the manufacturer. Such a benefit is supported by many studies, including Handfield et al. (1999), who report in their survey of 71 manufacturers that collaboration led to reduction of the material purchase costs by 2.6%–50%.

However, despite the obvious benefits that collaborative cost reduction brings, it may not always be a good proposition for the supplier. Because 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 screening contract based on price and quantity is known in the literature to be an effective mechanism to deal with information asymmetry existing in procurement environments, in the setting that we consider, it presents inefficiency in that it hinders the supplier's ex ante incentive to collaborate, thereby creating and aggravating a holdup problem.
- Price commitment, which is frequently mentioned in the literature as an effective means to alleviate the negative consequences of the holdup 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

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

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.

2. Related Literature

This paper contributes to the stream of literature in operations management (OM) that investigates procurement contracting, with a unique focus on how contracting strategies interact with collaborative product development. It shares some similarities to other OM papers, especially those that study collaborative processes in production and service delivery settings and those that analyze procurement contracts in the presence of asymmetric cost information and moral hazard.

The topic of supply chain collaboration has received much attention in the business press, but formal analyses of collaborative processes are relatively sparse in the academic literature, especially in the 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. Although 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 (e.g., Stallkamp 2005). Bernstein and Kök (2009) investigate cost reduction in an assembly network and their model shares some similarities to ours, but they do not consider collaboration or information asymmetry. Roels et al. (2010) is one of the few OM papers that formalize the notion of collaboration, but their model is developed in the context of service provisioning, whereas ours applies to product development in a manufacturing environment. Özer et al. (2011) 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 how the collaboration level is represented in our model.

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). There are few papers in this literature that investigate the topic of interfirm collaboration. The only exception, to the best of our knowledge, is Bhaskaran and Krishnan (2009). They do not, however, touch on how product development decisions interact with procurement contracting, and they sidestep agency issues created by information asymmetry, which plays a key role in our model. A recent paper by Kim and Swinney (2011) analyzes joint decisions in product development and production/procurement stages, as we do in our paper.

A number of recent papers in the OM area study sourcing contracts in the presence of asymmetric cost information, including Ha (2001), Corbett et al. (2004), Iyer et al. (2005), Li and Debo (2009), Kaya and Özer (2009), and Kostamis and Duenyas (2011), and our paper contributes to this stream of research. Among them, Iyer et al. (2005) is quite related to this paper because they also consider the use of a screening contract in the context of product development. However, many aspects of the two papers are different, especially in that we focus on how collaboration incentives are influenced by various types of procurement contracts (not just a screening contract) in a dynamic setting. Kaya and Özer (2009) share some similarities to this paper in that they study outsourcing contracts in the presence of asymmetric cost information and noncontractible quality, which bears resemblance to the cost reduction effort in our model. They do not, however, consider double moral hazard issues that arise naturally in the collaboration context or the interaction between cost and demand variability, two of the main features of our model. Outside of the sourcing context, Chen (2005) is related to this paper because he considers a model that combines moral hazard with adverse selection. Zhang and Zenios (2008) provide an extensive discussion of the revelation principle, a key solution concept in mechanism design problems, in dynamic settings. To learn about subtle aspects of adverse selection problems, see Lovejoy (2006).

One of the key elements of our model is the contract offer timing decision, which naturally brings up the holdup problem (Klein et al. 1978) and the issue of evaluating operational flexibility versus 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 a similar theme, 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 reduction. 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.

Our model can also be viewed as a variant of the models that combine adverse selection and moral hazard (see Bolton and Dewatrinpont 2005 for a comprehensive treatment of these topics), because, in our model, the supplier exerts a discretionary, nonverifiable effort, and subsequently possesses private information about his cost. In the economics literature there are numerous papers 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 offers 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 effort should be expended. In this respect, our model shares some similarities to the models that consider double moral hazard (Bhattacharyya and Lafontaine 1995, 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.

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 product that has a short life span because of 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, and that it is the only outsourced 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, because it has to be custom-made for the end product that features novel functionalities. Consequently, the unit cost c of producing a component is uncertain at the start of stage 1. This uncertainty can be reduced by collaborating with the manufacturer, who provides the supplier with useful (but incomplete) guidance to build a component that satisfies functional requirements. In addition to uncertainty reduction, a higher level of collaboration lowers the expected unit production cost. Hence, collaboration lowers both the expected unit cost and uncertainty around it, presenting potential benefits to the manufacturer and the supplier. 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 completed. 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 starts afterward. For simplicity we normalize the cost of manufacturing the end product to zero, but we relax this assumption in §8.3. Because the production lead time is long, the manufacturer has to order production quantity q in advance, when demand uncertainty exists. (In §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. This assumption is in line with many observed practices. 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 §8.5 and examine the consequences.

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, probability density function (pdf) f, and cumulative distribution function (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 $\bar{F}(\cdot) \equiv 1 - F(\cdot)$ and $J(y) \equiv \int_0^y x f(x)\,dx$, 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 a secondary market.

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

[2] Lee and Whang (2002) motivates their newsvendor-based model using the examples from similar product categories.

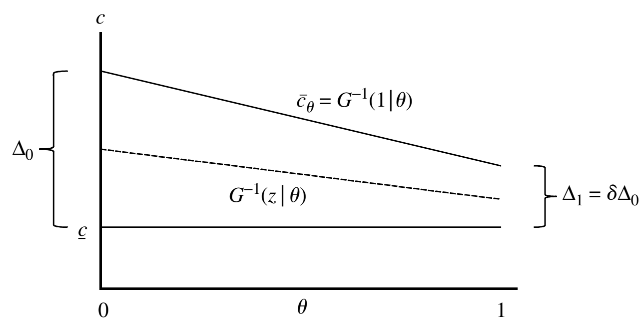
to which the unit cost is reduced through collaboration. We refer to θ simply as the "collaboration level." At $\theta = 0$ the firms are completely disengaged ("arm's length relationship"), whereas $\theta = 1$ corresponds to the maximum level of collaboration that can be achieved. The collaboration 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 because $\partial^2\theta/\partial e_m \partial e_s > 0$. By construction, positive collaboration level ($\theta > 0$) is obtained if and only if both parties exert nonzero efforts. We assume a deterministic relationship between the efforts and θ to enable tractable analysis; a similar assumption is found in Roels et al. (2010) and other papers that consider double moral hazard. As we discuss in §8.4, adding a stochastic component to θ does not alter the insights.

Exerting an effort is costly to both the manufacturer and the supplier, and for simplicity, we assume that the cost of effort is linear: $k_m e_m$ and $k_s e_s$. This cost may include, among others, expenses incurred for communication, personnel exchanges, prototype testing, etc. We use the shorthand notation $K \equiv (k_m/\alpha)^{\alpha}(k_s/(1-\alpha))^{1-\alpha}$ 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 $c \mid \theta$ is a random variable defined on a finite support with the conditional cdf $G(\cdot \mid \theta)$ and the pdf $g(\cdot \mid \theta)$. As the mapping $G^{-1}(z \mid \theta)$ uniquely identifies the unit-cost realization for a fixed θ at the zth quantile, $z \in [0, 1]$, we present our model in the transformed (θ, z)-space instead of the original (θ, c)-space. Throughout the paper we refer to $G^{-1}(\cdot \mid \theta)$ as the *unit-cost function*. To enable tractable analysis while capturing the essence of how collaboration impacts the unit-cost function, we develop our model under the following simplifying assumptions:

[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 to simplify analysis. The same assumption is frequently found in the economics literature, especially because it offers intuitive interpretations (e.g., Varian 2003, p. 83). Note that, like in our paper, Roels et al. (2010) 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 versus decreasing returns to scale is of small concern, because 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.

Figure 1 **An Example of a Unit-Cost Function Satisfying Assumption 1**



Assumption 1. (i) *$c \mid \theta$ is uniformly distributed with a constant lower support bound $\underline{c}$ and an upper support bound $\bar{c}_\theta$, which varies with θ*; (ii) *$G^{-1}(z \mid \theta)$ decreases linearly in θ for all $z \in (0, 1]$*; (iii) *$\delta \equiv \Delta_1/\Delta_0 < 1$, where $\Delta_\theta \equiv \bar{c}_\theta - \underline{c}$.*

Figure 1 illustrates the features of $G^{-1}(\cdot \mid \theta)$ summarized in Assumption 1. The quantity δ 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. By letting $G^{-1}(z \mid \theta)$ decrease in θ for all $z > 0$ but setting it to a constant value $\underline{c}$ at the lower support bound $z = 0$, we essentially assume that it is only the upside cost uncertainty that can be reduced through collaboration (see §8.2 where this assumption is relaxed). Notice that the *spread* $G^{-1}(z_2 \mid \theta) - G^{-1}(z_1 \mid \theta)$ for $0 \le z_1 < z_2 \le 1$, i.e., the gap between any two equiquantile curves, decreases in θ. This formalizes the idea that a higher level of collaboration leads to lower expectation and lower uncertainty of the unit cost. Under these assumptions, we can express the unit-cost function simply as

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

Information asymmetry emerges at the end of stage 1, after collaboration is completed and the efforts by both parties determine the value of θ. At that point, the supplier privately learns the realized cost, or equivalently, the supplier's "type" $z \mid \theta$. 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 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

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

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 because the unit cost can be significantly reduced with relatively small effort cost.

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 e_m and e_s. We assume that the effort levels are unverifiable and therefore noncontractible.[4] Moreover, 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 because the supplier has an informational advantage, i.e., he keeps his realized unit cost private.

Motivated by the majority of procurement practices, we focus on the contracts that specify the unit price w and the quantity q of the component. Depending on whether the manufacturer offers the contract in stage 1 or stage 2, however, the contract may or may not consist of a single price-quantity pair (w, q). In particular, if the manufacturer offers the contract immediately before production starts, i.e., at the beginning of stage 2 (at which point the collaboration level θ is set and information asymmetry about the unit cost is in place), she may take advantage of the fact that the supplier would prefer a certain price-quantity pair based on the realized unit cost he privately learns; in other words, the manufacturer will be better off by offering a menu of price-quantity pairs $\{(w(z\mid\theta), q(z\mid\theta))\}$, each pair tailored to the supplier's realized type $z\mid\theta$.

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 §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 presourcing effort (Dyer 2000). Volume commitments are also frequently used as a way to improve supply chain relationships (Corbett et al. 1999).

The sequence of events is summarized as follows. At the start of stage 1, 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, 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. Afterward, the supplier learns the true unit cost, but he keeps this information from the manufacturer. At the start of stage 2, the manufacturer may offer contract

[4] This assumption reflects the common reality that it is difficult for a third party (e.g., court) to disentangle each party's contribution to a collaborative product development process that involves complex interactions among the firms and is often ad hoc in nature. Even if the firms may observe the other collaborating party's actions, it is impractical for them to actively monitor and objectively document every move made by the other party in such circumstances. This is especially true in product development environments because firms typically race against time to introduce their new product to the market quickly. Such lack of undisputable evidence precludes enforcing a contract based on effort levels, as a court cannot verify a claim of negligence in case a dispute arises. The same assumption is employed in Bhattacharyya and Lafontaine (1995), Roels et al. (2010), and numerous others.

terms, depending on the strategy set in the beginning. The supplier then manufactures and delivers the components in the quantity q and receives payment at the unit price w, as specified in the procurement contract. The manufacturer in turn manufactures the end products by putting the procured component together with other parts, and sells them in the market at the retail price r.

4. Integrated Supply Chain

We first establish the first-best 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. Because 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

$$(\mathscr{B})\quad \max_{e_m,\, e_s} \left\{ \int_0^1 \big(rE[\min\{D, q(z \mid \theta)\}] - G^{-1}(z \mid \theta) q(z \mid \theta) \big)\, dz - k_m e_m - k_s e_s \right\}$$

$$\text{s.t.}\quad q(z \mid \theta) = \arg\max_q \{ rE[\min\{D, q\}] - G^{-1}(z \mid \theta) q \},$$

$$0 \le \theta = e_m^{\alpha} e_s^{1-\alpha} \le 1.$$

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 on optimal purchase price and quantity.

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

Proofs of selected results are found in the appendix; omitted proofs are available from the authors upon request.

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 quite intuitive. Observe that the cost-contribution ratios k_m/α and $k_s/(1-\alpha)$ 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 k_m/α 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 the Screening Contract

In a decentralized supply chain, the manufacturer procures the component from the supplier through contracting. In this section we investigate the procurement strategy under which the manufacturer offers a contract to the supplier in stage 2, after collaborative cost reduction is completed and the final value of θ is known. The presence of information asymmetry in this stage creates inefficiency because, without perfect knowledge of the supplier's unit cost, the manufacturer has limited ability to structure the contract terms that are favorable to herself. In the procurement contracting literature, truth-revealing screening contracts have been extensively studied as the standard mechanism to deal with such inefficiencies (e.g., Ha 2001, Iyer et al. 2005), given that certain technical conditions are met (which our model does).[5] With this type of contract, the manufacturer "screens" supplier types by offering a menu of price-quantity pairs $\{(w(z \mid \theta), q(z \mid \theta))\}$, which is structured so that a supplier of type z for a given value of θ will choose the price $w(z \mid \theta)$ and the quantity $q(z \mid \theta)$ that are specifically designated for him. That the manufacturer can restrict her contract choice among those that implement such a truth-revealing self-selection mechanism is established by the revelation principle (Myerson 1979), which guarantees that an optimal contract can be found among them.

The optimal menu, denoted by the superscript $*$, is determined from the following optimization problem:

$$(\mathscr{S}_2)\quad \max_{\{(w(z \mid \theta),\, q(z \mid \theta))\}} \int_0^1 \big(rE[\min\{D, q(z \mid \theta)\}] - w(z \mid \theta) q(z \mid \theta) \big)\, dz$$

$$\text{s.t.}\quad \pi_s(z, z \mid \theta) \ge 0, \quad \forall z \in [0,1]; \qquad \text{(IR-S)}$$

$$\pi_s(z, z \mid \theta) \ge \pi_s(z, \hat{z} \mid \theta), \quad \forall z, \hat{z} \in [0,1]; \qquad \text{(IC-S)}$$

$$0 \le \theta = e_m^{\alpha} e_s^{1-\alpha} \le 1.$$

Here, $\pi_s(z, \hat{z} \mid \theta) \equiv [w(\hat{z} \mid \theta) - G^{-1}(z \mid \theta)] q(\hat{z} \mid \theta)$ is the z-type supplier's stage 2 profit when he accepts the

[5] In particular, the distribution of the agent's type ($z \mid \theta$ in our model) should be properly ordered to have a fully separating equilibrium. A sufficient condition is that the hazard rate of the distribution is increasing (Bolton and Dewatripont 2005), which is satisfied in our model.

price-quantity pair $(w(\hat{z} \mid \theta), q(\hat{z} \mid \theta))$ that is intended for the $\hat{z}$-type supplier. The incentive compatibility constraint (IC-S) is put in as a direct application of the revelation principle, and it states that a supplier of a given type maximizes his profit by voluntarily choosing a price-quantity pair designated for him, thus revealing his true type. The participation constraint (IR-S) ensures that the resulting profit for the supplier is nonnegative regardless of the realized cost. Note that the reservation profit of the supplier (right-hand side of (IR-S)) is normalized to zero, reflecting the fact that the supplier is not able to market the component outside of his bilaternal relationship with the manufacturer as it was designed specifically for the manufacturer's end product. The solution of $(\mathcal{S}_2)$ is as follows.

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

Note that the optimal contract terms $w^*(z \mid \theta)$ and $q^*(z \mid \theta)$ are monotone in z, implying that the price-quantity pairs are fully distinguished from one another. 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 profits $U_m(e_m \mid e_s) \equiv r\int_0^1 J(q^*(z \mid \theta))\,dz - k_m e_m$ and $U_s(e_s \mid e_m) \equiv \Delta_0(1-(1-\delta)\theta)\int_0^1 zq^*(z \mid \theta)\,dz - k_s e_s$. 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). *A Nash equilibrium of the effort game under the screening contract exists. Let* $\psi(\theta) \equiv -q^*(1 \mid \theta) + \int_0^1 zq^*(z \mid \theta)\,dz$ *and*

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

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* $\Psi(\theta) = K$.

Although Proposition 2 identifies the equilibrium solution for θ, 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. However, essential insights can be obtained by investigating the solution behavior in the following limiting case, for which uniqueness of the equilibrium is verified analytically.

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

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

In the limit $K \to 0$, *the equilibrium collaboration level* θ^S *approaches* $\hat{\theta}^S = \min\{((\underline{c} + 2\Delta_0 - r\bar{F}(\hat{y}))/(2\Delta_0(1-\delta)))^+, 1\}$. *Moreover,* $\theta^S \leq \hat{\theta}^S$ *for* $K > 0$.

Note that $\hat{\theta}^S$ is the upper bound of the equilibrium collaboration level θ^S, which is attained in the limit $K \to 0$. According to the corollary, $\hat{\theta}^S$ can take any value between 0 and 1, depending on the parameter values and the shape of the demand distribution F (we discuss this further in §7). In addition, $\hat{\theta}^S < 1$ if $\delta = 0$ (which is easily verified), implying that full collaboration is *never* attained if collaborative cost reduction is so effective that the residual cost uncertainty can be completely removed. These observations provide strong evidence that, in general, the equilibrium collaboration level under the screening contract tends to be lower than the first-best level $\theta = 1$. Provided that the supplier's expected cost savings is greatest at $\theta = 1$ and therefore the manufacturer and the supplier can take the maximum advantage of efficiency gain at that point, the fact that the equilibrium collaboration level tends to be less than one implies that they make suboptimal effort decisions; they forego an opportunity to generate an extra surplus in the supply chain that could have been shared among them.

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. Whereas smaller average unit cost benefits the supplier as it leads the manufacturer to increase the order quantity,[6] 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: Although the volume increase resulting from collaboration benefits him, he simultaneously reveals more information about his cost to the opportunistic manufacturer. This trade-off restrains the supplier from fully collaborating. The next result, which compares the allocation of equilibrium efforts e_m^S and e_s^S with that under the first best, further identifies the supplier's unwillingness to collaborate as the primary reason for the suboptimal outcome under the screening contract.

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

Part (i) of the proposition makes it clear that the supplier's effort level in equilibrium is lower than the benchmark level (as long as $0 < \theta^S < 1$). In addition, part (ii) says that the supplier's relative share of the joint effort under the screening contract is smaller than that of the benchmark case. As an illustration, assume that the manufacturer and the supplier are symmetric with respect to their effort cost-contribution ratios, i.e., $k_m/\alpha = k_s/(1-\alpha)$. Then the efforts are evenly allocated in the benchmark case ($e_s^B/e_m^B = 1$), 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, although offering a screening contract at the outset of production to procure the component enables the manufacturer to effectively deal with information asymmetry, it creates a holdup 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 holdup problem as the source of an 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 contract approach 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 holdup problem cannot be avoided as long as the contract is offered after collaboration is completed, a point in time when information asymmetry exists and the manufacturer offers a screening contract. 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 approach.

Because 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 risks leaving a larger portion of the rent to the supplier than she would without the commitment, because the flexibility inherent in the menu of multiple price-quantity contracts (which is designed to maximize the manufacturer's profit in the presence of information asymmetry) is lost if one or both of price and quantity terms are committed ex ante, i.e., before the unit cost is revealed to the supplier. Therefore, the choice between the screening contract approach and the commitment strategy can be viewed as a trade-off between extracting the maximum amount of rent from the supplier ex post and (potentially) incentivizing the supplier to collaborate more ex ante.

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, because 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

[6] It is optimal for the newsvendor manufacturer to increase the order quantity in response to the reduced unit cost of the supplier, because it enables the manufacturer to lower her marginal cost, i.e., the purchase price.

level θ, which determines the mean unit cost. The uncertainty in the unit cost is resolved afterward, and subsequently the manufacturer offers to the supplier a quantity q.[7] Quantity commitment and price-quantity commitment follow similar sequences of events.

Under price commitment, reduced unit-cost uncertainty no longer presents a risk to the supplier because 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 holdup problem and induce the supplier to exert a higher level of collaborative effort, potentially leading to full collaboration. As the following proposition reveals, however, this reasoning tells only half of the story.

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 result 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 also, because the optimal quantity is determined by the constant underage cost $r - w$ and the constant overage cost w. (Recall that the manufacturing/assembly cost and other costs unrelated to procuring the supplier's component are normalized to zero.) Because exerting an effort incurs a cost 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 $e_s = 0$ also, because 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 holdup problem is again the culprit. The optimal price w that the manufacturer sets in stage 2 is lower if the unit-cost uncertainty is smaller, implying that the supplier's profit margin goes down with higher θ. Because 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 $e_m = 0$ also. Therefore, not all commitments alleviate the holdup problem; with quantity commitment, the problem is actually exacerbated. The same result is obtained for price-quantity commitment by a similar reasoning.

Thus, 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, whereas 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. 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 EMC, the manufacturer commits to pay a constant margin v above the expected unit cost $\int_0^1 G^{-1}(z \mid \theta)\, dz$, no matter what collaboration level θ results from their mutual efforts. EMC is similar to but different from price commitment, since, although commitment is made on price, the price 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 because 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 because 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. This is in contrast to the screening contract, under which the supplier's margin is eroded with collaboration. Hence, EMC has a potential to neutralize the holdup 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, because it does not enable her to extract rents from the supplier as efficiently as she could have with a screening contract. We consider this trade-off further in the next section. First, let us characterize the equilibrium collaboration

[7] A combination of w and a menu of quantities, i.e., $\{q(z \mid \theta)\}$, is insufficient to implement the truth-revealing screening mechanism because 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 $\{q(z \mid \theta)\}$ that maximizes his profit regardless of his type.

level under EMC. We use the superscript M to denote the equilibrium outcomes under EMC.

Proposition 5 (Equilibrium Collaboration Level Under Expected Margin Commitment). *A Nash equilibrium of the collaborative effort game under EMC exists. Let*

$$q^{\dagger}(\theta) \equiv F^{-1}\left(1 - \frac{1}{r}\left[v + \underline{c} + \frac{\Delta_0}{2}(1-(1-\delta)\theta)\right]\right)$$

and

$$\Gamma(\theta) \equiv \frac{1}{2}\Delta_0(1-\delta)(q^{\dagger}(\theta))^{\alpha}\left(\frac{v}{rf(q^{\dagger}(\theta))}\right)^{1-\alpha}.$$

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 because 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 $v^M = (\Delta_0/2)\cdot(1-(1-\delta)\theta^M)$.[8] 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 maximum value 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 $\hat{\theta}^S$ 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 trade-off in the next section with a goal of identifying the conditions under which one contracting approach dominates the other.

[8] This assumes the ex post participation constraint $\pi_s(z \mid \theta^M) \geq 0$, $\forall z \in [0,1]$, 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.

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 drives many procurement decisions in practice. In our setting, demand variability not only influences the terms of procurement contracts 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 $\hat{\theta}^S$ of the equilibrium collaboration level under the screening contract. As we found there, the shape of the demand distribution F determines whether $\hat{\theta}^S$ is equal to zero, one, or a value in between. To make this observation more concrete, let us assume that demand is normally distributed and examine how $\hat{\theta}^S$ 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 $\partial\hat{\theta}^s/\partial\sigma > 0$ for $0 < \hat{\theta}^S < 1$.*

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., $\partial\theta^s/\partial\sigma > 0$ 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) identify the collaborative demand forecast sharing as one of the four strategies for mitigating the bullwhip effect. However, this intuition does not apply to our setting, because in our model demand information is symmetric; demand forecast sharing is a built-in assumption in our model.

Instead, the result in Proposition 6 arises from a subtle interaction between demand variability and collaborative cost reduction. The reasoning (inferred from analytical and numerical observations) 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 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 conjecture that the difference in θ between the screening contract and EMC is larger when demand variability is low, whereas the opposite is true when demand variability is high. An example in Figure 2(a) supports this hypothesis. In this example, $\theta^M = 1$ is always attained in equilibrium under EMC whereas θ^S steadily increases with σ under the screening contract. However, as Figure 3(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 2, i.e., 20% reduction is achieved by full collaboration, whereas $\delta = 0.95$ in Figure 3, i.e., 5% reduction is achieved. These numerical observations suggest that it is the combination of demand variability and the degree of cost reduction that determines the collaboration level. The remaining question is: Under what circumstance is it better for the manufacturer to adopt EMC over the screening contract approach, and vice versa? The following result, which focuses on special cases, provides an analytical support for the answer to this question.

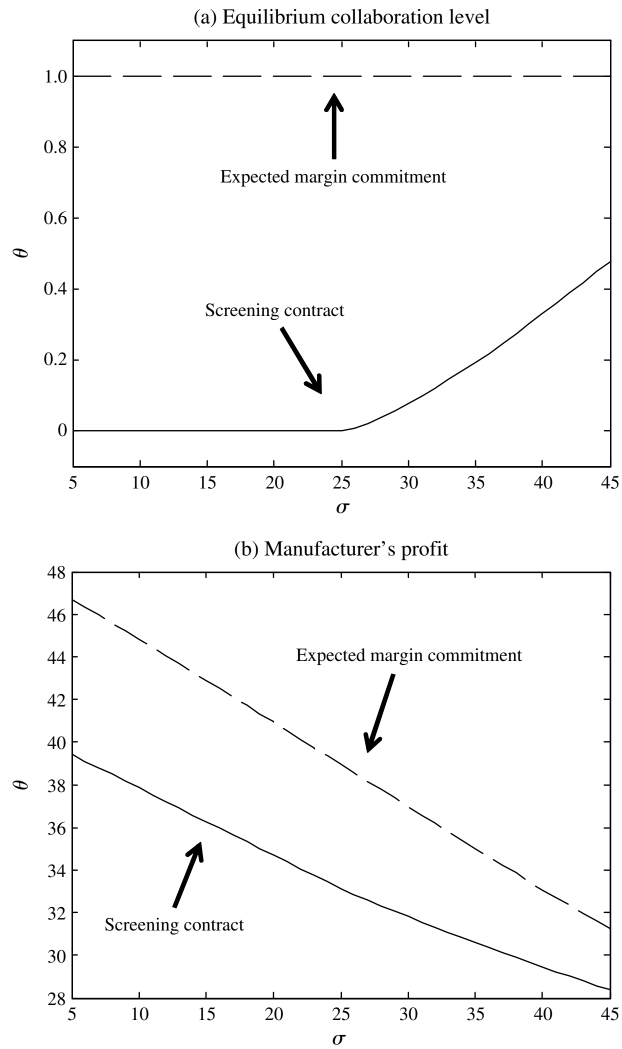
Proposition 7. *Let π_m^S and π_m^M be the manufacturer's stage 2 expected profits in the limit $K \to 0$ under the screening contract and EMC, respectively. For π_m^S, π_m^M, and $\hat{y}$, which is specified in Corollary 1, the following holds:*

(i) *If $\bar{F}(\hat{y}) \le (1/r)(\underline{c} + 2\delta\Delta_0)$, then $\pi_m^S > \pi_m^M$.*

(ii) *If $\bar{F}(\hat{y}) \ge (1/r)(\underline{c} + 2\Delta_0)$, there is a unique $\hat{\delta} \in (0, 1)$ such that $\pi_m^S < \pi_m^M$ for $\delta < \hat{\delta}$ and $\pi_m^S > \pi_m^M$ for $\delta > \hat{\delta}$.*

If demand is normally distributed, it can be shown that the condition in (i) is satisfied when demand variability is sufficiently large, and similarly, (ii) is satisfied when variability is sufficiently small. Under the condition in (i), $\theta^S = \theta^M = 1$. Under the condition in (ii), $\theta^S = 0$ whereas $\theta^M = 1$. According to the proposition, the manufacturer's stage 2 expected profit is always higher under the screening contract

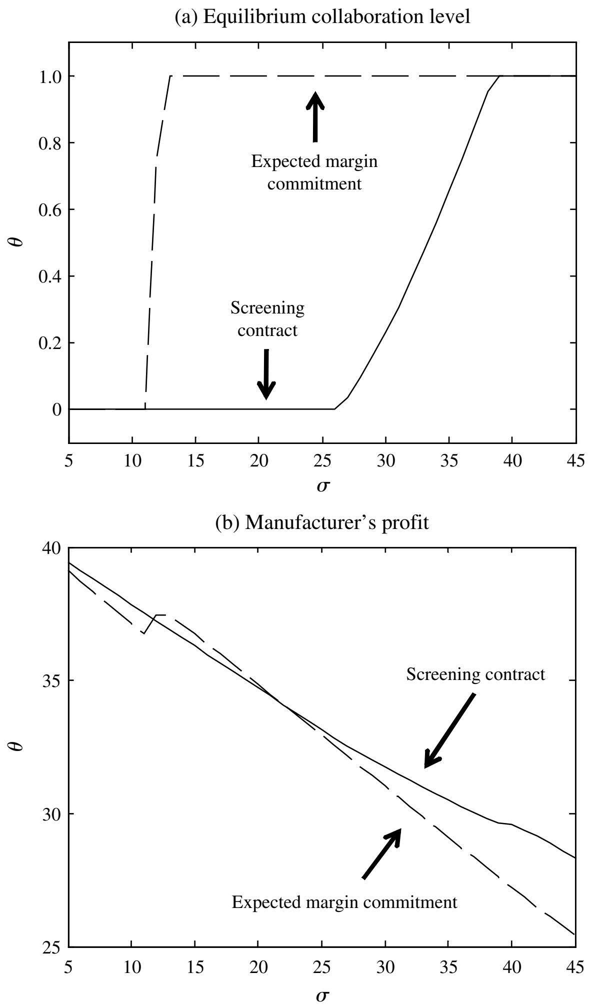
Figure 2 **Comparison of Screening Contract and Expected Margin Commitment: Example 1**



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

when demand variability is sufficiently large. On the other hand, when variability is sufficiently small, a similar statement can be made only when δ is over the threshold value $\hat{\delta}$; otherwise, EMC produces higher expected profit. Extending this result to include the remaining case $((1/r)(\underline{c} + 2\delta\Delta_0) < \bar{F}(\hat{y}) < (1/r) \cdot (\underline{c} + 2\Delta_0))$ and accounting for the effort costs incurred in stage 1, we numerically verify the insights suggested by Proposition 7: the manufacturer prefers EMC to the screening contract when (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 2(b), which shows that EMC dominates the screening contract especially when demand variability is small. In contrast, 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;

Figure 3 **Comparison of Screening Contract and Expected Margin Commitment: Example 2**



Notes. In this example, $\lambda = 0.95$. Other parameter values are the same as those in Figure 2.

see Figure 3(b) that shows the screening contract dominating EMC for large values of σ.[9]

8. Discussion of Assumptions and Robustness of the Results

8.1. Collaboration in a Make-to-Order Production System

Our analysis has been based on the assumption that production lead time is long and therefore the manufacturer has to procure the component well before demand is realized. Although this assumption is quite reasonable for the 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 production is relatively short and the customers' willingness to wait is high. The benefit of having such a system is clear: because 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 question.

Proposition 8 (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 noncommitment and EMC, leading to the equilibrium collaboration level $\theta = 0$. Furthermore, the manufacturer is indifferent between the two contract choices.*

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

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 noncommitment, because the supply exactly matches the demand in a make-to-order production system and this is equivalent to having zero demand 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 cost 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 $e_m = 0$. Thus, neither contracting strategy promotes collaboration in a make-to-order production system.

This finding suggests that an ex post improvement of supply chain efficiency may bring an unintended

[9] In Figure 3(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 (see Figure 3(a)); effort cost is too high under both contracts. Because the 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.

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 reduce 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.[10] 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. Nonconstant Lower Bound of the Unit-Cost Distribution Support

One of the restrictive assumptions of the main model is that the lower bound of the unit-cost distribution support is fixed at the constant value $\underline{c}$, a simplifying assumption that enables tractable analysis. We now investigate the consequences of relaxing this assumption. In doing so, we maintain the premise that the unit-cost function varies linearly in θ and that collaboration leads to lower values of both the mean and the spread of the unit cost. Through numerical experiments, we verify that the main findings from the earlier sections remain intact. Namely, EMC tends to promote collaboration better than the screening contract does, and EMC is preferred when demand variability is relatively small and when the degree to which the mean and the spread of the unit cost are reduced through collaboration is relatively large. Hence, no structural changes occur as a result of relaxing the assumption of a constant lower bound.

An interesting special case permitted under the relaxed assumption is the limit $\delta \to 1$, i.e., when collaboration leads to reduction of the mean of the unit cost but not of the spread. In this case, the unit-cost function $G^{-1}(z \mid \theta)$ decreases in θ at a uniform rate for all z. It can be proved that, in this case, both the manufacturer and the supplier exert maximum efforts to induce the full collaboration level $\theta = 1$ regardless of whether the screening contract or EMC is employed. This is because, in this limit, reduction of the mean leads to expected cost savings and a volume increase for both parties, while at the same time, the supplier does not lose his informational advantage; the net benefits are positive for both. Because both contracts lead to $\theta = 1$, the manufacturer prefers the screening contract approach to EMC since the former is more effective in extracting rents from the supplier for a given level of collaboration.

8.3. Manufacturing Cost Reduction

In the main model we assumed that the manufacturer's marginal cost of manufacturing and assembling the end product is unaffected by collaboration and normalized its value to zero. We now relax this assumption and include the term $-\kappa(\theta)q$ in the manufacturer's objective function, where $\kappa(\theta) > 0$ is the cost of manufacturing a unit of end product that depends on the collaboration level. To succinctly capture the notion that collaboration leads to an improvement in the manufacturing efficiency, we assume that $\kappa(\theta)$ is linearly decreasing as $\kappa(\theta) = \kappa_0 - \kappa_1\theta$ with $\kappa_0 > \kappa_1$.

We observe analytically and numerically that the equilibrium collaboration level increases in κ_1 under both the screening contract and EMC. That is, as the marginal benefit of manufacturing cost reduction through collaboration increases (higher κ_1), the firms exert larger collaborative efforts. This benefit creates an added incentive to the manufacturer (in addition to the reduction in her procurement cost) to exert her effort, which in turn leads to a higher effort by the supplier as the efforts are complementary. The net outcome is a larger collaboration level θ. The main conclusion of the pervious section, namely, that the screening contract is preferred when the degree of the supplier's cost reduction is small and the demand variability is large, remains the same. However, we find numerically that higher κ_1 expands the region of parameter combinations where the screening contract dominates EMC. This happens as the firms collaborate more readily, thus softening the main disadvantage of the screening contract approach.

8.4. Uncertainty in Collaboration Level

In specifying the link between the efforts and the collaboration level, we have assumed the deterministic relationship $\theta = e_m^{\alpha} e_s^{1-\alpha}$. Although this captures the essence of the complementary nature of the efforts, in reality, an exogenous shock that neither party can control may result in an uncertain collaboration outcome. To investigate what effects such uncertainty has on our findings, assume an alternate specification $\theta = \varepsilon e_m^{\alpha} e_s^{1-\alpha}$, where ε is a random variable with a known distribution and $E_\varepsilon[\varepsilon] = 1$. With this addition,

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

we modify the sequence of events as follows: (1) the manufacturer and the supplier choose the effort levels simultaneously; (2) ε is realized and observed by both parties, determining the collaboration level θ; (3) the unit cost $c \mid \theta$ is realized and is known only to the supplier. In addition, comparison of the collaboration level should be based on the expectation $E_\varepsilon[\theta]$.

Adding this stochastic variable significantly complicates analysis, which is expected given that our model then includes three sources of randomness: demand, the unit cost, and the effort outcome. However, numerical examples reveal that the qualitative insights we obtained in the previous section remain intact. This is in fact not surprising, because the structure of the game does not change except that an additional expectation operator $E_\varepsilon[\cdot]$ is added to the first-order equations that describe the equilibrium. Therefore, the main conclusions of our model are robust to this additional source of uncertainty.

8.5. Retail Pricing

As we mentioned in §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 completed. To investigate the impact of allowing such endogenous retail pricing, 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 completed.

We focus on the role of consumers' price sensitivity, represented by the parameter β_1; the larger β_1, the higher the sensitivity. From numerical examples, we find 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 §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 examples, EMC 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. We focus 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 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 investigate the consequences of using a screening contract based on price and quantity after collaboration is completed and the supplier privately learns his cost realization. This approach is appealing to the manufacturer because 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 her imperfect knowledge about the supplier's unit cost, the supplier is reluctant to contribute a large amount of effort to the joint cost reduction initiative because 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 holdup problem and convince the supplier to collaborate, the manufacturer may instead commit to contract terms 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 holdup problem for the supplier, it leaves the manufacturer with no share of the cost reduction benefit; because 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 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.

This paper focuses on a specific aspect of supply chain collaboration, and as such, the insights obtained from our analysis are to be understood in the context of the model assumptions. Relaxing some of these assumptions and including other real-world considerations that are not captured in our model will enrich the managerial insights and bring a more complete picture of the incentive dynamics in which collaboration plays a key role.

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Appendix. Proofs of Selected Results

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

Proof. Inverting $q^*(z \mid \theta) = F^{-1}(1 - (1/r)[\underline{c} + 2\Delta_0(1 - (1-\delta)\theta)z])$ yields $z = (r\bar{F}(q) - \underline{c})/(2\Delta_0(1-(1-\delta)\theta))$ and $dz = -rf(q)/(2\Delta_0(1-(1-\delta)\theta))\,dq$. Then

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

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

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

Then $\psi(\theta)$ can be rewritten as $\tilde{\psi}(y)/(\bar{F}(y) - \underline{c}/r)^2$, where $\tilde{\psi}(y)$ is defined in Corollary 1. Hence, $\psi(\theta)$ and $\tilde{\psi}(y)$ have the same sign, and therefore, our goal of showing that there exists $\hat{\theta}$ such that $\psi(\theta) > 0$ for $\theta < \hat{\theta}$ and $\psi(\theta) < 0$ for $\theta > \hat{\theta}$ is achieved by showing that there exists $\hat{y}$ such that $\tilde{\psi}(y) > 0$ for $y < \hat{y}$ and $\tilde{\psi}(y) < 0$ for $y > \hat{y}$. Note that the lower and upper bounds of y that are defined for $\tilde{\psi}(y)$, i.e., 0 and $F^{-1}(1 - \underline{c}/r)$, correspond to $\theta = -(r - \underline{c} - 2\Delta_0)/(2\Delta_0(1-\delta))$ and $\theta = 1/(1-\delta)$, which are obtained from the relation $y = q^*(1 \mid \theta) = F^{-1}(1 - 1/r[\underline{c} + 2\Delta_0 \cdot (1-(1-\delta)\theta)])$. Taking a derivative, $\tilde{\psi}'(y) = -\eta_1(y)\eta_2(y)$, where $\eta_1(y) \equiv \bar{F}(y) - yf(y) - \underline{c}/r$ and $\eta_2(y) \equiv \bar{F}(y) - \underline{c}/r$. 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. Because F has the IGFR property, $\bar{F}(y) - yf(y) < \bar{F}(y)$ 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 $\lim_{y\to y_2}\eta_1(y) = -y_2f(y_2) < 0$. 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 $\tilde{\psi}'(y) > 0$ for $y_1 < y < y_2$. In addition, observe that (i) $\tilde{\psi}(0) = \int_0^{y_2}(\bar{F}(x) - \underline{c}/r)xf(x)\,dx > 0$, (ii) $\tilde{\psi}'(0) = -(1 - \underline{c}/r)^2 < 0$, (iii) $\lim_{y\to y_2}\tilde{\psi}(y) = 0$, and (iv) $\lim'_{y\to y_2}\tilde{\psi}(y) = 0$. Summarizing, $\tilde{\psi}(y)$ 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 $\hat{y} \in (0, y_1)$ such that $\tilde{\psi}(y) > 0$ for $0 \le y < \hat{y}$, $\tilde{\psi}(\hat{y}) = 0$, and $\tilde{\psi}(y) < 0$ for $y > \hat{y}$, the result we set out to prove. □

Proof of Corollary 1. In the limit $K \to 0$, $\Psi(\theta) = K$ is reduced to $\psi(\theta) = 0$. In the proof of Lemma 2 we showed that $\psi(\theta) = 0$ can be rewritten as $\tilde{\psi}(y) = 0$, which has a unique solution $\hat{y}$, with the change of variables $y = F^{-1}(1 - (1/r)[\underline{c} + 2\Delta_0(1-(1-\delta)\theta)])$, or equivalently, $\theta = (\underline{c} + 2\Delta_0 - r\bar{F}(y))/(2\Delta_0(1-\delta))$. The rest of the proof is straightforward and hence 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 $0 < \hat{\theta} < 1$, $\tilde{\psi}(\hat{y}) = 0$ and $\hat{\theta}$ defined in Corollary 1 can be written as

$$\tilde{\psi}(y) = -\hat{y}\left(\bar{\Phi}\left(\frac{\hat{y}-\mu}{\sigma}\right) - \frac{\underline{c}}{r}\right)^2 + \int_{(\hat{y}-\mu)/\sigma}^{\Phi^{-1}(1-\underline{c}/r)}\left(\bar{\Phi}(\zeta) - \frac{\underline{c}}{r}\right)(\mu + \sigma\zeta)\phi(\zeta)\,d\zeta = 0, \tag{3}$$

$$\hat{\theta} = \frac{\underline{c} + 2\Delta_0 - r\bar{\Phi}((\hat{y}-\mu)/\sigma)}{2\Delta_0(1-\delta)}, \tag{4}$$

where we have let $\zeta = (x-\mu)/\sigma$ in (3). Implicit differentiation of (3) with respect to σ yields

$$0 = -\left(\frac{\partial\hat{y}}{\partial\sigma}\right)\left(\bar{\Phi}\left(\frac{\hat{y}-\mu}{\sigma}\right) - \frac{\underline{c}}{r}\right)^2 + \hat{y}\left(\frac{\partial\hat{y}}{\partial\sigma} - \frac{\hat{y}-\mu}{\sigma}\right)\frac{1}{\sigma}\phi\left(\frac{\hat{y}-\mu}{\sigma}\right)\left(\bar{\Phi}\left(\frac{\hat{y}-\mu}{\sigma}\right) - \frac{\underline{c}}{r}\right) + \int_{(\hat{y}-\mu)/\sigma}^{\Phi^{-1}(1-\underline{c}/r)}\left(\bar{\Phi}(\zeta) - \frac{\underline{c}}{r}\right)\zeta\phi(\zeta)\,d\zeta$$

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

Rearranging (3), the last integral can be expressed as $(\hat{y}/\sigma)(\bar{\Phi}((\hat{y}-\mu)/\sigma) - (\underline{c}/r))^2 - \mu/\sigma \int_{(\hat{y}-\mu)/\sigma}^{\Phi^{-1}(1-\underline{c}/r)} (\bar{\Phi}(\zeta) - \underline{c}/r) \cdot \phi(\zeta)\,d\zeta$. Substituting this,

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

The following can be shown by integration by parts: $\int_a^b \phi(\zeta)\Phi(\zeta)\,d\zeta = \frac{1}{2}(\Phi(b)^2 - \Phi(a)^2)$. Using this relation and after a few steps of algebra, $\int_{(\hat{y}-\mu)/\sigma}^{\Phi^{-1}(1-\underline{c}/r)} (\bar{\Phi}(\zeta) - \underline{c}/r)\phi(\zeta)\,d\zeta = \frac{1}{2}(\bar{\Phi}((\hat{y}-\mu)/\sigma) - \underline{c}/r)^2$. Substituting this back into the above equality, we get $\partial\hat{y}/\partial\sigma - (\hat{y}-\mu)/\sigma = (\mu/2\sigma)(\eta_2(\hat{y})/\eta_1(\hat{y}))$, where $\eta_1(y) \equiv \bar{F}(y) - yf(y) - \underline{c}/r = \bar{\Phi}((y-\mu)/\sigma) - (y/\sigma) \cdot \phi((y-\mu)/\sigma) - \underline{c}/r$ and $\eta_2(y) \equiv \bar{F}(y) - \underline{c}/r = \bar{\Phi}((y-\mu)/\sigma) - \underline{c}/r$. Recall from the proof of Lemma 2 that $\hat{y} < y_1$, where y_1 is the unique solution of $\eta_1(y) = 0$ such that $\eta_1(y) > 0$ for $y < y_1$. Hence, $\eta_1(\hat{y}) > 0$. It is also shown in the same proof that $\hat{y} < y_2$, where y_2 solves $\eta_2(y) = 0$. Because $\eta_2(y)$ is a decreasing function, $\eta_2(\hat{y}) > 0$. In sum, we have $\eta_1(\hat{y}) > 0$ and $\eta_2(\hat{y}) > 0$. Then, differentiating (4) yields $\partial\hat{\theta}/\partial\sigma = r/(2\Delta_0(1-\delta))(\partial\hat{y}/\partial\sigma - (\hat{y}-\mu)/\sigma)(1/\sigma)\phi((\hat{y}-\mu)/\sigma) = (r/(2\Delta_0(1-\delta)))(\mu/2\sigma^2)(\eta_2(\hat{y})/\eta_1(\hat{y}))\phi((\hat{y}-\mu)/\sigma) > 0$, where we used the result $\partial\hat{y}/\partial\sigma - (\hat{y}-\mu)/\sigma = (\mu/2\sigma)(\eta_2(\hat{y})/\eta_1(\hat{y}))$ obtained above. □

Proof of Proposition 7. Under EMC, $\theta^M = 1$ in the limit $K \to 0$, according to Corollary 2. Substituting this yields the expected stage 2 profit $\pi_m^M = rJ(q^M)$, where $q^M = F^{-1}(1-(1/r)(\underline{c}+\delta\Delta_0))$. Under the screening contract, $\pi_m^S = r\int_0^1 J(q^*(z \mid \theta^S))\,dz$, where $q^*(z \mid \theta) = F^{-1}(1-(1/r)[\underline{c}+2\Delta_0(1-(1-\delta)\theta)z])$. Define $\chi_\theta(z) \equiv J(q^*(z \mid \theta)) - J(q^M)$. Observe that

$$
\begin{aligned}
\chi'_\theta(z) &= \frac{\partial}{\partial z}\left(\int_0^{q^*(z|\theta)} xf(x)\,dx - \int_0^{q^M} xf(x)\,dx\right) \\
&= q^*(z \mid \theta)f(q^*(z \mid \theta))\frac{\partial q^*(z \mid \theta)}{\partial z} \\
&= q^*(z \mid \theta)f(q^*(z \mid \theta))\left(-\frac{2\Delta_0(1-(1-\delta)\theta)}{rf(q^*(z \mid \theta))}\right) \\
&= -\frac{2\Delta_0(1-(1-\delta)\theta)}{r}q^*(z \mid \theta) < 0,
\end{aligned}
$$

and $\chi''_\theta(z) > 0$, which follows from the fact that $q^*(z \mid \theta)$ decreases in z. Therefore, $\chi_\theta(z)$ is a convex decreasing function. Consider case (i). According to Corollary 1, $\theta^S = 1$ if $\bar{F}(\hat{y}) \le (1/r)(\underline{c}+2\delta\Delta_0)$. Hence, $\pi_m^S - \pi_m^M = r\int_0^1 \chi_1(z)\,dz$ in this case. Because $\chi_1(z)$ is convex decreasing and $\chi_1(1/2) = 0$, we have $\int_0^{1/2} \chi_1(z)\,dz > -\int_{1/2}^1 \chi_1(z)\,dz$ and therefore $\pi_m^S - \pi_m^M = r\int_0^1 \chi_1(z)\,dz > 0$. Consider case (ii). According to Corollary 1, $\theta^S = 0$ if $\bar{F}(\hat{y}) \ge (1/r)(\underline{c}+2\Delta_0)$. Hence, $\pi_m^S - \pi_m^M = r\int_0^1 \chi_0(z)\,dz$ in this case. Because $\chi_0(z)$ is convex decreasing and $\chi_0(\delta/2) = 0$, $\chi_0(z) > 0$ for $z < \delta/2$ and $\chi_0(z) < 0$ for $z > \delta/2$. Therefore, $\pi_m^S - \pi_m^M = r\int_0^1 \chi_0(z)\,dz = r(\int_0^{\delta/2} \chi_0(z)\,dz + \int_{\delta/2}^1 \chi_0(z)\,dz)$ becomes negative as $\delta \to 0$ and positive as $\delta \to 1$, the latter following from the finding in (i). Combining this with $(\partial/\partial\delta)\chi_0(z) = (\partial/\partial\delta)(-\int_0^{q^M} xf(x)\,dx) = -q^M f(q^M)\partial q^M/\partial\delta > 0$, we conclude that $\pi_m^S - \pi_m^M$ crosses zero exactly once from negative to positive as δ goes from 0 to 1. □

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