Coordinating Supplier Competition via Auctions

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Abstract

This paper studies market schemes in which auctions are used to coordinate the buyer and competing suppliers in a procurement setting. While auction is typically considered a price-determination mechanism, it could also serve as a coordination mechanism. Possible auction and market mechanisms and their expected payoffs are analyzed in a two-supplier, one-buyer system. The auction mechanism could have a significant impact on the payoffs received by the players and on system efficiency. To establish basic insights, we first consider the case where the players have *complete information* on each others' costs. This is followed by *asymmetric information* analysis where the players' costs are private information while each supplier's cost is known probabilistically. Channel coordination can be achieved with a *two-part contract auction* where the buyer announces a price-sensitive order function, and the suppliers compete in an ascending-bid side-payment auction. To achieve coordination, a third-party intermediary must prevent the buyer from manipulating the order function, thus truthfully transferring the market demand function to the suppliers. Insights from the analysis allow us to rank different market mechanisms by their impact on expected channel efficiency, and the expected payoffs for the buyer and the winning supplier.

(Keywords: *Auction, Supply Chain Coordination, Supplier Competition, Contracting, Game Theory)*

1 Introduction

Procurement Auction is a market mechanism in which an object, service, or a set of objects desired by a buyer is communicated to the bidders (suppliers). After the bidders respond, the mechanism specifies the rules that determine which bidder wins the right to supply to the buyer. Auction provides a mechanism that offers the buyer direct assess to numerous competing suppliers at a relatively low search cost. For the suppliers, it offers a transparent form of competition that relies on quantitatively defined terms (e.g., price, delivery time), takes place at a pre-specified time period, and treats the participants nondiscriminatory under the rule. Procurement auction has gained significant momentum over the past decade (Kalagnanam and Parkes, 2004). A key advantage of this form of supplier competition is the significantly increased scalability. Freemarkets, a firm specializes in industrial procurement auctions, reported that in the first quarter of the year 2002 a total of 125 buyers traded in their auction market with about 21,000 suppliers. After Freemarkets' merger with Ariba in July, 2004, not only the scale but the scope of their procurement and sourcing services increase.

Supply chain coordination studies different incentive mechanisms (e.g., contracts) for suppliers and buyers to achieve higher channel (Pareto) efficiency. In recent years, a sizable literature has been developed that proposes different means of supply chain coordination via contracting (see the reviews by Cachon (2004), and Tsay et al. (1999)). As contracts are typically formed between two parties, much of the contracting research focuses on the one-supplier, one-buyer setting. Of particular relevance to this paper is the subset of the coordination literature that examines the effects of competition (Van Mieghem, and Dada 1999). However, most existing research in this regard concentrates on the retailer (buyer) competition: to compete for limited supply, each retailer must decide on an order quantity prior to observing demand; as the ordering decision can be often justified by a newsvendor-type trade-off, these are also known as the *competing newsvendor* models (Lippman and McCardle (1997), Annupindi and Bassok (1999), Li and Ha (2003), Netessine and Rudi (2003), and Mahajan and Van Ryzin, (2001)). In addition to *competing newsvendeor*, there is also a growing literature on market-share competition based on service quality, c.f., Gans (2002), Ha et al. (2003), and Bernstein and Federgruen, (2004). Until quite recently (Cachon and Zhang (2003), Jin and Wu (2002), and Bajaafar et al. (2004)) few researchers examine supplier competition and the implications of this competition to supply chain coordination. This paper is motivated by the following observations:

1. In upstream supply chain operations such as procurements, the competition among suppliers is prevalent. In the context of such competition, auction offers a simple and robust demand allocation mechanism that is not only well-studied in the literature but widely used in practice. Thus, for the same reason that contracting offers a convenient setting to analyze bilateral interactions in the supply chain, auctions provides a useful platform to analyze multilateral interactions such as supplier competitions.

2. There is a vast literature on auctions theory (c.f., the review by Klemperer (1999)) but it has virtually no intersection with the literature on supply chain coordination. Cross fertilization of the two literature-bases could be fruitful and potentially beneficial. On one hand, auction could serve as an integral part of a coordination mechanism and helps to characterize the outcomes of a multi-player competition. On the other hand, the notion of channel coordination establishes new efficiency criteria for the design of auction mechanisms, e.g., does a particular style of auction produces the most efficient outcomes for the buyer *and* the suppliers involved? Could the efficiency be improved?

Motivated by the above observations, this paper sets out to examine supply chain coordination in a procurement context where supplier-competition arises in the context of auctions. We are interested to find out if auction could be incorporated as an integral part of a coordination mechanism that achieve channel efficiency, and the effects of (cost) information asymmetry in this context. The exposition starts with a straightforward *complete information* analysis, leading into the more general *asymmetric information* cases, with more emphasis on the latter. Since information asymmetry introduces inefficiencies that curtail coordination, we are also interested to know if and how a third-party intermediary could eliminate such inefficiency.

In the supply chain contracting literature, researchers also examine the effects of information asymmetry. Cachon and Lariviere (2001) propose contracts that promote information sharing, and they demonstrate the benefits of information sharing to system coordination. Chen (1997) considers the general issue of information decentralization and delay in the supply chain and their effects to efficiency. Ha (1998) study the value of information using the buyer's unit handling cost and its effects on the supplier's decisions. Lee and Rosenblatt (1986) and Weng (1995) consider the use of quantity-discounts as a means to pass demand information and to increase the supplier's profit. Corbett et al. (2004) investigate various two-part contracts under a one-supplier, one-buyer setting and they examine the effects of asymmetric information to the coordination outcomes.

Market intermediaries are only considered in the supply chain literature recently. Wu (2004) provides an overview of theoretical models that examine why intermediaries exist, different forms they operate, and the way they influence supply chain efficiency. Distinctions are drawn between a *transactional intermediary* and an *information intermediary*. The former provides immediacy by buying, selling, and holding inventory, while the latter synthesizes or arbitrates information to reduce information asymmetry. An auctioneer might be considered a form of *information intermediary*. Of relevance to supply chain coordination is the need for a market intermediary who exserts effort so as to ensure a certain trade property. For example, the impossibility theory by Vickrey (1961) states that it is impossible to design a mechanism (such as an auction) that satisfies incentive compatibility and ex post Pareto efficiency at the same time without subsidy. However, as shown in (Wu, 2004), it is possible for the intermediary to exsert efforts so as to stop an unprofitable trade from taking place, thus eliminating the need for subsidy. As we will show later in the paper, to achieve coordination under information asymmetry, it may be necessary for an information intermediary to preside over the trade, and to exsert effort to eliminate inefficiency.

This paper is organized as follows: in the next section, we consider a two-supplier one-buyer system with complete information. This analysis provides basic insights on the effects of supplier competition. In the section that follows and the rest of the paper, we examine the asymmetric information case under four different market schemes; we analyze the relative efficiencies of the market schemes from different players' perspectives. The paper finishes with a summary of main analytical insights, and the conclusions.

2 Two-Supplier, One-Buyer System with Complete Information

This paper considers a two-supplier and one-buyer setting as depicted in Figure 1. A key feature here is that the suppliers must compete to get the buyer's order.

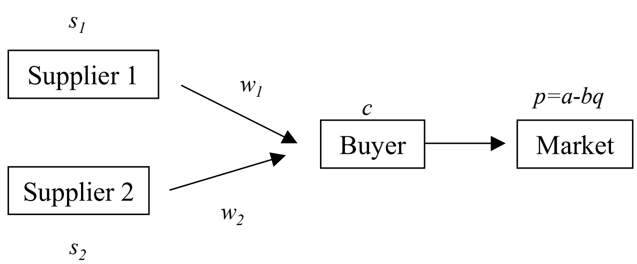

Figure 1. the Two Supplier-One Buyer Contracting Environment

Assume that supplier i has a fixed marginal cost s_i, and the buyer faces a unit handling cost c. Demand in the market is price sensitive as a linear market function: $p = a - bq$ (p: retail price, q: quantity, a, b: positive parameters). To ensure market competitiveness, any supplier i's marginal cost is assumed to satisfy $a - c - s_i \geqslant 0$ and $s_i \leqslant \frac{a-c+\min_j s_j}{2}$. Otherwise, supplier i is considered non-competitive and could not stay in this market.

Without loss of generality, Supplier 1 is assumed to be the lower cost supplier of the two. Thus, the channel coordinated system optimum has order quantity $q_c^* = \frac{a-c-s_1}{2b}$ and profit $\pi_{T,c}^* = \frac{(a-c-s_1)^2}{4b}$. To gain some insights, we first consider three different market schemes under complete information: *(c1) catalog auction without coordi-*

nation, (c2) two-part contract initiated by the suppliers, and *(c3) two-part contract initiated by the buyer.* To compare them with the one supplier case, please refer to the results in the paper of Corbett et al. (2004).

2.1 *Scheme c1*: Catalog Auction without Contract Coordination

We first define *catalog auction* as follows:

1. Each supplier announces her wholesale price w_i for general product categories on an (electronic) catalog. A supplier may *revise* her posted wholesale price in real-time if any other suppliers offer a lower price that is still higher than her own cost.

2. The buyer has direct access to the catalogs and will choose the supplier offering the lowest wholesale price.

3. The buyer determines her order quantity q.

Thus, without conducting a formal auction, the on-line catalog mechanism described above has the essential features of a reverse auction. Under the above scheme, the buyer's decision problem is as follows:

$$b_{c1} : \max_q \pi_{b,c1}(q) = \max_q (a - c - bq - w_{c1})q. \tag{1}$$

The optimal order quantity is $q^*_{c1} = \frac{a-c-w_{c1}}{2b}$. Thus, the supplier's problem is as follows:

$$S_{c1} \quad : \quad \max_{w_{c1}} \ \pi_{s,c1}(w_{c1}) \tag{2}$$

$$\textit{where } \pi_{s,c1}(w_{c1}) \quad = \quad q^*_{c1}(w_{c1} - s) = \frac{a - c - w_{c1}}{2b}(w_{c1} - s). \tag{3}$$

Because of the competition from supplier 2, the best strategy for Supplier 1, who has the lower cost, is to set her wholesale $w_{c1} = s_2$ to maximize her profit. Thus, the profit for Supplier 1 is:

$$\pi^*_{s_{1,c1}} = \frac{(a - c - s_2) \cdot (s_2 - s_1)}{2b}, \tag{4}$$

and the profit for the buyer is

$$\pi^*_{b,c1} = \frac{(a - c - s_2)^2}{4b}. \tag{5}$$

with the order quantity $q^*_{c1} = \frac{a-c-s_2}{2b}$. Since $s_2 > s_1$, the system can not reach channel coordination and will have a lower order quantity. The phenomenon is consistent with the result of *double marginalization* in the one-supplier, one-buyer system. However, due to the competition, the buyer's profit increases, and the system is closer to channel coordination, compared to the one-supplier system. Without any coordination, the buyer gains more profit by introducing competition among the suppliers. This is consistent with the intuition from the Bertrand model of price competition (Bernstein and Federgruen, 2000).

In principal/agent contracting literature (Fundenberg and Tirole, 1990), it is typically assumed that under complete information the principal (the buyer) will be able to enforce a selling price marginally above the agent's (the supplier) participation constraint defined by π_s^- (i.e., the minimal acceptable profit for the agent to participate in the transaction). Such an assumption would essentially eliminate all impacts of competition. We do not adopt the same assumption in Scheme $c1$ for the following reasons: first, catalog auction does not provide an *incentive compatible* mechanism that would motivate the agent to act in the interest of the principal. Second, under the setting of catalog auction, it would be unrealistic for the suppliers to justify a participation threshold that would truly represent the *individual rationality constraint*, as in the simple contract setting.

2.2 *Scheme c2*: Two-Part Contract Auction Initiated by the Suppliers

We now show that under a supplier-initiated two-part contract, the buyer could still extract more profit by introducing competition. Consider a two-part contract auction as follows:

1. The suppliers compete in a two-part contract auction where they each proposes a wholesale price w and a side payment L to be charged to the buyer (e.g., the engineering fee).

2. The buyer first chooses the more favorable of the two contracts, then determines her order quantity q. The suppliers' decision problem is as follows:

$$S_{c2} \qquad \max_{w,L} \; \pi_{s,c2}(w_{c2}, L_{s,c2}) \tag{6}$$

where
$$\pi_{s,c2}(w_{c2}, L_{s,c2}) = q^*_{c2}(w_{c2} - s) + L_{s,c2} = \frac{a - c - w_{c2}}{2b}(w_{c2} - s) + L_{s,c2} \; . \tag{7}$$

From previous results, we know that the suppliers should set the wholesale price at cost and extract profits only from the side payment. Since Supplier 2 has higher cost $w_{c2} = s_2$, she must lower her side payment L in order to compete with Supplier 1 . However, the most she could do is to set $L = 0$, and she receives no profit

($\pi_s = 0$). Thus, the buyer would extract all channel profit, i.e., $\frac{(a-c-s_2)^2}{4b}$. Under complete information, this amount would be the minimum that the buyer expects. In order to win the auction, Supplier 1 must offer a discount on the side payment no less than the amount of $\frac{(a-c-s_2)^2}{4b}$. Thus, the best strategy for Supplier 1 is to offer the following contract:

$$L_{s,c2} = \frac{(a-c-s_1)^2}{4b} - \frac{(a-c-s_2)^2}{4b} \text{ and } w_{c2} = s_1. \tag{8}$$

Under this scheme, the system will achieve channel coordination, but the supplier can not extract channel profit as in the one-supplier, one-buyer case Corbett et al. (2004). Thus, the buyer gains a profit of $\frac{(a-c-s_2)^2}{4b}$ because of the competition.

2.3 *Scheme c3*: Two-Part Contract Auction Initiated by the Buyer

We now propose a buyer-initiated two-part contract auction that can also achieve channel coordination:

1. The buyer announces a side payment L_b to be charged from the suppliers, and commits to place an order based on a function of the wholesale price: $q = \frac{a-c-w}{b}$.

2. Given the announced order function, the suppliers compete in a wholesale price auction, which results in w.

3. The buyer places an order with the amount of q based on w and the announced order function.

The above scheme achieves channel coordination as the buyer's order function transfers the market demand function to the supplier after deducting the buyer's unit handling cost c. When Supplier 1 has a minimal required profit, $\pi_{s_1}^-$, and it is known by the buyer, the buyer can extract the channel profit from the side payment as $L_b = \frac{(a-c-s_1)^2}{4b} - \pi_{s_1}^-$. Supplier 1 will win the auction with wholesale price $w = \frac{a-c+s_1}{2}$ and the resulting order quantity is$\frac{a-c-s_1}{2b}$. However, in reality, the buyer may not know with certainty the suppliers' profit functions, minimal required profits, and/or marginal supply costs.

3 Two-Supplier, One-Buyer System with Asymmetric Information

The complete information analysis establishes basic insights for supplier competition in the two-supplier, one-buyer system. From now, we will focus on the more general case where the suppliers and the buyer hold asymmetric cost information. Each supplier i knows only her own marginal cost s_i, and the buyer knows her own unit handling cost c. The market still faces a price sensitive demand $p = a - bq$, where a is only known by the buyer while b is assumed to be public information. A market intermediary is assumed to represent the third-party market maker. The buyer holds a prior probability density function $f(s)$ with supports $\underline{s}$ and $\bar{s}$ over the suppliers' marginal cost s_i, and she believes that $s_1$and s_2 are independent from each other. Supplier i holds the same prior probability density function $f(s)$ over the other supplier's marginal cost s_j. This prior distribution function may be offered by the market intermediary, who has access to historic supplier information and is willing to share this information in order to attract more customers into the market. We assume that these functions are correct and stationary and have credibility among all players. To streamline the analysis, we make some additional assumptions on the density function. Define random variable $t = s - \underline{s}$, and random variable T as the *larger* number of any two samples of random variable t. We assume that $f(s)$ satisfies the inequalities $E[t^2] \geq E[T] \cdot E[t]$ and $2E[T] \leq 3E[t] \leq 2.5E[T]$. These assumptions are satisfied by most distribution functions such as Uniform,Weibull and its special cases. All players in this market are assumed to be risk-neutral, so the expected profit is their only concern. It is still assumed that the market imposes a competitiveness requirement, $\bar{s} \leq \frac{a-c+\underline{s}}{2}$ on all participating players.

We examine four different forms of auction for the interest of achieving supply channel coordination: *(a1) wholesale price auction,* where the suppliers bid wholesale prices for an order with announced quantity, *(a2) catalog auction,* where the buyer determines the order quantity based on suppliers' posted catalog prices, *(a3) two-part contract auction,* where side payments are introduced for channel coordination, but the buyer's retail price and handling cost are observable by the market intermediary, and *(a4)* the same as *a3* except that the retail price and the handling cost are buyer's private information. The focus of our exposition will be to analyze the impact of different auction mechanisms on the interests of the suppliers and the buyer.

3.1 The System Optimal Solution

We first establish the system optimal solution as a benchmark. Suppose there is a central agent in the system, and the suppliers and the buyer submit their true costs voluntarily. A channel coordinated solution determines which supplier would process the current order with what quantity so as to optimize the system profit. The central agent will assign the order to the supplier with smaller marginal cost, and the maximal profit $\pi_T^*(s_1, s_2)$ is

$$\pi_{T,a}^*(s_1, s_2) = \frac{(a - c - \min(s_1, s_2))^2}{4b} \tag{9}$$

with the optimal quantity

$$q_a^*(s_1, s_2) = \frac{a - c - \min(s_1, s_2)}{2b}. \tag{10}$$

The expected maximal profit for the system will be

$$E[\pi_{T,a}^*] = 2\int_{\underline{s}}^{\bar{s}} \frac{(a-c-s)^2}{4b} f(s)[1-F(s)]ds, \tag{11}$$

and the expected optimal quantity with central agent will be

$$E[q_a^*] = \frac{a - c - 2E[s] + 2\eta}{2b}. \tag{12}$$

Here, $\eta = \int_{\underline{s}}^{\bar{s}} sf(s)F(s)ds$ and $E[s] = \int_{\underline{s}}^{\bar{s}} sf(s)ds$. If the distribution function is uniform, η would be $\frac{2\bar{s}+\underline{s}}{6}$.

3.2 *Scheme a1:* Wholesale Price Auction

In a buyer-centric procurement market, the most straightforward and widely adopted form of auction would be the *wholesale price auction*, also known as the reverse auction. The sequence of the events is as follows:

1. The buyer announces her order quantity q with other order specifications.
2. The suppliers bid on the wholesale price w through a simultaneous descending bid auction. The wholesale price is determined from the result of the auction.
3. The order is transacted between the buyer and the winning supplier following the announced quantity.

Since simultaneous descending bid auction is used, the resulting wholesale price as $w(s_1, s_2) = max(s_1, s_2)$, and the lowest price supplier will be rewarded the second lowest price. Note that from the buyer's perspective $s_1$and s_2 are random variables with known density function. The decision problem for the buyer is as follows:

$$\begin{aligned}
B_{a1} \qquad & \max_q E[\pi_{b,a1}(q)] \qquad (13)\\
where \qquad & \pi_{b,a1}(q, s_1, s_2) = (p(q) - c - w)q \\
& \qquad\qquad = (a - c - bq - max(s_1, s_2))q.
\end{aligned}$$

The optimal quantity q_{a1} to $B_{a1}$is

$$q_{a1} = \frac{a - c - 2\eta}{2b}. \tag{14}$$

Given (s_1, s_2), the profit for the buyer is

$$\pi_{b,a1}(s_1, s_2) = \frac{[a - c + 2\eta - 2\max(s_1, s_2)](a - c - 2\eta)}{4b}, \tag{15}$$

and the optimal expected profit for the buyer will be

$$E[\pi^*_{b,a1}] = \frac{(a - c - 2\eta)^2}{4b}. \tag{16}$$

For any distribution function $f(s)$ defined in a bounded interval, we have $2\eta \geqslant E[s]$. Thus, the expected optimal profit for the buyer can be found through η, which is the half of the expected cost of the higher-cost supplier. On the other hand, each supplier i knows her own marginal cost s and the prior distribution of the other supplier's marginal cost. Therefore, the expected profit for a specific supplier with marginal cost s is as follows:

$$E[\pi_{s,a1}(s)] = \frac{a - c - 2\eta}{2b} \int_s^{\bar{s}} (x - s) f(x) dx. \tag{17}$$

Given (s_1, s_2) , the system's profit function is

$$\pi_{T,a1}(s_1, s_2) = \frac{(a - c - 2\eta)(a - c + 2\eta - 2\min(s_1, s_2))}{4b}, \tag{18}$$

and the expected value for the system's profit is

$$E[\pi_{T,a1}] = \frac{(a - c - 2\eta)(a - c + 6\eta - 4E[s])}{4b}. \tag{19}$$

Theorem 1 *Regardless of the prior distribution of the supplier's cost, the wholesale price auction results in (a) lower expected total profit, and (b) lower expected order quantity, when compared to the system optimum.*

The result concerning lower expected profit should be intuitive and is trivial to prove. The result concerning lower expected order quantity follows directly from (12), (14), and the fact that $2\eta \geqslant E[s]$. While the above result seems similar to the double marginalization results under complete information, it is in fact because of asymmetric information. With uncertainty on the suppliers' cost, the buyer acts more conservatively and orders less than the optimal amount.

3.3 *Scheme a2:* Catalog Auction

We now re-examine the *catalog auction* scheme introduced in the complete information cases. This is another common form of buyer-supplier interaction in the procurement setting. Under this scheme, each supplier posts her wholesale price in an on-line catalog for each general product category, and she may *revise* her posted prices in response to competition. Kephert, et al. (2000) study price dynamics of electronic catalog sales under software agents known as *shopbot* and *pricebots.* Given the seller-posted items and prices in a variety of electronic catalogs, the buyer may deplete a shopbot (c.f., *addall.com* for book shopping) to compare prices for a particular product on the web and to find the best prices. On the other hand, the seller may deplete a pricebot, an automated pricing agent, to investigate posted prices by her competitors and to adjust the posted catalog price automatically. The use of software agents such as the pricebot makes on-line catalog posting essentially a form of auction. *Books.com*, for instance, uses pricebot to automatically adjust its listed prices such that they are slightly less than the minimum prices offered by *Amazon, Barnes and Noble,* and *Borders*, so long as the prices are still above the costs.

Catalog auction can be viewed as a variant of the *wholesale price auction* as follows:

1. The suppliers participate in a simultaneous descending bid wholesale price auction for general product categories. The auction determines the wholesale price w.

2. The buyer chooses the order quantity q based on the wholesale price w.

The buyer's decision problem now becomes the following:

$$\begin{aligned} B_{a2} \qquad & \max_q \ \pi_{b,a2}(q, s_1, s_2), \qquad (20) \\ \textit{where} \qquad & \pi_{b,a2}(q, s_1, s_2) = (p(q) - c - \max(s_1, s_2))q. \end{aligned}$$

The optimal quantity $q_{a2}(s_1, s_2)$ for the buyer can be expressed as

$$q_{a2}(s_1, s_2) = \frac{a - c - \max(s_1, s_2)}{2b}, \qquad (21)$$

and the optimal profit for the buyer is

$$\pi^*_{b,a2}(s_1, s_2) = \frac{(a - c - \max(s_1, s_2))^2}{4b}. \qquad (22)$$

The expected profit for the buyer will be as follows:

$$E[\pi^*_{b,a2}] = \frac{(a-c)^2 - 4\eta(a-c) + 2\int_{\underline{s}}^{\bar{s}} s^2 F(s) f(s) ds}{4b}. \qquad (23)$$

For supplier i with cost s, her expected profit with given parameters a, b,and c will be

$$E[\pi_{s,a2}(s)] = \frac{(a-c)\int_s^{\bar{s}}(x-s)f(x)dx - \int_s^{\bar{s}}(x-s)xf(x)dx}{2b}. \tag{24}$$

Theorem 2 *When compared to the wholesale price auction, the catalog auction leads to (a) higher expected profit for the buyer, i.e.,* $E[\pi_{b,a2}(a,b,c)\ ] \geqslant E[\pi_{b,a1}(a,b,c)]$ *, and (b) lower expected profit for the supplier, i.e.,* $E[\pi_{s,a2}(a,b,c,s)\ ] \leqslant E[\pi_{s,a1}(a,b,c,s)\ ]$ *for any given market parameters* $a, b,$ *and* c*.*

The formal proof of this theorem can be found in the Appendix. The total profit for the system can be expressed as follows:

$$\pi_{T,a2}(s_1,s_2) = \frac{a-c+\max(s_2,s_1) - 2\min(s_1,s_2)(a-c-\max(s_1,s_2))}{4b}. \tag{25}$$

The optimal order quantity decided by the buyer is

$$q_{a2}(s_1,s_2) = \frac{a-c-\max(s_1,s_2)}{2b},$$

and the expected order quantity is

$$E[q_{a2}] = \frac{a-c-2\eta}{2b}. \tag{26}$$

The expected value for the system's profit is

$$\begin{aligned} E[\pi_{T,a2}(s_1,s_2)] &= 2\int_{\underline{s}}^{\bar{s}}[\int_{\underline{s}}^{s_2} \frac{(a-c+s_2-2s_1)(a-c-s_2)}{4b} f(s_{2)}ds_2]f(s_{1)}ds_1 \\ &= \frac{(a-c)(a-c+4\eta-4E[s])+2E^2(s) - 2\int_{\underline{s}}^{\bar{s}} s^2 f(s)F(s)ds}{4b} \end{aligned} \tag{27}$$

Theorem 3 *When compared to the wholesale price auction, the catalog auction yields (a) the same expected order quantity, but (b) higher expected system profit if and only if the following condition is satisfied:* $2E[(M-E[s])^2] \geqslant 3E[(M-E[M])^2]$*, where* $M = max(s_1,s_2)$ *and* $E[M] = 2\eta$*.*

The above condition can be easily obtained by comparing 19 and 27. Given the suppliers' cost distribution function, the market efficiency of the *wholesale price auction* and the *catalog auction* varies. Unfortunately, neither scheme could achieve channel coordination that maximizes the expected system profit.

Theorem 4 *Regardless of prior distribution on the supplier's cost, the catalog auction results in (a) lower expected total profit, and (b) lower expected order quantity, when compared to the system optimum.*

Because the wholesale price auction and the catalog auction result in the same expected order quantity (Theorem 3), the first part of the theorem is straightforward, while the proof for the second part is similar to that of Theorem 1.

3.4 Coordination Based on the Two-Part Contract Auction

As shown by Theorems 1 and 4, neither of the above two market schemes results in channel coordination. Since both schemes are common practice in procurement, it is of interest to explore improvements that would overcome the inherit inefficiency. As stated above, a main source of inefficiency is information asymmetry, which is further complicated by supplier competition. A key issue is that due to the uncertainty associated with the (winning) supplier's cost, the buyer will act conservatively and orders less than the optimal quantity. The complete information analysis ($c3$) shows that a *two-part contract auction* could achieve channel coordination: the buyer announces an order function and a side payment, the former transfers the market demand function to the supplier while recovering the buyer's handling cost, the latter extracts additional system surplus (for the buyer). Under asymmetric information, a similar two-part contract scheme would encounter two main difficulties: (1) without knowing the suppliers' costs, the buyer will not be able to calculate the side payment ex ante, and (2) the buyer may have incentive to misrepresent his handling cost and extracts additional gains. To address these issues, we first introduce a modified two-part contract scheme where the suppliers enter an auction to determine the side payment. We then explore the roles of an *information intermediary* who provides a means to mitigate adverse selection due to information asymmetry.

In the following, we outline a *two-part contract auction* scheme modified from ($c3$). The basic scheme includes an order charge $w \cdot q$, and a side payment L from the supplier to the buyer. The sequence of events is as follows:

(Two-Part Contract Auction)

1. The buyer announces an *order function* in w : $q = \frac{(\hat{k}-w)}{b}$, where $\widehat{k}$ is determined by the buyer.

2. The suppliers attend a simultaneous ascending bid auction on the side payment L.

3. The winning supplier sets the wholesale price w^*.

4. The order quantity is determined by the announced order function and the wholesale price w^*, i.e., $\frac{(\hat{k}-w^*)}{b}$.

5. The transaction takes place between the buyer and the winning supplier with the final order quantity of $\frac{(\hat{k}-w^*)}{b}$.

Unlike the wholesale price auction (where the buyer commits to an order quantity up-front) the buyer commits to an order function that is a function of the wholesale price; this allows the buyer to pass on the market demand information without losing her flexibility. The suppliers are assured that the final transaction will take place based on the order function, which gives them confidence to make their decisions of L and w^* by solving a deterministic optimization problem. We separate the decisions of L and w^* so that the auction mechanism itself is simple and the suppliers still have the incentive to reveal their true costs. Now consider the practicalities of the proposed scheme. The two key elements of the above scheme are motivated by contract mechanisms practiced in the industry. First, the auction on the supplier's side payment L is similar in concept to the auction on *slotting allowance* demanded by large retailers from competing vendors (for shelf access), a widespread practice in the retail industry (FTC, 2001). Slotting allowance provides the retailer an opportunity to generate additional revenues, taking advantage of the competition for scarce shelf space. It also provides a risk-sharing mechanism between the retailer and the vendors in the case of new product introduction. Second, the use of a buyer-announced *order function* is common in fuel procurement contracts in the utility industry (Bonser and Wu, 2001). As the demand on energy and the fuel prices could both fluctuate significantly during the contract period, the contract agreement (which has to be specified *ex ante*) stipulates the order quantity as a function of a certain price index. In this context, the two-part contract auction could be augmented such that Steps 1 and 2 take place early on during contract negotiation, while Steps 3 to 5 occur over time as the demands unfold. However, this extension requires more complex dynamic game analysis, which we will not address in this paper.

In the following, we will examine two variants of the *two-part contract auction* scheme: in the first setting, there is an *information intermediary* who eliminates the opportunity for the buyer to manipulate the unit handling cost. In the second case, there is no *information intermediary* and the retail price and unit handling cost are private information owned by the buyer. The main purpose of the analysis is to explore the effect of information asymmetry to coordination, and the potential benefit of an *information intermediary.*

3.4.1 *Scheme a3:* Two-Part Contract Auction with Information Intermediary We first consider two-part contract auction under *Scheme a3* in which an *information intermediary* presides over the trade. A key role of the intermediary is to audit the buyer's handling costs c and to impose a restriction such that the buyer's retail price covers only the wholesale price she pays and the unit handling cost she incurs. The buyer is compensated with a portion of the system surplus via the side payment. The suppliers compete in the side- payment auction that determines the winning supplier and the sidepayment amount. Note that the market base price a remains the buyer's private information. We will show that this scheme stops the buyer from manipulating the retail price, while passing the market demand information truthfully to the suppliers.

Theorem 5 *If the information intermediary imposes a restriction on pricing as $p = w + c$, the two-part contract auction yields channel coordination.*

A supplier with marginal cost s may calculate her maximal attainable profit as $\frac{(\hat{k}-s)^2}{4b}$ after the buyer's order function is announced. Since the supplier who loses the side payment auction will have zero gain, the low-cost supplier must offer a side payment no less than $L(s_1, s_2, \hat{k}, b) = \frac{(\hat{k}-\max(s_1,s_2))^2}{4b}$. As specified in Step 3 of the two-part contract auction scheme, the winning supplier from the side payment auction will solve a decision problem to determine the wholesale price w^*. Suppose Supplier 1 wins the auction, she will solve the following problem:

$$S_{a3} \qquad \max_{w} \ \pi_{s,a3}(w, s_1) = \frac{(w - s_1)(\hat{k} - w)}{b} - L. \tag{28}$$

The solution to this problem is

$$w_{a3} = \frac{\hat{k} + s_1}{2}, \text{ and } \ q_{a3} = \frac{\hat{k} - s_1}{2b}. \tag{29}$$

Since the intermediary imposes a restriction on the retail price as $p = w + c$, the profit maximizing problem for the buyer would be

$$B_{a3} \qquad \max_{\hat{k}} \ \pi_{b,a3}(\hat{k}, b, s_1, s_2) \tag{30}$$

$$where \ \pi_{b,a3}(\hat{k}, b, s_1, s_2) = \begin{cases} \frac{(\hat{k}-\max(s_1,s_2))^2}{4b} & \text{if } \hat{k} \leqslant a - c \\ \frac{(\hat{k}-\max(s_1,s_2))^2}{4b} - \frac{(\hat{k} \ -a+c)}{b} \cdot \frac{\hat{k}+\min(s_1,s_2)}{2} & \text{if } \hat{k} > a - c \end{cases}$$

When $\hat{k} > a-c$, the buyer will order $\frac{\hat{k}-\min(s_1,s_2)}{2b}$, but she can only sell $\frac{2a-2c-\hat{k}-\min(s_1,s_2)}{2b}$ with the wholesale price $\frac{\hat{k}+\min(s_1,s_2)}{2} + c$ so that she has to face a loss from the order. The solution for the buyer will be thus $\hat{k} = a - c$. In other words, the buyer will truthfully transfer the market demand function to the suppliers after deducting her unit handling cost. Thus, we get $q_{a3} = \frac{a-c-\min(s_1,s_2)}{2b} = q^*$ so that the system achieves channel coordination. The buyer will receive profit as follows:

$$\pi_{b,a3}(s_1, s_2) = \frac{(a - c - \max(s_1, s_2))^2}{4b}. \tag{31}$$

Note that the buyer's profit is restricted to the side payment from the winning supplier, and the amount of the profit is equivalent to what she would receive under *catalog auction (a2)*. More interestingly, the supplier would receive higher expected profit under the current scheme. This is shown in the following theorem.

Theorem 6 *Compared to the catalog auction (a2), the two-part contract auction under Scheme a3 yields (a) the same expected profit for the buyer, but (b) higher expected profit for the supplier.*

Proof: Part (a) of the theorem is trivial to prove. To prove part (b), suppose Suppliers 1 and 2 have marginal costs $s_1$and s_2 respectively, and $s_1 < s_2$. The profit for Supplier 1 would be

$$\pi_{s1,a3}(s_1, s_2) = \frac{(a-c-s_1)^2}{4b} - \frac{(a-c-s_2)^2}{4b}.$$

For the supplier with cost s, the expected profit is

$$E[\pi_{s,a3}(s)] = \frac{2(a-c)\int_s^{\bar{s}}(x-s)f(x)dx - \int_s^{\bar{s}}(x^2-s^2)f(x)dx}{4b}. \quad (32)$$

Comparing this with the expected supplier profit $E[\pi_{s,a2}(s)]$ under *catalog auction* , we can verify part (b) knowing the fact that $\int_s^{\bar{s}}(x-s)^2 f(x)dx \geq 0$. □

Recall that *catalog auction (a2)* generates less profits for the supplier than *wholesale price auction (a1)*. In the following, we show that *Scheme a3* could be more attractive than *a1* for a supplier with cost below a certain threshold.

Theorem 7 *Compared to the wholesale price auction (a1), the two-part contract auction under Scheme a3 yields higher expected profit for the supplier who has a marginal cost $s \leqslant 4\eta - \bar{s}$.*

The proof of this theorem is provided in the Appendix. Although not all suppliers can have higher expected profit, the ones with cost below the stated threshold would indeed gain a higher profit. This should benefit the supply chain in the long run. Obviously, the buyer gets more profit under the current scheme than *wholesale price auction*.

3.4.2 *Scheme a4*: Two-Part Contract Auction without Intermediary

We now consider two-part contract auction when there is no information intermediary; the unit handling cost c and the market base price a are both private information owned by the buyer. It will be shown that in this case the buyer has incentive to manipulate the order function $(\widehat{k})$ for her own gain, and will not truthfully transfer the market demand function to the supplier. Again, we assume that $s_1 \leqslant s_2$.

Theorem 8 *In two-part contract auction under Scheme a4, the buyer has incentive to inflate her unit handling cost c, or deflate the base market price a when computing* $\hat{k}$ *in the order function (Step 1).*

The buyer's decision problem is as follows:

$$B_{a4} \qquad \max_{\hat{k}} \; E[\pi_{b,a4}(\hat{k}, s_1, s_2)], \tag{33}$$

$$\textit{where} \qquad \pi_{b,a4}(\hat{k}) = \frac{(2(a-c)-\hat{k}-s_1)(\hat{k}-s_1)}{4b} + \frac{(\hat{k}-s_1)^2-(\hat{k}-s_2)^2}{4b}.$$

Solving problem B_{a4}, we can get

$$\hat{k}_{a4} = a - c + 2E[s] - 4\eta. \tag{34}$$

Because $2\eta - E[s] \geqslant 0$, the reported $\hat{k}_{a4}$ is less than the true value $a - c$.

Theorem 9 *Compared to the wholesale price auction (a1) and the catalog auction (a2), the two-part contract auction under Scheme a4 yields (a) higher system profit , but (b) equivalent expected order quantity.*

Part (b) is easy to verify, the expected order quantity is as follows:

$$E[q_{a4}] = E[\frac{a-c+2E[s]-4\eta-s_1}{2b}] = \frac{a-c-2\eta}{2b}. \tag{35}$$

The expected profit for the system is

$$E[\pi_{T,a4}] = \frac{(4E[s]-4\eta)^2+(a-c)4\eta-4E[s])(a-c)+2E[s^2]-2\int_{\underline{s}}^{\bar{s}} s^2F(s)f(s)ds}{4b}. \tag{36}$$

Comparing this expression with (19) and (27), we find that $E(\pi_{T,a4}) \geqslant E(\pi_{T,a1})$ and $E(\pi_{T,4}) \geqslant E(\pi_{T,a2})$. The proof is given in the Appendix.

Theorem 10 *Compared to the wholesale price auction (a1) and the catalog auction (a2), the two-part contract auction under Scheme a4 yields higher expected profit for the buyer.*

This theorem is intuitively obvious. Since the buyer would get the same (more) profit as in the *catalog auction (wholesale price auction)* by truthfully transferring the market demand to the supplier (as in *a3*), the buyer would gain the same or more profit by manipulating $\hat{k}$. Now consider the impact to the supplier. The wholesale price for the winning supplier is

$$w_{a4} = \frac{a-c+2E[s]-4\eta+s_1}{2}.$$

For the supplier with marginal cost s, the expected profit is

$$E[\pi_{s,a4}(s)] = \frac{2(a-c+2E[s]-4\eta)\int_s^{\bar{s}}(x-s)f(x)dx - \int_s^{\bar{s}}(x^2-s^2)f(x)dx}{4b}. \quad (37)$$

Whether (*a4*) can yield more expected profit for the supplier than other schemes depends on the distribution function $f(x)$ and the marginal cost s. It is more difficult to reach a general conclusion. In summary, by comparing $E[\pi_{T,a4}]$ and $E[\pi_{T,a3}]$, we may conclude that the presence of an information intermediary who exerts effort to learn the buyer's unit handling cost c and market parameter a, could improve overall the system profit by $\frac{(E[s]-2\eta)^2}{b}$.

4 Discussion and Conclusions

In this paper, we examine supply chain coordination under supplier competition in a procurement setting. It is shown that information asymmetry and different forms of market scheme have a significant impact to overall system efficiency. In the following, we will conclude our findings and rank the four market schemes based on different players' perspectives.

Complete Information Cases (Schemes c1 to c3):

When competition is introduced among the suppliers, the buyer always benefits. Without contract coordination (*c1*), the buyer gets more profit since the suppliers face a Bertrand price competition which forces them to set a lower wholesale price. The buyer even benefits from a supplier-initiated two-part contract auction (*c2*), because the winning supplier with the lowest cost must charge a lower side payment in order to stop the buyer from choosing the competitor. In the case of a buyer initiated two-part contract (*c3*), the buyer announces a price-sensitive order *function* and a fee from the winning supplier; the suppliers in turn determine the wholesale price. In this case, the buyer has the incentive to transfer the market demand function to the supplier after deducting her unit handling cost. Both two-part contract auctions (*c2* and *c3*) achieve channel coordination.

Asymmetric Information Case (Schemes a1 to a4):

1. Most simple price auctions in procurement can be considered a form of *wholesale price auction* where the buyer specifies the features of an order (e.g., order quantity), and the suppliers bid on the wholesale price through an auction. This auction results in lower expected order quantity and lower expected system profit than the channel coordinated solution. The inefficiency is due to information asymmetry; with only the suppliers' cost distributions, the buyer behaves more conservatively, which results in a smaller-then-optimal order quantity.

2. Supplier posted electronic catalog is considered in a procurement setting. Since the pricing in catalogs could be real-time updated in response to competition, this is a form of auction: *catalog auction*. In this case, the buyer determines the order quantity using the catalog posted wholesale price (after competition). The buyer's risk is reduced due to the decreased pricing uncertainty and is expected to gain more profit. The suppliers are expected to earn less profit in the catalog auction than in the case without competition. Compared with the wholesale price auction, the catalog auction yields the same expected order quantity but achieves higher expected system profit. However, the expected order quantity and system profit are both lower than the system optimum.

3. We proposed a *two-part contract auction* where a side payment from the supplier to the buyer (e.g., slotting allowance) is to be included as a part of the contract. The buyer's announcement of a price-sensitive *order function* rather than a definite *order quantity* is a key feature here. Knowing this order function, the suppliers participate in an auction on the side payment. The supplier who offers the highest side payment wins the order, and this supplier sets the wholesale price based on the order function and her own cost structure. The final order quantity is determined by the buyer's order function and the wholesale price. The two-part contract auction achieves channel coordination when the market intermediary places restriction on the retail price by knowing the base market price and the buyer's handling cost. However, if the base market price and/or the buyer's handling cost are private information, the buyer has incentive to inflate her handling costs and/or deflate the market price when computing the order function. This has a negative effect to the suppliers' profit, and channel coordination is no longer guaranteed. Nonetheless, in either case the two-part contract auction achieves higher channel efficiency than the commonly seen *wholesale price auction* and *catalog auction*.

Ranking the Market Schemes

We now rank the market schemes from the viewpoints of different players and the system as a whole. Based on channel efficiency (measured in the total system profits), the four market schemes are ranked in the order of *a3, a4* and *a2* or in the order of *a3, a4 and a1*. We could only rank *a2* above *a1* when the special condition stated in Theorem 3 is satisfied. On the other hand, the buyer would prefer the ranking of *a4, (a3* tie *a2*), and *a1*. In general, two-part contract auction achieve better system efficiency *and* buyer profitability than the other two auctions. The suppliers would prefer the *wholesale price auction* (*a1*) over the *catalog auction* (*a2*). Of the *two-part contract auction,* the supplier would prefer *a3* over *a4* and prefer *a3* over *a2*. Furthermore, a low-cost supplier as defined in Theorem 7 would prefer *a3* over *a1*.

In general, the supplier's expected profit is more difficult to compare as it depends on the supplier's marginal cost distribution function.

This paper focuses on a two-supplier one-buyer system, but similar results could be obtained for n-suppliers systems. Moreover, we assume the supplier's cost is linear in quantity, but in reality, the marginal cost may be convex or concave. In either case, a single distribution function is not sufficient to describe the supplier's cost under asymmetric information. This would complicate the buyer's order quantity decisions, especially under the wholesale price auction and catalog auction. However, the buyer's decision under two-part contract auction will not be affected as much, and the system can still reach the channel coordination.

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Appendix

Proof of Theorem 2.

To prove $E[\pi_{b,a2}(a,b,c)\ ] \geq E[\pi_{b,a1}(a,b,c)\ ]$:

Because $\int_{\underline{s}}^{\bar{s}}(s-2\eta)F(s)f(s)ds = 0$ and $(s-2\eta)F(s)f(s)$ changes from negative to positive exactly once between $[\underline{s},\bar{s}]$, we can assume that $D = -\int_{\underline{s}}^{2\eta}(s-2\eta)F(s)f(s)ds = \int_{2\eta}^{\bar{s}}(s-2\eta)F(s)f(s)ds \geq 0$. Mean Value Theorem implies that

$$
\begin{aligned}
(E[\pi_{b,a2}\ ] - E[\pi_{b,a1}\ ])\cdot 2b &= \int_{\underline{s}}^{2\eta} s(s-2\eta)F(s)f(s)ds + \int_{2\eta}^{\bar{s}} s(s-2\eta)F(s)f(s)ds \\
&= D(\alpha-\beta)
\end{aligned}
$$

here $\alpha \in [2\eta,\bar{s}]$ and $\beta \in [\underline{s},2\eta]$, which indicates $\alpha \geq \beta$. Thus, we get the result $E[\pi_{b,a2}(a,b,c)\ ] \geq E[\pi_{b,a1}(a,b,c)\ ]$. $\square$

To prove $E[\pi_{s,a1}(s)\ ] \geq E[\pi_{s,a2}(s)\ ]$:

Define $G(s) = (E[\pi_{s,a1}(s)\ ] - E[\pi_{s,a2}(s)\ ])\cdot 2b = \int_{s}^{\bar{s}}(x-2\eta)(x-s)f(x)dx$

Obviously when $s \geq 2\eta$, $G(s) \geq 0$. In general, $G(s) = \int_{\underline{s}}^{\bar{s}}(x-2\eta)(x-s)f(x)dx - \int_{\underline{s}}^{s}(x-2\eta)(x-s)f(x)dx$

$$
\begin{aligned}
\frac{dG}{ds} &= 2\eta - E[s]\int_{s}^{\bar{s}}(2\eta-x)f(x)dx \\
\frac{d^2G}{ds^2} &= (s-2\eta)f(s)
\end{aligned}
$$

Since $\frac{d^2G}{ds^2} \leqslant 0$, when $s \leqslant 2\eta$, $G(s)$ is a concave function in s between $[\underline{s}, 2\eta]$. With the assumption that $E[(s-\underline{s})^2] \geq E[M-\underline{s}] \cdot E[s-\underline{s}]$, we know $G(\underline{s}) \geq 0$. So, we get $G(s) \geq 0$, for any s in $[\underline{s}, \bar{s}]$, with the fact that $G(s) \geq 0$ when $s \geq 2\eta$. $\square$

Proof of Theorem 7. To prove $E[\pi_{s,a3}(s)] \geq E[\pi_{s,a1}(s)]$

when $s \leq 4\eta - \bar{s}$, clearly $s \leq 2\eta$

$$\begin{aligned}
\Delta(s) &= (E[\pi_{s,a3}(s)] - E[\pi_{s,a1}(s)]) \cdot 4b \\
&= (\bar{s}-s)(4\eta - \bar{s} - s) - \int_{2\eta}^{\bar{s}} (4\eta - 2x)F(x)dx - \int_{s}^{2\eta} (4\eta - 2x)F(x)dx \\
&\geq (\bar{s}-s)(4\eta - \bar{s} - s) + F(2\eta)\int_{2\eta}^{\bar{s}} (2x - 4\eta)dx - F(2\eta)\int_{s}^{2\eta} (4\eta - 2x)dx \\
&= (\bar{s}-s)(4\eta - \bar{s} - s)(1 - F(2\eta)) \geq 0 \quad \square
\end{aligned}$$

Proof of Theorem 9. To prove $E[\pi_{T,a4}] \geq E[\pi_{T,a2}]$

$$\begin{aligned}
(E[\pi_{T,a4}) - E(\pi_{T,a2}]) \cdot 2b &= 8\eta E[s] + E[s^2] - 8\eta^2 - 3E^2[s] \\
&= \int_{\underline{s}}^{\bar{s}} (s-2\eta)(s+4\eta-3E[s])f(s)ds
\end{aligned}$$

$(s+4\eta-3E[s])f(s)$ changes sign from negative to positive only once at $3E[s]-4\eta$ between $[\underline{s}, \bar{s}]$, and $\int_{\underline{s}}^{\bar{s}}(s+4\eta-3E[s])f(s)ds = 4\eta - 2E[s] \geq 0$. Let $D = \int_{3E[s]-4\eta}^{\bar{s}}(s+4\eta-3E[s])f(s)ds \geq 0$ and let $d = -\int_{\underline{s}}^{3E[s]-4\eta}(s+4\eta-3E[s])f(s)ds \geq 0$, we have $D \geq d$.

From $\in [3E[s]-4\eta, \bar{s}]$ and $b \in [\underline{s}, 3E[s]-4\eta]$. We can find $(b-2\eta) \leq 0$. So,

$$\begin{aligned}
(a-2\eta) * D - (b-2\eta) * d &\geq (a+E[s]-4\eta) * D - (b+E[s]-4\eta) * D \\
&= (a-b) * D \geq 0 \quad \square
\end{aligned}$$

To prove $E[\pi_{T,a4}] \geq E[\pi_{T,a1}]$

$$\begin{aligned}
(E[\pi_{T,a4}] - E[\pi_{T,a1}]) \cdot 2b &= E(s^2) - \int_{\underline{s}}^{\bar{s}} s^2 F(s)f(s)ds + 4\eta E[s] - 2E^2[s] - 2\eta^2 \\
&= \int_{\underline{s}}^{\bar{s}} (s-2\eta)(s+2\eta-2E[s])(1-F(s))f(s)ds
\end{aligned}$$

Because $\int_{\underline{s}}^{\bar{s}}(s+2\eta-2E[s])(1-F(s))f(s)ds = 0$ and $(s+2\eta-2E[s])(1-F(s))f(s)$ change only once from negative to positive at $2E[s]-2\eta$ between $[\underline{s}, \bar{s}]$ and $\underline{s} \leq$

$2E[s]-2\eta \leq \bar{s}$, we define $D=\int_{2E[s]-2\eta}^{\bar{s}}(s+2\eta-2E[s])(1-F(s))f(s)ds \geq 0$

$$\begin{aligned} & \int_{\underline{s}}^{\bar{s}}(s-2\eta)(s+2\eta-2E[s])(1-F(s))f(s)ds \\ = \quad & (\alpha-\beta)\cdot D \geq 0 \end{aligned}$$

here $\alpha \in [2E[s]-2\eta, \bar{s}]$ and $\beta \in [\underline{s}, 2E[s]-2\eta]$. $\square$

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