Supplier Sustainability Assessments in Total-Cost Auctions

Karca D. Aral
Martin J. Whitman School School of Management, Syracuse University, Syracuse, New York 13244; Phone (315) 443-3392, Fax (315) 443-9517, kdaral@syr.edu

Damian R. Beil
Stephen M. Ross School of Business, University of Michigan, Ann Arbor, Michigan 48109; Phone (734) 936-5934, Fax (734) 764-2555, dbeil@umich.edu, (Corresponding Author)

Luk N. Van Wassenhove
INSEAD, Technology & Operations Management Area, Blvd. de Constance, 77305 Fontainebleau France; Phone +33 1 60 72 42 66, Fax +33 (0)1 60 74 55 00, luk.van-wassenhove@insead.edu

Buyers are increasingly pressured to ensure sustainability of their suppliers, but they are also under pressure for low-cost procurement. To make a more informed procurement decision, a buyer can choose to invest in sustainability assessments, and select a supplier based on their price bids and cost markup terms informed by the sustainability assessments. However, sustainability assessments are costly, and whether to use them is at the discretion of the buyer. Hence, the buyer can instead choose to forgo the assessments and select a supplier based on price only. In this paper, we explore this tradeoff. We find that the value of assessments depends on the buyer's business environment in some surprising ways. For example, although sustainability assessments are used to identify the suppliers' sustainability levels, greater ex ante variability and a decrease in suppliers' average sustainability levels (e.g., facing a supplier base in a country with looser sustainability regulations) can decrease the value of sustainability assessments. We find that the presence of an outside option (e.g., internal production) alters the assessment policy significantly. We also explore when the buyer may prefer to assess only a subset of her suppliers. Although motivated by the use of sustainability assessments, our results are generalizable to settings where the buyer has the option to invest in total-cost assessments on her potential suppliers' unknown, non-biddable, differentiator-type attributes.

Key words: Total-Cost Auctions, Supplier Assessments, Sustainable Procurement, Sustainability Assessments

History: Received: December 2016; accepted: September 2020 by Haresh Gurnani after three revisions.

1. Introduction

Sustainable procurement, although recognized by many as one of the most important levers of corporate social responsibility, is limited even within large publicly listed companies (Thorlakson et al. 2018). The main reasons for this limited scope are the discretionary nature of sustainable procurement, limitations of guidelines, difficulties in assigning a dollar value to supplier sustainability, difficulties in evaluating the supplier sustainability levels, and supplier sustainability assessment costs.

ISO20400 Sustainable Procurement Guideline (ISO 2017) and UN Procurement Handbook (UN 2017) provide some guidelines on sustainable procurement with an emphasis on supplier sustainability assessments. However, supplier assessments are costly, buyers are under pressure for low-cost procurement, and procurement managers are often incentivized by the amount of monetary savings. In order to prevent costly assessments from becoming an obstacle to sustainable procurement, it is crucial to analyze and understand when and how to use supplier assessments in the most effective way to attain the lowest total procurement cost.

In this paper, we address this issue in the context of supplier selection, in which the buyer needs to select a supplier assessment policy that will minimize the total procurement cost while facing uncertainty in supplier sustainability levels and uncertainty in purchase price.

Supplier sustainability assessments require deep domain expertise. Our industry partner, EcoVadis, is a supplier sustainability assessment firm and employs technical analysts to provide supplier sustainability ratings to buyer firms by collecting information from numerous qualified sources, and evaluating a number of corporate social responsibility criteria including water, biodiversity, local pollution levels, chemicals & waste, product use, product end of life, customer health and safety, second-tier supplier evaluations, and so on (EcoVadis(a) 2018). After the assessment process, EcoVadis assigns a sustainability rating to the supplier (a score out of 100). In many cases, the suppliers themselves lack the technical capability, in-house expertise, and information needed to assess and quantify their rating. Hence, unlike other supplier quality dimensions, without proper assessments the sustainability ratings are unobservable to any party to start with. Furthermore, in contrast to many other quality dimensions that the suppliers can adjust in order to win a buyer's business, they cannot change their sustainability ratings in the buyer's imminent contract term. Being unobservable to any party without assessments and its rigid nature renders sustainability **non-biddable**. This is one of the reasons why supplier sustainability is different from biddable supplier quality dimensions, and requires further attention in the context of a competitive-bid process.

EcoVadis reports that their clients (buyer firms) use a weighted total-cost ranking approach in their procurement auctions (which is in line with ISO20400 Sustainable Procurement Guidance, ISO (2017), page 26) by converting sustainability ratings into unsustainability cost markup terms (by using a cost-multiplier) which are then added on to the price bids of the respective suppliers:

"*The sustainability rating of suppliers can be integrated into different procurement processes. As it is a score out of 100, it makes it easy for procurement professionals to use as an objective, quantifiable metric. For example, in a RFP/tender, it can be used as a weighted percentage of the overall award decision.*" EcoVadis(b) (2018)

UN Procurement Handbook describes a similar approach for incorporating sustainability into the supplier selection process:

"*The evaluation and contracting stage makes use of the standard evaluation methods; however, it should place specific emphasis on use of weighted and ranked criteria incorporating the specific performance criteria and specifications that address sustainable procurement factors.*" UN (2017)

The weighted total-cost ranking approach described above is called a "Total-Cost Auction" in the procurement auction literature. Numerous papers (e.g., Elmaghraby et al. (2012), Kostamis et al. (2009), Haruvy and Katok (2013), Engelbrecht-Wiggans et al. (2007), Rezende (2009)) have studied total-cost procurement auction settings in which the total cost of ownership (TCO) is captured via an additive, non-biddable, **known** cost markup which needs to be added onto the supplier's price bid to come up with the total cost of ownership associated with that particular supplier.

The implicit assumption in the previous procurement auction literature is that the buyer is pre-endowed with the information on the cost markups to start with. In reality, however, this assumption may not hold. Unsustainability cost markups, as explained above, are unobservable to any party without costly assessments; hence it becomes unrealistic to assume that the buyer is pre-endowed with knowledge of them. In our paper, in contrast to the previous total-cost auction literature, we treat the cost markups as uncertain, however the buyer has the option to learn them at her own cost (e.g., paying EcoVadis for the supplier sustainability assessments). The crux of the problem then becomes whether or not the buyer decides to learn the cost markups in order to make a more informed supplier selection decision. To our knowledge, ours is the first paper to take a step back and address this fundamental issue at the heart of total-cost auctions.

Per the UN handbook quoted above, the buyer should always incorporate sustainability assessments into her procurement decision. But the problem is likely more complicated than that. In practice, investment levels in supplier assessments to inform competitive procurement events vary greatly from one buyer to another (Ellram 2006). Hence, it is more plausible that the value of sustainability assessments is situation-dependent, and could change depending on the buyer's business setting. This presents a tradeoff for the buyer. On one hand, she would like to assess her potential suppliers in order to make a more informed supplier selection decision that takes into account the supplier sustainability ratings. On the other hand, supplier sustainability assessments to inform supplier ratings are costly and it is not possible to foresee how the assessments will change the procurement auction outcome.

In order to address this trade-off, we first characterize the value of supplier assessments, more specifically the expected value of incorporating information from supplier assessments into the supplier selection decision. We then investigate how the value of supplier assessments change in response to changes in the business environment, considering several factors including the uncertainty in supplier production costs, uncertainty in unsustainability cost markups, and the cost of the buyer's outside option (such as whether or not the buyer has a low-cost in-house production option). Determining the buyer's optimal supplier assessment policy for attaining the lowest expected total procurement cost (which includes the cost of supplier assessments, if any) is the focus of this paper. Formalizing this important problem is our first contribution to the literature.

The analysis of how the value of supplier assessments changes in response to the buyer's business environment lends itself to some interesting results. Intuitively, the buyer should use the sustainability assessments when facing a less sustainable supplier base. However, we find that the opposite may hold, and the buyer may derive higher value from conducting assessments when facing a more sustainable supplier base. We find that the presence of an outside option (e.g., internal production) alters the assessment policy significantly. We also explore when the buyer finds it profitable to assess only a subset of her suppliers. This and other insights are explored in Section §4. Our second contribution is providing these managerial insights alongside others about the circumstances under which to use supplier assessments given the specifics of the buyer's business environment.

Although the use of supplier sustainability assessments in supplier selection is our original motivation and is the focus of our discussions, our results and insights are generalizable to myriad other settings where (1) the buyer would like to use a total-cost perspective when selecting a supplier, (2) the cost markups are non-biddable and initially unknown to the suppliers and buyer, (3) the buyer has the option to use costly assessments to evaluate the cost markups. Consider, for example, a manufacturer who produces some components in-house, but needs to select a supplier for a particular component she does not have the expertise to make herself. The costs of compatibility — which is the cost the manufacturer would incur to integrate a supplier's particular component with the other components — is initially unknown to the manufacturer and the supplier. But the buyer can, through costly testing, assess the compatibility costs associated with each supplier's component. These costs can then be treated as cost markups during supplier selection. Another example is the cost consequences of different suppliers' locations which could affect the buyer's logistics costs in complex ways. For example, a supplier's location relative to the buyer's preexisting suppliers for other components would affect the buyer's ability to combine shipments from all suppliers. This effect would be something the buyer would have to asses for herself, at a cost, if she chooses to incorporate it to inform her supplier selection decision.

2. Related Literature

The main features of our model are as follows: (a) suppliers submit price-only bids; (b) there is intrinsic uncertainty around the non-biddable cost markups of suppliers (for both the buyer and the suppliers themselves); and (c) the buyer has the option of reducing this uncertainty at a cost.

Feature (a) is self-explanatory. Feature (b) arises in settings in which evaluating a non-price cost markup requires effort from the buyer's side (e.g., using costly lab and field tests or hiring a sustainability rating firm) and/or depends on buyer's private preferences (e.g., when evaluating switching costs, the level of technological compatibility, or match quality). Feature (c) simply states that the buyer needs to decide on whether or not to invest in reducing the cost markup uncertainty. Features (b) and (c) are in this sense related to the widely studied notion of transaction costs, dating back to the work of Coase (1937). Since the buyer may collect information on the non-price attribute through supplier assessments, our work is related to the "informed principal" literature. Skreta (2011) provides a recent overview of informed principal problems in an auction framework, as well as a result we find useful for our setting: in an optimal mechanism, the auctioneer cannot increase her payoff by not sharing the information she has with the bidders on competing bidders' exogenous characteristics.

Research on information acquisition in auctions has generally focused on bidders' acquisition of information, in which a key question is to what extent the auctioneer should make information available to the bidders. Examples include work on the linkage principle and auction format choice (e.g., Milgrom and Weber (1982)), and more recently Bergemann and Pesendorfer (2007), Shi (2012) and Zhao et al. (2014)).

Information acquisition by auctioneers (buyers) in procurement auctions is extremely relevant in practice but has only recently started to gain research attention. In an attempt to explain unconsummated procurement auctions Carr (2003) studies an equilibrium analysis with suppliers' endogenous entry decisions due to costly entry and risk of auction cancellation, in which the buyer's decision to cancel the auction depends on the cost of bid evaluation. Yin et al. (2013) study when a buyer should acquire information on the suppliers' production costs to set a reserve price that puts downward pressure on the suppliers' price bids in a price-only auction. Chen et al. (2008) analyze a profit-sharing setting in which only the winning supplier is audited ex post to verify his production cost. After verifying the production cost of the winning supplier, the buyer shares the supply chain profit with the winning supplier accordingly. So, like the cost modeling in Yin et al. (2013), in Chen et al. (2008) the audit is used for acquiring information on the production cost (albeit in a simplified setting in which the only information acquired is about the winning supplier). Our paper studies a different problem: the buyer's assessment policy on her potential suppliers' non-biddable non-price attributes in order to make a more informed total-cost decision in supplier selection. To the best of our knowledge, we are the first to identify and study this important problem.

There are a number of studies in procurement auctions on settings where supplier qualification screening is required prior to awarding the contract (Zhang et al. (2020), Chen et al. (2018), Wan et al. (2012), Wan and

Beil (2009)). This literature considers binary qualifications in deciding whether the suppliers are qualified for the contract or not in price-only auctions. In contrast, "assessments" in our setting are used to learn about the additive cost markups – and hence helps the buyer to evaluate the *total-cost of ownership* associated with potential suppliers in total-cost auctions.

A number of studies on total-cost auctions (see for example the scoring auctions in Che (1993), Branco (1997), Beil and Wein (2003), and Asker and Cantillon (2008)) model the non-price attribute as an endogenous, biddable attribute that can be instantaneously controlled by the suppliers (such as lower manufacturing lead time at a higher production cost). In our setting however, as explained in §1, what we are capturing are the *non-biddable* non-price exogenous attributes (i.e., cost markups) in which the crucial point is that if the buyer wishes to become informed on these attributes she needs to perform a costly assessment (e.g., hiring a supplier sustainability assessment firm).

There is a stream of research on total-cost procurement auctions that seeks to understand how various auction formats perform, and why, in the presence of exogenous, known, and non-biddable cost markups. Kostamis et al. (2009) compares open versus sealed total-cost auctions in which the bids are marked up. Engelbrecht-Wiggans et al. (2007) compare price-based (second price) and buyer-determined (second-score) auctions in which the buyer applies cost markups after price bidding has ended. Santamaría (2015) compares open total-cost auctions against buyer-determined (scoring) auctions in which the buyer applies markups to the best price bids and bidders bid myopically, and Elmaghraby et al. (2012) compare sealed-bid, rank-only feedback, or full-price feedback auction formats in the presence of cost markups. The implicit assumption in this stream of literature is that the buyer is pre-endowed with the information on the cost markups. In this paper, in contrast to the existing literature, the cost markups are unknown, the buyer has the option to assess them at a cost (e.g., paying EcoVadis for the sustainability ratings).

Kostamis et al. (2009), Engelbrecht-Wiggans et al. (2007), Santamaría (2015), and Elmaghraby et al. (2012) collectively study seven different total-cost auction mechanisms. These papers study the effect of the buyer's choice among different suboptimal auction formats, which affects the level of information on cost markups revealed to the suppliers and in turn influences the suppliers' bidding behavior and hence the buyer's outcome. The underlying assumption in this stream of literature is that the buyer is already informed about suppliers' cost markups. By contrast, in our paper, we forgo this assumption and analyze the circumstances under which the buyer should invest in learning the cost markups. Hence, in our setting, there is an additional level of uncertainty that is not accounted for in the previous literature.

Sustainable procurement has gained some recent interest within the operations management literature (Guo et al. (2015), Chen and Lee (2016)). Our work complements this stream of literature by studying the role of sustainability assessments within the supplier selection context.

Ganuza (1995) studies the optimal procurement mechanism when the buyer is readily informed about non-biddable supplier cost markups. Rezende (2009) investigates two scenarios for a buyer facing two ex ante identical suppliers: one in which the buyer can opt to choose a supplier through an auction taking into account the cost markups, and the other in which the buyer does not have commitment power and relies on negotiations after the auction takes place to choose a supplier. The latter scenario is the main focus of Rezende (2009). The former scenario is the closest to our setting. The author characterizes the optimal mechanism for two suppliers. In his setting with costless information and two suppliers the buyer finds it optimal to always acquire information about the cost markups under the optimal mechanism. Unlike Ganuza (1995) and Rezende (2009), we do not assume that it is costless for the buyer to acquire information on the cost markups (reflecting a realistic setting in which the buyer needs to pay for supplier assessments, e.g., hiring a third-party like EcoVadis). Furthermore, given these assessment costs, our analysis focuses on the buyer's optimal supplier assessment policy, to minimize the total procurement cost (including the cost of assessments, if any).

3. Base Model

A risk-neutral buyer wishes to award an indivisible contract to one of N competing suppliers through a reverse auction. The suppliers submit price-only bids in the auction. However, the buyer cares about the total cost of procurement, which is equal to the purchase price paid to the chosen supplier plus a non-biddable cost markup associated with that supplier, and the cost of assessments (if any). The cost markup represents, from the buyer's perspective, the expected additional costs the buyer incurs when doing business with a supplier (e.g., unsustainability cost markups).[1]

The cost markups can only be assessed using a costly supplier assessment process. Note that both the supplier assessments and suppliers' proposal preparation (deciding how much to bid) take time. Hence, in practice carrying out the assessments in parallel to suppliers' proposal preparation, and prior to the actual bidding stage, ensures the timely completion of the procurement process. Similarly, assessments for different suppliers are carried out simultaneously (rather than sequentially) in order to save time. The supplier assessment cost $K(N)$ is weakly convex increasing in the number of assessed suppliers N.

In this setting, the buyer faces two types of uncertainty: purchase price and cost markup. During the supplier assessment stage the buyer can invest in resolving the uncertainty on the cost markups at a cost. The uncertainty on price will be resolved during the proceeding auction stage. Due to this assessment cost, and uncertain benefit from the supplier assessments, a buyer may choose to forgo the assessments and simply select a supplier observing the price bids only. If the buyer chooses to invest in supplier assessments, she can then observe the cost markups.

We denote by Δ_i the cost markup associated with supplier i, where for all i, Δ_i is a non-negative random variable identically and independently distributed according to publicly known distribution F with mean μ_Δ and finite support $[\Delta_{(l)}, \Delta_{(u)}]$. The distribution F captures situations where the buyer is not intimately familiar with each supplier in the supply base, and it is difficult ex ante to distinguish between their cost markups. This happens, for example, when a buyer seeks to outsource production of a new product category, or a buyer outsources an existing product to a new set of suppliers. Reflecting this, in our model neither the buyer, nor the supplier i can directly observe the realization of Δ_i (denoted as δ_i) without an assessment.

[1] Given the difficulties of assigning a dollar value to supplier sustainability, as part of the current industry practice, procurement managers simply use ad-hoc cost multipliers to convert sustainability ratings into unsustainability cost markup terms. Although how this conversion is done is irrelevant for the purposes of our main analysis, in practice it is important that this cost markup multiplier reflects the true dollar value of the relevant markup for the buyer firm. In the Online Supplement, we analyze a setting in which the buyer is uncertain about how precisely to map the results from a supplier assessment to a monetary term and analyze how the value of such information (which can be acquired through market research, industry benchmarking, etc.) changes with the buyer's business environment.

However, with or without assessments, if she awards the business to supplier i, the buyer incurs a total cost that equals the payment made to the supplier plus δ_i (the latter being the non-price cost of doing business with the supplier).

On one hand, if the buyer conducts an assessment on a supplier, she will learn the value of the cost markup. On the other hand, if the buyer does not conduct an assessment on the supplier, the buyer will only know that the cost markup is distributed according to the cost markup distribution F. If the buyer chooses to carry out the supplier assessments, we assume that the buyer truthfully and privately reveals to each of the assessed suppliers what their cost markup is before the auction, as is done in practice for transparency purposes (transparency policy regarding the cost markups is documented in previous studies, see for example Ellram (1994), page 71).

For each supplier i, c_i denotes the supplier's production cost. This cost represents the minimum price at which the supplier would accept the contract, capturing things like the supplier's production efficiency, current book of business, inventory levels, strategic objectives, etc. We take the pair (c_i,Δ_i), $\forall i$ to be statistically independent (we relax this assumption in §4.4). Take, for example, a supplier with low production cost doing standard but water-intensive work such as corn processing. This supplier may be associated with a high unsustainability cost markup simply because it happens to be located upstream of an area with impending water scarcity (e.g., see Gassert et al. (2013)). Additionally, as in industry practice, in our setting the buyer uses the assessment process as a way to evaluate the cost markups, rather than an attempt to discover suppliers' production costs. The production cost c_i is the supplier's private information, but its distribution G, which has finite support $[c_{(l)}, c_{(u)}]$, is common knowledge. Also, the pair (c_i,Δ_i) is independent across i.

As is common in the auctions literature, we assume that the c_i's are independently and identically distributed and that $J(c) \triangleq c + \frac{G(c)}{g(c)}$ (the virtual production cost) is strictly increasing in c (in the rest of the paper, unless otherwise mentioned "increasing" and "decreasing" are used in the weak sense). This regularity condition is satisfied, for example, by log-normal distributions, including uniform, exponential, and normal; see Bagnoli and Bergstrom (2005). We denote by $\tilde{G}$ the cdf of the virtual production cost J, by H the cdf of $\mu_\Delta + J$, and by H_a the cdf of $\Delta + J$. Suppliers are assumed to be risk-neutral, fully rational, and they seek to maximize their expected payoffs.

To summarize, the sequence of events is as follows: First, nature reveals production costs to suppliers, which remain private to them. Second, the buyer chooses whether or not to assess suppliers. If suppliers are assessed, the buyer observes the value δ_i of the uncertain cost markup Δ_i associated with each supplier. If suppliers are not assessed, the buyer (and suppliers) remain uncertain on the cost markups. Third, the buyer runs a procurement auction. If the buyer awards the contract to a supplier, the buyer pays the winning supplier, and incurs the total procurement cost which is the payment to the supplier and the cost markup of the winning supplier. In other words, even if the suppliers were not assessed earlier, the buyer (in a costless manner) observes and incurs the cost markup associated with the winning supplier after the auction.

Expected Assessment Value

Investing in assessing the cost markups enables the buyer to make a more informed supplier selection decision taking into account the cost markups alongside price, and select a supplier with the lowest total cost. If the buyer does not invest in assessments, the winning supplier would be chosen without the information on cost markups (potentially leading to a higher total cost for the buyer). Consequently, supplier assessments are valuable for the buyer to the extent of expected total cost savings they provide.

Based on our discussions with EcoVadis, it is currently common practice that buyers simply assess either all of the competing suppliers or none of them. To quantify the value of information from assessing all suppliers, we compare the expected total cost of ownership (TCO) when the buyer assesses none of the suppliers with the expected total cost of ownership when the buyer assesses all of the suppliers. We define the **Expected Assessment Value** as: $EAV \triangleq E[\text{TCO without assessments}] - E[\text{TCO with assessments}]$.

EAV is the expected value of information on cost markups for the buyer, that is the amount of savings in total cost the buyer can expect to attain if she chooses to invest in supplier assessments. As we will explain at the outset of the next section, the buyer will decide her assessment policy by comparing *EAV* with the cost of supplier assessments.

Auction Format

In the above discussion of *EAV*, we have not yet specified what auction format will be used by the buyer. Let "auction strategy" refer to the pair of auction formats the buyer will use with and without supplier assessments. Let c_0 denote the known total-cost of the buyer's outside option. We will first discuss the format that the buyer uses without assessments.

LEMMA 1. *If the buyer does not use assessments, her expected total cost is minimized by using a standard (price-only) open-descending or sealed-bid auction with reserve price $r^* = J^{-1}(c_0 - \mu_\Delta)$. The buyer's expected total cost is $E[\textit{TCO without assessments}] = E_{\mathbf{J}}[\min\{\mu_\Delta + J_{1:N}, c_0\}]$, where $1 : N$ denotes the lowest order statistic out of N draws.*

Proofs of Lemma 1 and Lemma 2 are provided in the Online Supplement. Proofs of all propositions are provided in the Appendix. It is worth noting that in the standard auction formats mentioned above the buyer uses a deterministic term, namely the average cost markup, as the cost markup for suppliers. Because without assessments the cost markup is the same for all suppliers, the suppliers are compared to each other only on price, i.e., the buyer uses a price-only auction. Intuitively, the cost markup for an unassessed supplier should be treated as a random variable. After all, facing a stochastic optimization problem, the buyer should not simply assign a deterministic term for the unknown cost markups (in the same way a risk-neutral newsvendor does not assume the demand is deterministic). Interestingly, however, the proof of Lemma 1 shows that the buyer can simply treat the cost markups of unassessed suppliers as the expected cost markup. To avoid considering auction strategies where *EAV* is artificially large due to a poorly designed auction without assessments, in this paper we will henceforth assume that the buyer's auction format without assessments achieves the minimum expected total cost in Lemma 1.

Now, what about when the buyer does assess the suppliers? It turns out that the open-descending or sealed-bid formats will no longer be optimal, because now the buyer must account for the fact that the suppliers have different cost markups. In practice, EcoVadis' customers use various formats - e.g., some use sealed-bid, some use open-bid, some tweak their scoring rule multipliers on the markups, some do not, etc. But one cannot possibly study all possible variants of auction mechanisms used in practice when the buyer uses supplier assessments. Instead, we assume that the buyer will implement the optimal mechanism, which we will define below in Lemma 2. By doing so, the *EAV* we compute under the optimal mechanism provides an upper bound on the *EAV* that buyer could expect under a broad class of auction formats that she might use in practice (see §4.5 where we compare *EAV* under different suboptimal auction formats and the optimal mechanism). Studying *EAV* for the optimal mechanism allows us to decouple the effect of the assessment policy on the buyer's procurement cost from the effect of the auction mechanism.

LEMMA 2. *The buyer's expected total-cost using the optimal mechanism after assessing all suppliers is* $E[\textit{TCO with assessments}|\boldsymbol{\delta}] = E_{\mathbf{J}}[\min\{\delta_1 + J(c_1), \ldots, \delta_N + J(c_N), c_0\}|\boldsymbol{\delta}]$.

Note that the buyer's scoring rule optimally weights the markups, per the scoring rule $\delta + J(c)$. For example, if supplier production costs are uniformly distributed on a support with lower bound 0, $J(c) = 2c$, and hence the buyer's scoring rule puts double the weight on the production cost. This is done to optimally limit suppliers' ability to take advantage of the fact that they have different cost markups. In the rest of the paper, for notational convenience we use J_i to denote supplier i's virtual production cost $J(c_i)$.

***EAV* under the Optimal Mechanism**

If the buyer chooses to use the assessments, the winning supplier is selected based on both cost markups and price bids (which are both unknown prior to assessments). If the buyer chooses not to use the assessments, as per Lemma 1, the suppliers can be treated as if they all have the mean cost markup μ_Δ. Hence, the competition would take place only through the price bids. Then, by combining Lemma 1 and Lemma 2, the expected assessment value when the buyer uses the optimal mechanism is:

$$\textit{EAV} = E_{\mathbf{J}}[\min\{\mu_\Delta + J_{1:N}, c_0\}] - E_{\mathbf{J},\boldsymbol{\Delta}}[\min\{(\Delta + J)_{1:N}, c_0\}]. \quad (1)$$

Note that the buyer needs to make a decision on whether to use the assessments or not prior to observing the production costs and the cost markups. Hence, the expectation of total cost with assessments (the second term on (1)'s righthand side) is over both the virtual production cost and the cost markup distributions, whereas the expectation of total cost without assessments (the first term on (1)'s righthand side) is over the virtual production cost only.

Buyers should be cognizant of the fact that the expected assessment value might be negative if supplier assessments are not used in conjunction with a suitably chosen auction format (see §4.5). In Proposition 1 below, we find that the expected assessment value when the buyer uses the optimal mechanism is always positive, and is the upper bound on the expected assessment value under any other auction strategy with assessments. Hence, studying the optimal mechanism provides a useful benchmark: If it is not cost effective to use the assessments under an optimal mechanism, it would never be cost effective to use assessments under a suboptimal format.

PROPOSITION 1. *For any supply base size N, if the buyer uses the optimal mechanism in Lemma 2 with supplier assessments, EAV (given in equation (1)) is always positive, and is bounded above by $\mu_\Delta - \Delta_{(l)}$. Furthermore, EAV using the optimal mechanism is an upper bound on the EAV that could be achieved when using any other auction format with supplier assessments.*

Interestingly, the buyer's expected savings is bounded above, by the gap between the average and the best possible markup ($\mu_\Delta - \Delta_{(l)}$). How tight the bound on *EAV* is depends on the specific cost distributions, and the buyer's outside option; see our discussion on page 20.

This bound can provide the buyer with a handy check of whether or not assessments will be worthwhile, as it is simple and does not depend on the number of suppliers or their cost distribution, and the bound holds for any auction format the buyer might use with supplier assessments. Indeed, the upper bound on the *EAV* is achievable when the production cost comes from a degenerate distribution (hence the production cost does not have an effect in determining the winner), and the cost markup of one of the suppliers happens to be the lower bound on the cost markup distribution ($\Delta_{(l)}$).

Furthermore, Proposition 1 shows that *EAV* using the optimal mechanism is an upper bound on the *EAV* using any other auction format (the tightness of which depends on several factors as explained in §4.5). Hence, for $K(N) > \mu_\Delta - \Delta_{(l)}$, the buyer should forgo the assessments irrespective of the auction format choice. However, if the average cost markup is large, assessments will not be ruled out based on this bound alone, in which case the buyer would need to understand what the benefits of the assessments would be, which we explore in the next section.

As Proposition 1 shows that *EAV* is highest under the optimal mechanism, unless stated otherwise, in the rest of the paper "*EAV*" refers to the expected assessment value under the optimal mechanism (as given in Equation (1)).

4. Assessment Policy Analysis

To quantify the value of assessing all suppliers, we compare the expected total cost when the buyer assesses all suppliers with the expected total cost when the buyer assesses none of the suppliers. The resulting *EAV* is the expected value of information on cost markups for the buyer, that is the amount of savings the buyer can expect to attain if she chooses to invest in supplier assessments. Hence, in order to evaluate whether supplier assessments are worthwhile, the buyer would need to compare the expected assessments value (*EAV*) with the cost of assessments. Thus, she would conduct the assessments only if *EAV* $- K(N)$ is positive. To reflect real-life situations where there is a fixed assessment cost per supplier, we model the cost of assessments $K(N)$ as weakly convex increasing in the size of the supply base N. For a given number of suppliers N, the assessment cost $K(N)$ is fixed, however, *EAV* can change with the buyer's business environment. Hence, to provide specific guidelines on when to use the sustainability assessments, we next explore in detail how different factors affect the *EAV*.

4.1. How buyer's assessment decision changes with buyer's outside option cost

The outside option is an important factor for the buyer when deciding on whether she should invest in supplier assessments. After all, the outside option represents the buyer's sure bet with a known total cost – the level of which should affect the buyer's willingness to invest in acquiring information about the potential suppliers:

> "*Outsourcing Analysis total cost of ownership goes beyond this. It involves comparing a thorough supplier based total cost of ownership factoring in the additional costs the organization will incur in working with the outsourced supplier, versus the internal process total cost of ownership of retaining the activity internally*" (Ellram 2006)

The decision on whether to use the outside option (e.g., retaining internal production) or to outsource depends on how the outside option cost compares to the potential suppliers, which may be completely different when the suppliers' cost markups are known versus when they are not.

Intuitively, when outside option cost is small, regardless of the outcome of the assessments, the buyer will probably still prefer her outside option, so she probably will not benefit much from assessing her potential suppliers. As outside option cost grows, the likelihood that the buyer will wish to contract with one of the potential suppliers increases, hence one would expect that the value of assessments should always increase. However, we find that this is not the case.

As a motivating example, Figure 1 illustrates the region where assessing suppliers is preferred to not assessing as a function of the outside option and the assessment cost. The shaded region is where the expected assessment value (*EAV*) exceeds the assessment cost. In this numerical experiment, the supplier base has $N = 2$ suppliers who have the same production cost and cost markup distributions. Figure 2 plots the cumulative distribution function for the adjusted virtual cost (H and H_a, without and with assessments, respectively).

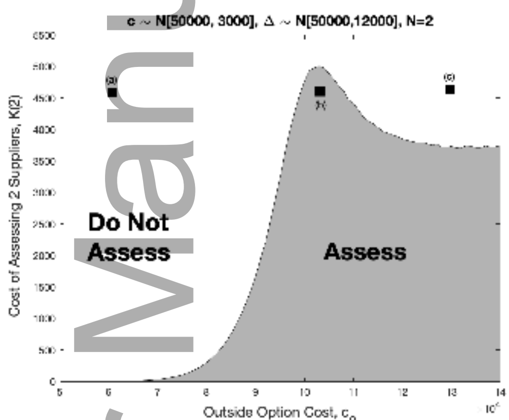


Figure 1 **Assessment/No Assessment regions**

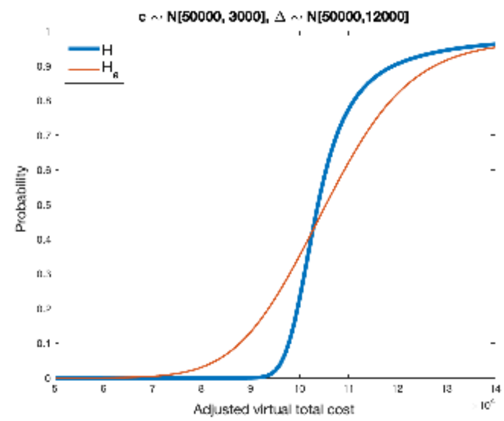


Figure 2 **CDFs of the total cost distributions**

Consider the points labeled (a), (b), and (c) in Figure 1. We see that point (a) is in the no-assessment region. This is intuitive, as for a small outside option cost we expect that assessments will not be needed as the buyer would be likely to use the outside option. Moving to the right, we see that point (b) is in the assessment region; this is also intuitive because the buyer has a good chance of transacting with one of the suppliers and would find it beneficial to identify the supplier with the lowest total cost as the outside option increases. But as the outside option increases further to point (c), the above intuition fails and assessments are no longer beneficial. Thus, even though one might expect that the value of assessments should be increasing in the outside option cost, this is not the case.

In fact, the expected assessment value (i.e., assessment region frontier) starts declining in the outside option cost beyond a particular point. To understand why this happens, note that, as the outside option continues to increase, it becomes a less viable alternative relative to the suppliers. In this region, assessments are still valuable, however less so than before. This is because they no longer serve in deciding whether or not to use the outside option instead of a potential supplier, but merely in determining which supplier to choose. The following result formalizes this.

PROPOSITION 2. *For any supply base size N, (1) There exists $x_1, x_2 \in \mathbb{R}^+$, $x_1 < x_2$, for $c_0 < x_1$, increasing c_0 can only make the buyer prefer assessments more; for $x_1 < c_0 < x_2$, increasing c_0 can only make the buyer prefer assessments less; and for $c_0 \geq x_2$ the buyer's decision is insensitive to c_0. (2) The value x_1 is where the cumulative distribution functions H and H_a cross. The value x_2 is $\Delta_{(u)} + J_{(u)}$ (the highest possible adjusted virtual cost, where $J_{(u)} = c_u + \frac{G(c_{(u)})}{g(c_{(u)})}$).*

Proposition 2 states that as the buyer's outside option cost increases and she becomes more reliant on contracting with a supplier, the value of assessments can decrease. The reason behind this is that the assessments do not only help the buyer to make total-cost comparisons across suppliers, but also in deciding whether to use her outside option. The takeaway for a buyer is as follows: when allocating budgets for assessments, the buyer should not necessarily focus only on those cases where she is most beholden to suppliers by virtue of not having an attractive outside option – in fact, assessments are most valuable when the outside option is already fairly good.

Assessments, which technically lead to a mean-preserving spread on the probability distribution of suppliers' adjusted virtual costs — make observing costs below and above a certain point x_1 more likely, than without assessments. In other words, an assessment reveals more information on the adjusted virtual cost of a given supplier – which may be good or bad news, and the point x_1 is simply the break point. As illustrated in Figure 2, this break point is exactly where the cumulative distribution functions of the adjusted virtual costs with and without assessments (H_a and H, respectively) cross. The benefit of assessments is largest when the buyer can leverage the good news to the greatest extent possible, and this happens when the outside option cost equals the break point x_1. As the outside option cost continues to increase beyond the highest possible adjusted virtual cost (i.e., x_2), the outside option ceases to have an effect on the buyer's assessment decision. In the rest of the paper, unless otherwise stated, x_1 and x_2 will be used as defined in Proposition 2 (further technical details about these break points and mean-preserving spread can be found in the proof of Proposition 2).

In summary, the buyer's outside option cost is an important consideration when sourcing. As the outside option cost changes, Proposition 2 reveals interesting non-monotonicity in the value of supplier assessments, and pinpoints where it happens. This result, which shows that *EAV* peaks when outside option cost is moderate ($c_0 = x_1$), provides a handy check for practitioners: if the assessment cost $K(N)$ is larger than this highest possible *EAV*, then the buyer will never find it beneficial to use assessments no matter what her outside option cost, or the auction format is.

4.2. How buyer's assessment decision changes with cost distributions

It is important to understand how the level of uncertainty and magnitude in production costs and the cost markups affect the value the buyer would derive from the assessments. Hence, we now analyze how *EAV* changes with the underlying distributions by scaling the cost markups and the virtual production costs.

The analysis lends itself to some interesting results. Consider two otherwise identical supplier bases A and B: supplier base A has lower cost markup magnitude and dispersion (e.g., a supplier base in a country with more stringent sustainability enforcement); supplier base B has a higher cost markup magnitude and dispersion (e.g., a supplier base in a country with less stringent sustainability enforcement). Intuitively, the buyer should be more willing to use supplier sustainability assessments when facing a supply base with higher average cost markup (e.g., a less sustainable supplier base). However, as shown in Figure 3, we find that the opposite may hold, and the buyer may derive higher value from assessments when facing supplier base with lower average cost markups (e.g., a more sustainable supply base). For small to moderate values of the outside option cost, assessments are optimal in supplier base A, whereas they are not in supplier base B (where the cost markups are scaled by $\gamma = 1.5$). The reason behind this stems from Proposition 2: Scaling up the cost markup can make the outside option more attractive relative to the suppliers, diminishing the value of supplier assessments. Hence, greater ex ante variability and an increase in suppliers' cost markups — which intuitively should increase the benefit of assessments – can actually decrease the value of assessments.

Now consider two otherwise identical supplier bases C and D: supplier base C has lower production cost magnitude and dispersion; supplier base D has higher production cost magnitude and dispersion. As the uncertainty and magnitude of suppliers' production costs increase, the uncertainty in total cost becomes more dominated by the production cost terms. Intuitively, this would lead to uncertainty on cost markups becoming less important for the buyer, which should cause the value of using supplier assessments to diminish. Yet, as demonstrated in Figure 4, which shows that assessments can be more valuable when facing supplier base D (where the production costs are scaled by $\kappa = 1.5$), this is not necessarily true either. And just as explained in the paragraph above, the reasoning stems from the insight of Proposition 2.

Will *EAV* always behave in such unexpected ways? It turns out that in settings where the buyer does not have an outside option (or has a very expensive outside option that can effectively be ignored), the buyer can rest assured that, as one would intuitively expect, *EAV* always decreases in the production cost multiplier κ, and increases in the cost markup multiplier γ. This result is formalized below in Proposition 3.

PROPOSITION 3. *For any supply base size N, in the absence of an outside option, keeping everything else the same, for all i:*

- *replace Δ_i by $\Delta_i + \nu$, for some $\nu \in \mathbb{R}$; EAV, and thus the buyer's assessment decision, is constant in ν.*
- *replace c_i by $c_i + \nu$, for some $\nu \in \mathbb{R}$; EAV, and thus the buyer's assessment decision, is constant in ν.*
- *replace Δ_i by $\gamma \cdot \Delta_i$, where $\gamma > 0$; EAV is increasing in γ, and thus the buyer prefers assessments more.*
- *replace c_i by $\kappa \cdot c_i$, where $\kappa > 0$; EAV is decreasing in κ, and thus the buyer prefers assessments less.*

Proposition 3 states that when the buyer does not have an outside option, *EAV* is not affected by distributional shifts, hence the supplier assessment decisions should not change as as the cost markup and the production cost distributions are shifted to the right or left. Also, facing a supply base with more dispersed cost markups (through an increase in the dispersion of the cost markup distribution while the mean stays the same, i.e., by multiplying Δ by γ and subtracting $\gamma \cdot \mu_\Delta$ for all suppliers), the benefit from assessments increases. This is because the buyer has a higher chance of finding a low-cost-markup-supplier with

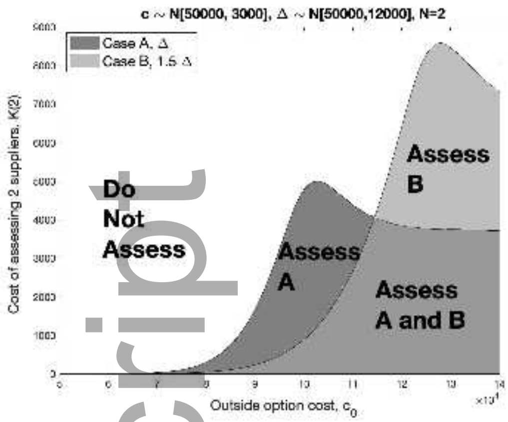


Figure 3 **Assessments can become less valuable as cost markup uncertainty and magnitude increase.**

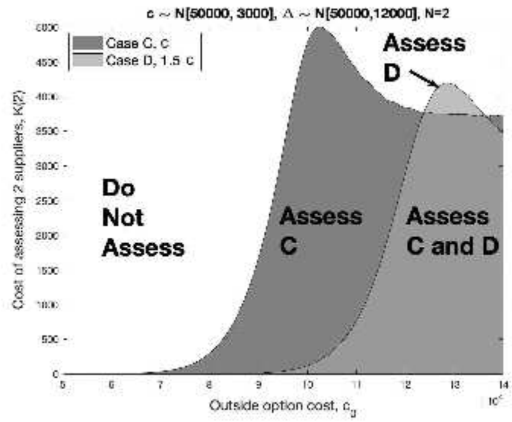


Figure 4 **Assessments can become more valuable as production cost uncertainty and magnitude increase.**

a low total cost as the cost markup dispersion increases. Conversely, as the dispersion of the production cost increases, the benefit from assessments decreases. This result suggests that, in the absence of an outside option, carrying out supplier assessments on a supplier base with high cost markups may not be any more preferable than carrying out assessments on a supplier base with low cost markups as long as the dispersions of the cost markup and the dispersions of the production cost distributions are similar in the two supplier bases. However, in the presence of an outside option, shifting the cost markup and the production cost distributions does play a role in the assessment decisions. More specifically, in this case, any distributional shift would affect the position of the corresponding cumulative distribution functions' (H and H_a) crossing points, and hence would lead to changes in *EAV*, exactly as explained after Proposition 2.

Proposition 3 also helps us gain insights on the tightness of the bound on *EAV* identified in Proposition 1 as it helps us understand the effects of the business environment. More specifically, in Proposition 3 we show that in the absence of an outside option, *EAV* increases as the cost markup dispersion increases, and as the production cost dispersion decreases. Consequently, the bound on *EAV* is tighter when the cost markup dispersion is high, and when the production cost dispersion is low. Conversely, the bound is looser when the cost markup dispersion is low, and when the production cost dispersion is high. When the buyer has an outside option, following the insights from Proposition 2, the upper bound is tighter for the moderate values of the outside option cost.

4.3. Limiting the number of assessed suppliers

The buyer's cost of assessments increases in the number of assessed suppliers. In many settings, the procurement managers have specific and limited budgets, hence, in this subsection, we explore the realistic possibility that the buyer may prefer to assess a smaller subset of the ex ante symmetric supply base.

As before, an assessed supplier i's cost markup term δ_i plus the virtual production cost term J_i comprise the total cost associated with procuring from this supplier. The suppliers who are not assessed can still participate in the auction; however, as their cost markups are not assessed, the buyer uses μ_Δ to substitute for their cost markups. We denote by *EAV*(M) the assessment value in this setting:

$$\begin{aligned}\mathit{EAV}(M) &\triangleq E[\text{TCO without assessments}] - E[\text{TCO with assessments on } M \text{ suppliers}] \\ &= E[\min\{\mu_\Delta + J_{1:N}, c_0\}] - E[\min\{\Delta_1 + J_1, \ldots, \Delta_M + J_M, \mu_\Delta + J_{M+1}, \ldots, \mu_\Delta + J_N, c_0\}].\end{aligned}$$

In Proposition 4 we prove that our earlier results continue to hold, and characterize buyer's optimal supplier assessment policy.

PROPOSITION 4. *Replace EAV with EAV(M); Propositions 1-3 hold as before. The buyer's optimal supplier assessment policy is as follows: Assess none if EAV*$(1) < K(1)$*; Assess all if EAV*$(N) \geq K(N)$*; Otherwise, there exists an interior solution* M^* *which is the lowest integer such that EAV*$(M^*+1)-$ *EAV*$(M^*) \leq K(M^*+1) - K(M^*)$. *The optimal number of suppliers to assess* M^* *is non-monotonic in the outside option cost* c_0*. Furthermore, having a larger supply base can decrease the optimal number of suppliers to assess; specifically,* $M^*(N+1) \leq M^*(N)$ *for small enough outside option cost (*$c_0 < x_1$*).*

Surprisingly, Proposition 4 suggests that with a larger supplier base, the optimal number of suppliers to assess can decrease when the outside option is small enough. Intuitively, this is because as the number of suppliers increases, buyer has a higher chance to find a lower production cost supplier – which in turn would compensate for the unknown cost markups. Hence, the buyer may need to focus on assessing more of her potential suppliers when the supplier base is already small. In fact, supplier assessments can act as a tool to compensate for the situations when the buyer does not have a large supply base. So, if the cost of identifying/developing a supplier to include in the supply base is considerably higher than assessing a supplier which is already in the supply base, the buyer may find it beneficial to focus on assessments. In the reverse case, the buyer may find it beneficial to focus on identifying and developing more suppliers to include to its supply base.

The takeaway from this subsection is twofold: First, per Proposition 4, we find that blanket "all-or-none" policies can be improved upon by assessing just a subset of suppliers, even if they are ex ante symmetric. That is, even when facing ex ante symmetric suppliers, the buyer may find it optimal to use an asymmetric assessment policy. This result shows that optimal assessments in a procurement decision does not have to be an all-or-nothing exercise. Companies should not ignore the reality that purchasing based solely on price is suboptimal, but at the same time they should not be daunted by the thought of needing to do a deep total cost analysis on all the suppliers. Instead, a buyer can attain the *lowest total procurement cost* by carefully designing an optimal assessment policy. Second, as per the insights from Proposition 4, we see that the optimal number of suppliers to assess, M^*, changes with the underlying business environment in some surprising ways. For example, making the outside option less attractive (hence making the buyer more reliant on suppliers) may make assessments less valuable and lead to assessing fewer suppliers.

4.4. Correlation between the production cost and the cost markup

One can imagine a correlation between supplier production costs and cost markups. In this subsection, we return to the all-or-nothing assessments case, but model correlation between the cost markups (Δ) and the production cost (c) as follows: production cost of supplier i is equal to $c_i = \epsilon_i + \beta\Delta_i$ where ϵ_i and Δ_i are independent, and are both iid across suppliers, and $\beta \in \mathbb{R}$ (note that when $\beta = 0$, this reduces to our main model). We denote the cdf of ϵ by G_ϵ, the cdf of Δ by F, and the cdf of the convolution c by G_c. We denote the corresponding virtual costs as follows: $J_c(c) = c + \frac{G_c(c)}{g_c(c)}$, $J_\epsilon(\epsilon) = \epsilon + \frac{G_\epsilon(\epsilon)}{g_\epsilon(\epsilon)}$. Furthermore, the value β, and the distributions G_ϵ, G_c, and F are are public knowledge. As before, supplier i's private information is its production cost c_i, and additional information can be obtained via assessments which reveal Δ_i to the buyer and supplier i.

In this setting, without assessments, we allow for the realistic possibility that the buyer can utilize the suppliers' bids as a tool to update her beliefs about the cost markups. Under her optimal mechanism (see

Online Supplement Part VII), the buyer awards the contract to supplier i with the lowest adjusted virtual cost $J_c(c_i) + E[\Delta_i|c_i]$ if $J_c(c_i) + E[\Delta_i|c_i] \leq c_0$, and otherwise uses her outside option. To ensure such a mechanism is incentive compatible, we need to slightly modify the regularity condition, namely, we require that adjusted virtual cost $J_c(c) + E[\Delta|c]$ is increasing in c.

Since a supplier i's production cost is driven partly by Δ_i, the buyer benefits from supplier assessments in two distinct ways: (1) She learns the value of the cost markup Δ_i that she would expect to incur if she did business with the supplier just as in our previous analyses. Hence, the assessments enable the buyer to resolve uncertainty on the cost markups as before. (2) She also resolves some of the uncertainty about the supplier's production cost, namely $\beta\Delta_i$. Hence, with assessments, supplier i's private information reduces to ϵ_i, which they reveal and earn information rents on. Note that the latter benefit from assessments is specific to the setting with correlation. We denote by *EAVC* the expected assessment value in this setting:

$$EAVC = E_{\mathbf{c}}[\min\{(J_c(c) + E[\Delta|c])_{1:N}, c_0\}] - E_{\epsilon,\mathbf{\Delta}}[\min\{(J_\epsilon(\epsilon) + (\beta+1)\Delta)_{1:N}, c_0\}].$$

EAVC is analytically intractable. We use numerical experiments (using the same parameters as in our previous numerical experiments for the independent cost components) to study the effect of our model parameters on *EAVC*. To ensure that the incentive compatibility constraint holds, we use $\beta \geq -0.05$ in our numerical experiments (see Online Supplement Part VII; intuitively, if higher cost is associated with much much lower markup (β is very negative), suppliers will have an incentive to inflate their cost, i.e., the incentive compatibility constraint will fail).

There are multiple effects at play as β and c_0 change. To help understand this, consider the case $\beta = 0$ (our original model) where only benefit (1) will be present, and the expected value of assessments will be non-monotonic in c_0, as explained in §4.1. Next, consider $\epsilon = 0$ (perfect correlation between production cost and cost markup); now only benefit (2) is present. That is, assessments are useful because they cut suppliers' informational rents. This becomes more valuable as the buyer becomes more likely to prefer a supplier to the outside option, and the expected value of assessments monotonically increases in c_0.

With these insights, we can now understand Figure 5, which illustrates *EAVC*. When β is small, benefit (1) dominates and the graphs look like what we saw before in §4.1. As β grows larger, benefit (2) dominates and we see that *EAVC* is no longer non-monotonic in the outside option cost, c_0.

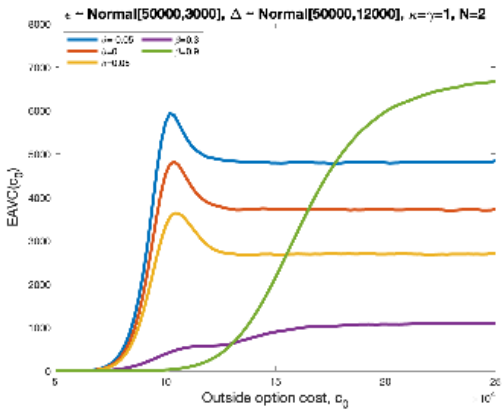


Figure 5 ***EAVC* is non-monotonic in c_0 for small $|\beta|$.**

In the absence of an outside option (or facing an outside option that is sufficiently large that it can effectively be ignored), further numerical experiments reported in the Online Supplement Part VII (to save space in the body) suggest that our previous insights on monotonicity in cost and cost markup multipliers as given in Proposition 3 still hold, and assessments become more (less) valuable as cost markup (independent production cost component ϵ) dominates the total-cost.

4.5. *EAV* under different auction formats

The expected assessment value when the buyer uses the optimal auction format is always positive, and is the upper bound on the expected assessment value under any other auction strategy with assessments as shown in Proposition 1. Hence, studying the optimal format provides a useful and handy benchmark: If it is not cost effective to use the assessments under the optimal auction, it would never be cost effective to use assessments under a suboptimal format.

Using the optimal auction ensures that the buyer can expect to collect the highest amount of benefit from the assessments, however, a buyer may also wish to use simpler auction format. In this section, we compare *EAV* under the optimal auction format with *EAV* under two practical formats: sealed and open-bid auctions.[2]

Suppliers bid prices in both the open-bid and sealed-bid formats, and the buyer awards the contract to the lowest total-cost bid (bid price plus cost markup) supplier. Without assessments, the markup is μ_Δ. With assessments, the suppliers' cost markups are realizations of Δ; suppliers know their own cost markup but

[2] Per Lemma 1, comparing *EAV* also directly yields a comparison of the expected TCO under the optimal and sub-optimal formats.

only know that their opponents' cost markups are distributed according to F. See Kostamis et al. (2009), which provides expressions for computing the equilibrium bids and the buyer's expected total-cost under open and sealed-bid formats when the buyer already knows the cost markups (Kostamis et al. (2009) did not examine *EAV*). We assume the buyer uses a reserve price, set at c_0 (further details are provided in our Online Supplement Part II).

We can gain insights into the buyer's expected total cost in sub-optimal auction formats by extrapolating the elegant (and mathematically complex) findings of Ganuza and Penalva (2010) (in particular, using the insights from their Theorem 5). The authors find that in a second-price auction (without a reserve price), greater dispersion in valuation distributions negatively affect the auctioneer's outcome when the number of bidders is small. In our setting, assessments lead to greater dispersion of suppliers' total costs. Applying Ganuza and Penalva (2010)'s insights suggest the following: When the number of bidders is small, buyer's expected total cost with assessments can increase when compared to the optimal format, as the winner's informational rent may increase too much (while the expected cost without assessments stays the same). This is because information rent is driven by the gulf between the suppliers' total costs, which increases with assessments. But, this problem is attenuated and assessments become attractive when the number of bidders becomes large, because competition drives down the information rents. Thus a key implication is that with sub-optimal auction formats, *EAV* can be negative, and the assessments may actually end up hurting the buyer if the buyer does not use the optimal auction format. We see this illustrated in Figure 6 (the expressions for *EAV* under the open and sealed-bid formats are too complex to analyze in closed-form, but can be studied numerically). We observe that when N is small (and c_0 is large enough to be ignored) *EAV* is negative. But this problem resolves as information rents decrease as N increases, and are truncated by an attractive outside option cost. Additionally, just like we saw in §4.1, *EAV* is non-monotonic in c_0 as shown in Figure 7. The same intuition as in §4.1 explains this, as well as where *EAV* peaks.

A key takeaway is that buyers should be cognizant of the fact that the expected assessment value might be negative if supplier assessments are not used in conjunction with a suitably chosen auction format. However, as we see in Figure 6, the *EAV* under both sealed and open bid formats are more similar to the *EAV* under optimal mechanism as the supply base size increases. This is because the advantage of the optimal mechanism (over the sub-optimal formats) wanes as fierce competition drives information rents down. The implication is that a buyer facing a large supply base size can safely expect to derive positive value from supplier assessments.

In our analysis we have thus far discussed the case where the buyer commits to using either the sealed-bid or open-bid format. Figures 6 and 7 reveal that both formats produce similar *EAV*s for the buyer. One interesting question is whether the buyer could somehow improve its *EAV* by making its auction format contingent on the cost markups she observes. Indeed, Kostamis et al. (2009) show that total-cost performance can be improved by making the auction format choice contingent on the cost markup values (again, they did not study *EAV*). When we apply this insight to *EAV*, the upshot is that by improving her total-cost performance when using assessments, the buyer can improve her *EAV* while still using simple auction formats. This brings her closer to the optimal mechanism's *EAV*. We observe that this insight holds in Figures 6 and 7. Hence, the buyers may find it helpful not to commit to an auction format until after observing the cost markups.

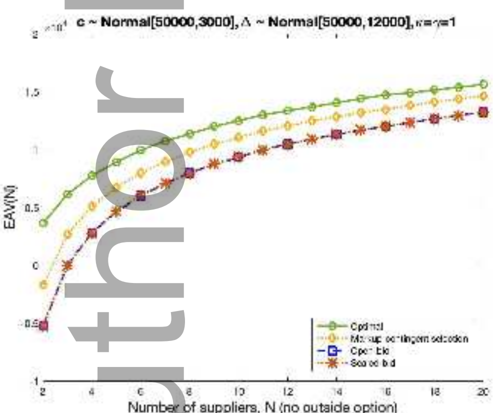


Figure 6 ***EAV*** **gap decreases in** N**.**

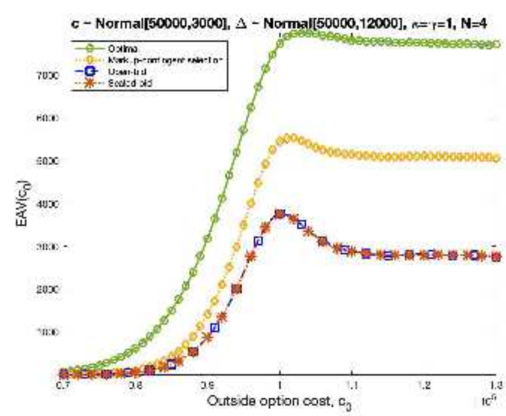


Figure 7 ***EAV*** **is non-monotonic in** c_0**.**

Echoing our findings in Proposition 3, further numerical analyses (reported in the Online Supplement Part VIII to save space in the body) suggest that in the absence of an outside option, and for large enough N, as the dispersion of the cost markups increases, *EAV* under all formats increase. Conversely, as the dispersion of the production costs increases, *EAV* under all formats decrease. As one might expect, the *EAV* gap is particularly large (small) for high values of the cost markup (production cost) multiplier.

Our takeaways for suboptimal auction formats are as follows. The open and sealed-bid formats coincide with the buyer's optimal auction when the buyer does not use assessments (Lemma 1). When the buyer does use assessments, using the optimal mechanism provides the buyer the most benefit from the supplier assessments. Although the value of assessments is lower for the practical auction formats (it may in fact be negative for small supply base sizes), the value of assessments becomes closer to optimal as the supply base size grows. Moreover, the qualitative behavior of assessments (how it changes in critical problem parameters like the outside option cost c_0) remain the same. The key takeaway is that buyers using these practical auction formats can utilize the insights of our paper to gauge the value of assessments for most cases. The one exception is when the supply base is very small, in which case assessments might have much less value (even negative value) compared to the optimal mechanism. In such cases, buyers could consider running a more complex mechanism (closer to the optimal mechanism) if they want to benefit from supplier assessments, or may choose to strategically forgo assessments.

5. Conclusion

Sustainable procurement has long been recognized as one of the main levers of corporate social responsibility. However, even large publicly traded companies are struggling in implementing policies pertaining to sustainable procurement (Thorlakson et al. 2018). Supplier selection is one of the most critical parts of the procurement process, and the buyers now have the option to work with sustainability assessment firms (such as our industry partner EcoVadis) during this step. However, supplier sustainability assessments are costly for the buyer, buyers are under pressure for low-cost procurement, and the procurement managers are often incentivized by the amount of monetary savings. Hence, guiding buyers on when and how to use supplier assessments in the most effective way in order to attain the lowest total procurement cost is crucial in overcoming costly assessments as an obstacle for sustainable procurement.

In this paper, we address this issue in the supplier selection context where the buyer needs to select a supplier sustainability assessment policy in order to minimize the total procurement cost while facing uncertainty in supplier sustainability levels and uncertainty in purchase price.

We first define the expected value of assessments, and then, using an optimal mechanism, identify *how* the buyer can maximize the expected value of supplier assessments by optimally incorporating them into a competitive bid supplier selection process.

Analyzing *when* the buyer should use sustainability assessments, we find that the answers depend on the underlying business factors in some surprising ways. For example, as the buyer's outside option cost decreases, she becomes less reliant on contracting with a supplier, hence one might expect the supplier sustainability assessments to become less valuable. However, we find that the opposite can happen, and a cheaper outside option cost for the buyer can cause the value of assessments to increase. The takeaway for a buyer is as follows: when allocating budgets for assessments, the buyer should not necessarily focus only on those cases where she is most beholden to suppliers by virtue of not having an attractive outside option. In fact, supplier sustainability assessments are most valuable when the outside option is already fairly good.

We find that a buyer may derive higher value from sustainability assessments facing a supply base which is more sustainable on average with less variability in sustainability levels (e.g., a supplier base in a country with more stringent sustainability regulations). We also find that an increase in ex ante magnitude and variability in suppliers' production costs can actually lead to an increase in the value of sustainability assessments. The managerial takeaway is as follows: the buyer should not commit to using sustainability assessments simply because of facing a less sustainable supply base, or forgo assessments simply because of facing a more sustainable supply base. Instead, the buyer should be cognizant of how different factors in her business environment compare, accounting for the total cost of internal production, cost of assessments, variability in the supplier sustainability levels, and the production costs.

Furthermore, we find that blanket assessment policies in which the buyer conducts assessments either on all competing suppliers or none of them are not necessarily optimal. The blanket policies can be improved upon by limiting the number of assessed suppliers even when the suppliers are ex ante symmetric. The managerial takeaway is that the blanket policies — although attractive in their simplicity — may be costing buyers money, in two ways. First, when choosing to "assess all", buyers may be assessing more suppliers than optimal. Second, when choosing "assess none" because the cost of assessing all is too onerous, the buyer may be forgoing the benefits of making decisions based on the total cost that could be gained by a more nuanced policy by limiting the number of assessments. Consequently, buyers who adopt our approach may actually want to use supplier assessments in a higher number of their bid competitions, wherein they assess only a subset of their suppliers (instead of using full blanket assessments in a smaller number of their bid competitions).

Our formalization leads to a host of interesting extensions. In §4.4, we study a setting where there is correlation between the production costs and the cost markups. In §4.5, we compare the assessment value under different practical auction formats with the assessment value under the optimal mechanism. In the Online Supplement, we take a step back and consider a buyer who, even if she had the data on cost markups, might not have a good sense of how to operationalize this data by incorporating it into a total-cost formula for evaluating suppliers. For completeness in the Online Supplement, we also study the case where the assessments may be imprecise, and a setting where the buyer faces an ex ante asymmetric supply base.

In brief, we provide a supplier assessment policy analysis for a buyer firm facing ex ante uncertainty on her potential suppliers' non-biddable cost markups in a total-cost procurement auction setting. The primary motivation in our analysis is the use of supplier sustainability assessments in procurement auctions; however, our results can be extended to similar settings where there are additive but unknown cost markups. It is important to understand when and to what extent buyers should invest in costly information acquisition on such cost markups for their various competitive bidding events. Surprisingly, little research has addressed this important issue. To the best of our knowledge, our paper is the first to identify and formalize this question. Future research could build on our paper's core ideas and take them further. For example, the effect of endogenous entry when the suppliers incur an assessment cost, whether the buyer should use voluntary or compulsory assessments, or how the buyer should share the assessment costs with the suppliers are all open research areas.

Acknowledgments

The authors received invaluable input from EcoVadis on an early draft of this manuscript. The opinions, findings and conclusions or recommendations expressed are those of the authors and do not necessarily reflect the views of EcoVadis. The authors also gratefully acknowledge very helpful comments from two anonymous referees and senior and department editors.

References

Asker, J., E. Cantillon. 2008. Properties of scoring auctions. *The RAND Journal of Economics*, 39 (1), 69–85.

Bagnoli, M., T. Bergstrom. 2005. Log-concave probability and its applications. *Economic Theory*, 26 (2), pp. 445–469.

Beil, D. R., L. M. Wein. 2003. An inverse-optimization-based auction mechanism to support a multiattribute RFQ process. *Management Science*, 49 (11), 1529–1545.

Bergemann, D., M. Pesendorfer. 2007. Information structures in optimal auctions. *Journal of Economic Theory*, 137 (1), 580–609.

Branco, F. 1997. The design of multidimensional auctions. *The RAND Journal of Economics*, 28 (1), 63–81.

Carr, S. M. 2003. Note on online auctions with costly bid evaluation. *Management Science*, 49 (11), 1521–1528.

Che, Y.-K. 1993. Design competition through multidimensional auctions. *Rand Journal of Economics*, 24 (4), 668–680.

Chen, L., H. L. Lee. 2016. Sourcing under supplier responsibility risk: The effects of certification, audit, and contingency payment. *Management Science*, 63 (9), 2795–2812.

Chen, W., M. Dawande, G. Janakiraman. 2018. Optimal procurement auctions under multistage supplier qualification. *Manufacturing & Service Operations Management*, 20 (3), 566–582.

Chen, Y.-J., S. Seshadri, E. Zemel. 2008. Sourcing through auctions and audits. *Production and Operations Management*, 17 (2), 121–138.

Coase, R. H. 1937. The nature of the firm. *Economica*, 4 (16), 386–405.

Diamond, P. A., J. E. Stiglitz. 1974. Increases in risk and in risk aversion. *Journal of Economic Theory*, 8 (3), 337–360.

EcoVadis(a) 2018. `http://www.ecovadis.com/about-us/`. Accessed: 02/06/2018.

EcoVadis(b) 2018. `http://help.ecovadis.com/buyer-help-center/2-4-how-can-i-integrate-csr-into-procurement-processes/`. Accessed: 02/06/2018.

Ellram, L. M. 1994. *Total Cost Modeling in Purchasing*. Center for Advanced Purchasing Studies.

Ellram, L. M. 2006. TCO - adding value to the supply chain. S. Croom, ed. *IPSERA Conference Proceedings*, pp. 6–8.

Elmaghraby, W. J., E. Katok, N. Santamaría. 2012. A laboratory investigation of rank feedback in procurement auctions. *Manufacturing & Service Operations Management*, 14 (1), 128–144.

Engelbrecht-Wiggans, R., E. Haruvy, E. Katok. 2007. A comparison of buyer-determined and price-based multiattribute mechanisms. *Marketing Science*, 26 (5), 629–641.

Ganuza, J.-J. 1995. Optimal procurement mechanism with observable quality. Working paper, Universidad Carlos III de Madrid Departamento de Economía.

Ganuza, J.-J., J. S. Penalva. 2010. Signal orderings based on dispersion and the supply of private information in auctions. *Econometrica*, 78 (3), 1007–1030.

Gassert, F., P. Reig, T. Luo, A. Maddocks. 2013. A weighted aggregation of spatially distinct hyrological indicators. Working paper, World Resources Institute.

Guo, R., H. L. Lee, R. Swinney. 2015. Responsible sourcing in supply chains. *Management Science*, 62 (9), 2722–2744.

Haruvy, E., E. Katok. 2013. Increasing revenue by decreasing information in procurement auctions. *Production and Operations Management*, 22 (1), 19–35.

ISO 2017. *ISO 20400 Sustainable Procurement Guidance*. The International Organization for Standardization.

Kostamis, D., D. R. Beil, I. Duenyas. 2009. Total-cost procurement auctions: Impact of suppliers' cost adjustments on auction format choice. *Management Science*, 55 (12), 1985–1999.

Milgrom, P. R., R. J. Weber. 1982. A theory of auctions and competitive bidding. *Econometrica*, 50 (5), 1089–1122.

Muller, A., D. Stoyan. 2002. *Comparison Methods for Stochastic Models and Risks*, 1st edition. Wiley.

Myerson, R. B. 1981. Optimal auction design. *Mathematics of Operations Research*, 6 (1), 58–73.

Rezende, L. 2009. Biased procurement auctions. *Economic Theory*, 38 (1), 169–185.

Rothschild, M., J. E. Stiglitz. 1970. Increasing risk: I. a definition. *Journal of Economic Theory*, 2 (3), 225 – 243.

Santamaría, N. 2015. An analysis of scoring and buyer-determined procurement auctions. *Production and Operations Management*, 24 (1), 147–158.

Shi, X. 2012. Optimal auctions with information acquisition. *Games and Economic Behavior*, 74 (2), 666–686.

Skreta, V. 2011. On the informed seller problem: Optimal information disclosure. *Review of Economic Design*, 15 (1), 1–36.

Thorlakson, T., J. F. de Zegher, E. F. Lambin. 2018. Companies' contribution to sustainability through global supply chains. *Proceedings of the National Academy of Sciences*, 115 (9), 2072–2077.

UN 2017. *UN Procurement Practitioner's Handbook*. UN-IAPWG New York.

Wan, Z., D. R. Beil. 2009. RFQ auctions with supplier qualification screening. *Operations Research*, 57 (4), 934–949.

Wan, Z., D. R. Beil, E. Katok. 2012. When does it pay to delay supplier qualification? Theory and experiments. *Management Science*, 58 (11), 2057–2075.

Yin, Y., H.-S. Ahn, D. R. Beil. 2013. The role of cost modeling in competitive bid procurement. Working paper, University of Michigan.

Zhang, W., Q. G. Chen, E. Katok. 2020. "Now or later?": When to deploy qualification screening in open-bid auction for re-sourcing. Working paper, University of Texas at Dallas.

Zhao, X., L. Xue, F. Zhang. 2014. Outsourcing competition and information sharing with asymmetrically informed suppliers. *Production and Operations Management*, 23 (10), 1706–1718.

Appendix

Proofs of Lemmas 1 and 2. Detailed proofs for Lemmas 1 and 2 can be found in the Online Supplement. In these proofs, when searching for the optimal auction mechanism, the revelation principle (Myerson 1981) allows us to focus without loss of optimality on direct mechanisms where each supplier truthfully reveals their private information, namely their production cost. Let p_i denote an assignment rule, and t_i a transfer rule for each i: $p_i(\mathbf{c})$ is the probability that the supplier i wins the auction given production cost vector $\mathbf{c} = (c_1, \ldots, c_N)$; $t_i(\mathbf{c})$ is the payment to supplier i given $\mathbf{c}$. Using a mechanism design analysis (e.g., Myerson (1981)), we characterize the buyer's optimal mechanism (p_i^*, t_i^*), and the associated total cost in the proofs for Lemmas 1 and 2.

Proof of Proposition 1. Definition (Rothschild and Stiglitz 1970): Let x and x_a be random variables distributed with H and H_a, respectively. H_a is a mean-preserving spread of H if and only if x_a is equal in distribution to $x + \epsilon$ where ϵ is a zero-mean random variable ($E[\epsilon|x] = 0$). Equivalently, H second-order stochastically dominates H_a, and the two distributions have the same means.

Consider the random variable: $\lambda_M = \min\{\Delta_1 + J_1, \Delta_2 + J_2, \ldots, \Delta_M + J_M, \mu_\Delta + J_{M+1}, \mu_\Delta + J_{M+2}, \ldots, \mu_\Delta + J_N\}$. Let us denote by $H(x) = Prob(\mu_\Delta + J \leq x)$ and $H_a(x) = Prob(\Delta + J \leq x)$. Then, $Prob(\lambda_M \leq x) = 1 - (1 - H(x))^{N-M}(1 - H_a(x))^M$, $\forall M \leq N$, $M \in \mathbb{N}$.

It follows that the buyer's expected total cost when assessing M suppliers can be written as: $E[\text{TCO assessing } M \text{ suppliers}] = \int_0^{c_0} 1 - (1 - (1 - H(x))^{N-M}(1 - H_a(x))^M)\, dx = \int_0^{c_0} (1 - H(x))^{N-M}(1 - H_a(x))^M dx$.

Now, consider the incremental change $d_M^{(1)}$ in $EAV(M) \triangleq E[\text{TCO without assessments}] - E[\text{TCO assessing } M \text{ suppliers}]$ by assessing the $(M+1)$st supplier:

$$
\begin{aligned}
d_M^{(1)} &= EAV(M+1) - EAV(M), \\
&= \int_0^{c_0} (1 - H(x))^{N-M}(1 - H_a(x))^M dx - (1 - H(x))^{N-M-1}(1 - H_a(x))^{M+1} dx, \\
&= \int_0^{c_0} (1 - H(x))^{N-M-1}(1 - H_a(x))^M (H_a(x) - H(x)) dx.
\end{aligned}
$$

We note that $(\Delta - \mu_\Delta)$ is a zero mean random variable, and the distribution of $(\Delta - \mu_\Delta) + \mu_\Delta + J$ is a mean-preserving spread of the distribution of $\mu_\Delta + J$. Hence, the distribution of $\Delta + J$ (denoted by H_a) is a mean-preserving spread of the distribution of $\mu_\Delta + J$ (denoted by H). This also means that H second order stochastically dominates H_a, i.e., $\int_0^t (H_a(x) - H(x))\,dx \geq 0$, $\forall t \in \mathbb{R}^+$. Hence, $\int_0^{c_0} (H_a(x) - H(x))\,dx \geq 0$. Furthermore, there exists a point $x_1 \in \mathbb{R}^+$ such that $\forall x < (>) x_1$, $H(x) \leq (\geq) H_a(x)$ (Diamond and Stiglitz (1974); Muller and Stoyan (2002), Definition 1.5.25 and Theorem 1.5.26).

First consider the case $c_0 < x_1$. Note that $(1 - H(x))^{N-M-1}(1 - H_a(x))^M$ is positive for all x, and that $\forall x < x_1$, $H(x) \leq H_a(x)$. Then, for $c_0 < x_1$, $\forall x \leq c_0$, the integrand $(1 - H(x))^{N-M-1}(1 - H_a(x))^M(H_a(x) - H(x)) \geq 0$, and $d_M^{(1)} = \int_0^{c_0}(1 - H(x))^{N-M-1}(1 - H_a(x))^M(H_a(x) - H(x))dx \geq 0$.

Now consider the case $c_0 > x_1$. Note that per the definition of second order stochastic dominance, $\int_0^{c_0} (H_a(x) - H(x))\,dx \geq 0$ for all c_0 values, and $\int_0^{x_1}(H_a(x) - H(x))dx \geq 0$, $\int_{x_1}^{c_0}(H_a(x) - H(x))dx \leq 0$. Also note that, $\int_0^{c_0} (H_a(x) - H(x))\,dx = \int_0^{x_1}(H_a(x) - H(x))dx + \int_{x_1}^{c_0}(H_a(x) - H(x))dx$. Furthermore, $(1 - H(x))^{N-M-1}(1 - H_a(x))^M$ is positive and decreasing in x. Hence, for $x > (<) x_1$, $(1 - H(x_1))^{N-M-1}(1 - H_a(x_1))^M \geq (\leq) (1 - H(x))^{N-M-1}(1 - H_a(x))^M$. Thus,

$$\begin{aligned}
d_M^{(1)} &= \int_0^{c_0} (1 - H(x))^{N-M-1}(1 - H_a(x))^M(H_a(x) - H(x))dx \\
&= \int_0^{x_1} (1 - H(x))^{N-M-1}(1 - H_a(x))^M(H_a(x) - H(x))dx \\
&\quad + \int_{x_1}^{c_0} (1 - H(x))^{N-M-1}(1 - H_a(x))^M(H_a(x) - H(x))dx, \\
&\geq (1 - H(x_1))^{N-M-1}(1 - H_a(x_1))^M \int_0^{x_1} H_a(x) - H(x)dx \\
&\quad + (1 - H(x_1))^{N-M-1}(1 - H_a(x_1))^M \int_{x_1}^{c_0} H_a(x) - H(x)dx, \\
&= (1 - H(x_1))^{N-M-1}(1 - H_a(x_1))^M \int_0^{c_0} H_a(x) - H(x)dx \geq 0.
\end{aligned}$$

Hence, the increment $d_M^{(1)}$ is positive, and *EAV*(M) is increasing in M. It follows that, *EAV*$(N) = E[\text{TCO without assessments}] - E[\text{TCO with assessments}] = \int_0^{c_0}(1 - H(x))^N dx - \int_0^{c_0}(1 - H_a(x))^N dx$ is positive. Now, we will show that *EAV*(M) is bounded above with $\mu_\Delta - \Delta_{(l)}$:

$$EAV(M) = E_{\boldsymbol{J}}[\min\{\mu_\Delta + J_{1:N}, c_0\}] - E_{\boldsymbol{J},\boldsymbol{\Delta}}[\min\{\Delta_1 + J_1, \ldots, \Delta_M + J_M, \mu_\Delta + J_{M+1}, \ldots, \mu_\Delta + J_N, c_0\}],$$

$$\leq E_{\boldsymbol{J}}[\min\{\mu_\Delta + J_{1:N}, c_0\}] - E_{\boldsymbol{J}}[\min\{\Delta_{(l)} + J_{1:N}, c_0\}],$$

$$= \mu_\Delta + E_{\boldsymbol{J}}[\min\{J_{1:N}, c_0 - \mu_\Delta\}] - \Delta_{(l)} - E_{\boldsymbol{J}}[\min\{J_{1:N}, c_0 - \Delta_{(l)}\}],$$

$$\leq \mu_\Delta + E_{\boldsymbol{J}}[\min\{J_{1:N}, c_0 - \Delta_{(l)}\}] - \Delta_{(l)} - E_{\boldsymbol{J}}[\min\{J_{1:N}, c_0 - \Delta_{(l)}\}] \;=\; \mu_\Delta - \Delta_{(l)}.$$

Given $M \leq N$, note that the first term in *EAV*(M), $E_{\boldsymbol{J}}[\min\{\mu_\Delta + J_{1:N}, c_0\}]$ is the same across any auction mechanism that implements the optimal mechanism when the suppliers are competing on price only. However, as per Lemma 3 (provided in the Online Supplement), the second term $E_{\boldsymbol{J},\boldsymbol{\Delta}}[\min\{\Delta_1 + J_1, \ldots, \Delta_M + J_M, \mu_\Delta + J_{M+1}, \ldots, \mu_\Delta + J_N, c_0\}]$ is the lowest TCO attainable when the competition is over total cost. Hence, *EAV*(M) is the highest when using an optimal mechanism.

Proof of Proposition 2 We now consider the changes *EAV*(M), for $M \leq N$, with respect to c_0. Note that $EAV(M) = \int_0^{c_0}(1-H(x))^N dx - \int_0^{c_0}(1-H_a(x))^M(1-H(x))^{N-M}dx$. Then, $\frac{EAV(M)}{\partial c_0} = (1 - H(c_0))^{N-M}((1-H(c_0))^M - (1-H_a(c_0))^M)$.

We note that by the proof of Proposition 1, there exists a x_1 such that $H(x) \leq H_a(x)$ for $x < x_1$, and $H(x) \geq H_a(x)$ for $x > x_1$. Hence, $(1-H(c_0))^M - (1-H_a(c_0))^M \geq 0$ for $c_0 < x_1$, and $\frac{EAV(M)}{\partial c_0} = (1 - H(c_0))^{N-M}((1-H(c_0))^M - (1-H_a(c_0))^M) \geq 0$. Then, *EAV*$(M)$ is increasing in c_0 for $c_0 < x_1$.

Let us denote $\Delta_{(u)} + J_{(u)}$ by x_2 (where $\Delta_{(u)}$ and $J_{(u)}$ are the upper bounds of the supports for the cost markup and virtual production cost distributions, respectively). Note that for $c_0 \geq x_2$, $H(c_0) = H_a(c_0) = 1$. Then, for all $c_0 \geq x_2$, $\frac{\partial EAV(M)}{\partial c_0} = 0$. Hence, *EAV*$(M)$ is constant in c_0 for $c_0 \geq x_2$.

Note that for $x_2 > c_0 > x_1$, $H(c_0) \geq H_a(c_0)$, and $(1-H(c_0))^M - (1-H_a(c_0))^M \leq 0$. Then, $\frac{\partial EAV(M)}{\partial c_0} \leq 0$ when $x_1 < c_0 < x_2$. Hence, *EAV*(M) is decreasing in c_0 for $x_1 < c_0 < x_2$.

It follows that, *EAV*(M) is unimodal in c_0, and it peaks at x_1, $\frac{\partial EAV(M)}{\partial c_0}|_{x_1} = 0$, and $H(x_1) = H_a(x_1)$. To illustrate this, Figure 2 plots the cumulative distribution functions of suppliers' adjusted virtual costs without assessment (H) and with assessments (H_a) for $M = N$. We see that the cumulative distribution function H_a has a single crossing point with H. In fact, exactly as predicted, the crossing point correspond to where the assessment region peaks in Figure 1.

Proof of Proposition 3. Here, we ignore the outside option. First, consider multiplying Δ by a positive constant γ.

For $M \leq N$, define

$$\mathit{EAV}(M,\gamma) \triangleq E[\min\{\gamma\mu_\Delta + J_1, \ldots, \gamma\mu_\Delta + J_N\}] - E[\min\{\gamma\Delta_1 + J_1, \ldots, \gamma\Delta_M + J_M, \gamma\mu_\Delta + J_{M+1}, \ldots, \gamma\mu_\Delta + J_N\}],$$
$$= \gamma\mu_\Delta + E[J_{1:N}] - \gamma\mu_\Delta - E[\min\{\gamma(\Delta_1 - \mu_\Delta) + J_1, \ldots, \gamma(\Delta_M - \mu_\Delta) + J_M, J_{M+1}, \ldots, J_N\}],$$
$$= E[J_{1:N}] - E[\min\{\gamma(\Delta_1 - \mu_\Delta) + J_1, \ldots, \gamma(\Delta_M - \mu_\Delta) + J_M, J_{M+1}, \ldots, J_N\}].$$

Let us denote by H_a^γ the distribution of $\gamma(\Delta_1 - \mu_\Delta) + J$. As before, $\tilde{G}$ denotes the distribution of J. Then,

$$\begin{aligned}\mathit{EAV}(M,\gamma_2) - \mathit{EAV}(M,\gamma_1) &= E[\min\{\gamma_1(\Delta_1 - \mu_\Delta) + J_1, \ldots, \gamma_1(\Delta_M - \mu_\Delta) + J_M, J_{M+1}, \ldots, J_N\}] \\ &\quad - E[\min\{\gamma_2(\Delta_1 - \mu_\Delta) + J_1, \ldots, \gamma_2(\Delta_M - \mu_\Delta) + J_M, J_{M+1}, \ldots, J_N\}], \\ &= \int_0^\infty (1 - \tilde{G}(x))^{N-M}((1 - H_a^{\gamma_1}(x))^M - (1 - H_a^{\gamma_2}(x))^M)dx.\end{aligned}$$

We note that $(\Delta - \mu_\Delta)$ is a zero mean random variable, and the distribution of $\gamma_2(\Delta - \mu_\Delta) + J$ is a mean-preserving spread of the distribution of $\gamma_1(\Delta - \mu_\Delta) + J$ for $\gamma_2 \geq \gamma_1$. Then, there exists a point $x_1^\gamma \in \mathbb{R}^+$ such that $\forall x < (>) x_1^\gamma$, $H_a^{\gamma_1}(x) \leq (\geq) H_a^{\gamma_2}(x)$. Then, for $x < x_1^\gamma$, $(1 - H_a^{\gamma_1}(x))^M - (1 - H_a^{\gamma_2}(x))^M \geq 0$, and for $x > x_1^\gamma$, $(1 - H_a^{\gamma_1}(x))^M - (1 - H_a^{\gamma_2}(x))^M \leq 0$. Also, note that per Proposition 1's proof, $\int_0^\infty (1 - H(x))^N - (1 - H_a(x))^N dx \geq 0$ for any generic N, H_a and H, where H_a is a mean-preserving spread of H. Then, $\int_0^\infty (1 - H_a^{\gamma_1}(x))^M - (1 - H_a^{\gamma_2}(x))^M dx \geq 0$.

Note that $(1 - \tilde{G}(x))^{N-M} \geq 0$ for all x, and is decreasing in x. Then for $x < (>) x_1^\gamma$, $(1 - \tilde{G}(x_1^\gamma))^{N-M} \leq (\geq)(1 - \tilde{G}(x))^{N-M}$. It follows that:

$$\begin{aligned}\mathit{EAV}(M,\gamma_2) - \mathit{EAV}(M,\gamma_1) &= \int_0^\infty (1 - \tilde{G}(x))^{N-M}((1 - H_a^{\gamma_1}(x))^M - (1 - H_a^{\gamma_2}(x))^M)dx \\ &= \int_0^{x_1^\gamma} (1 - \tilde{G}(x))^{N-M}((1 - H_a^{\gamma_1}(x))^M - (1 - H_a^{\gamma_2}(x))^M)dx \\ &\quad + \int_{x_1^\gamma}^\infty (1 - \tilde{G}(x))^{N-M}((1 - H_a^{\gamma_1}(x))^M - (1 - H_a^{\gamma_2}(x))^M)dx \\ &\geq (1 - \tilde{G}(x_1^\gamma))^{N-M} \int_0^{x_1^\gamma} (1 - H_a^{\gamma_1}(x))^M - (1 - H_a^{\gamma_2}(x))^M dx \\ &\quad + (1 - \tilde{G}(x_1^\gamma))^{N-M} \int_{x_1^\gamma}^\infty (1 - H_a^{\gamma_1}(x))^M - (1 - H_a^{\gamma_2}(x))^M dx\end{aligned}$$

$$= (1-\tilde{G}(x_1^{\gamma}))^{N-M}\int_0^{\infty}(1-H_a^{\gamma_1}(x))^M-(1-H_a^{\gamma_2}(x))^M dx$$

≥ 0. Hence, $EAV(M,\gamma_2)-EAV(M,\gamma_1)$ is positive.

Now, consider multiplying the production c by a positive constant κ. We first show that $J(\kappa c)$ is equivalent to $\kappa J(c)$. Let $y=\kappa\cdot c$. Then: $G_y(y)=G_c(\frac{y}{\kappa})$, $g_y=G'_y=\frac{1}{\kappa}\cdot g_c(\frac{y}{\kappa})$. Now, consider the virtual cost function: $y+\frac{G_y(y)}{g_y(y)}=y+\frac{G_c(\frac{y}{\kappa})}{\frac{1}{\kappa}\cdot g_c(\frac{y}{\kappa})}=y+\kappa\cdot\frac{G_c(\frac{y}{\kappa})}{g_c(\frac{y}{\kappa})}=\kappa\cdot c+\kappa\cdot\frac{G_c(c)}{g_c(c)}$. Hence, $J(\kappa\cdot c)=\kappa\cdot J(c)$. For $M\leq N$, define:

$$EAV(M,\kappa)\triangleq E[\min\{\mu_\Delta+\kappa J_1,\ldots,\mu_\Delta+\kappa J_N\}]-E[\min\{\Delta_1+\kappa J_1,\ldots,\Delta_M+\kappa J_M,\mu_\Delta+\kappa J_{M+1},\ldots,\mu_\Delta+\kappa J_N\}],$$
$$=\mu_\Delta+\kappa E[J_{1:N}]-E[\min\{\Delta_1+\kappa J_1,\ldots,\Delta_M+\kappa J_M,\mu_\Delta+\kappa J_{M+1},\ldots,\mu_\Delta+\kappa J_N\}].$$

We will show that for $\kappa_2\geq\kappa_1$, $EAV(M,\kappa_1)-EAV(M,\kappa_2)$ is positive. Note that

$$E[\min\{\Delta_1+\kappa_2 J_1,\ldots,\Delta_M+\kappa_2 J_M,\mu_\Delta+\kappa_2 J_{M+1},\ldots,\mu_\Delta+\kappa_2 J_N\}]$$
$$-E[\min\{\Delta_1+\kappa_1 J_1,\ldots,\Delta_M+\kappa_1 J_M,\mu_\Delta+\kappa_1 J_{M+1},\ldots,\mu_\Delta+\kappa_1 J_N\}],$$
$$=E[\min\{\Delta_1+\kappa_1 J_1+(\kappa_2-\kappa_1)J_1,\ldots,\Delta_M+\kappa_1 J_M+(\kappa_2-\kappa_1)J_M,\mu_\Delta+\kappa_1 J_{M+1}+(\kappa_2-\kappa_1)J_{M+1},\ldots,$$
$$\mu_\Delta+\kappa_1 J_N+(\kappa_2-\kappa_1)J_N\}]$$
$$-E[\min\{\Delta_1+\kappa_1 J_1,\ldots,\Delta_M+\kappa_1 J_M,\mu_\Delta+\kappa_1 J_{M+1},\ldots,\mu_\Delta+\kappa_1 J_N\}],$$
$$\geq E[\min\{\Delta_1+\kappa_1 J_1+(\kappa_2-\kappa_1)J_{1:N},\ldots,\Delta_M+\kappa_1 J_M+(\kappa_2-\kappa_1)J_{1:N},\mu_\Delta+\kappa_1 J_{M+1}+(\kappa_2-\kappa_1)J_{1:N},\ldots,$$
$$\mu_\Delta+\kappa_1 J_N+(\kappa_2-\kappa_1)J_{1:N}\}]$$
$$-E[\min\{\Delta_1+\kappa_1 J_1,\ldots,\Delta_M+\kappa_1 J_M,\mu_\Delta+\kappa_1 J_{M+1},\ldots,\mu_\Delta+\kappa_1 J_N\}],$$
$$=\ (\kappa_2-\kappa_1)E[J_{1:N}]\quad \text{which proves the result.}$$

We now show that adding a constant to the production cost leads to an increase in the virtual cost by the same amount. Let $y=c+\tau$, then $G_y(y)=G_c(y-\tau)$ and $g_y(y)=g_c(y-\tau)$. Furthermore, $y+\frac{G_y(y)}{g_y(y)}=y+\frac{G_c(y-\tau)}{g_c(y-\tau)}=c+\tau+\frac{G_c(c)}{g_c(c)}$. Hence, $J(c+\tau)=J(c)+\tau$. Now consider the changes in $EAV(M)$ when adding a constant τ, to either random variable Δ or c. Also note that $EAV(M,\tau)=E_{\boldsymbol{J}}[\mu_\Delta+J_{1:N}+\tau]-E_{\boldsymbol{J},\boldsymbol{\Delta}}[\min\{\Delta_1+J_1,\ldots,\Delta_M+J_M,\mu_\Delta+J_{M+1},\ldots,\mu_\Delta+J_N\}+\tau]=E_{\boldsymbol{J}}[\mu_\Delta+J_{1:N}]-E_{\boldsymbol{J},\boldsymbol{\Delta}}[\min\{\Delta_1+$

$J_1, \ldots, \Delta_M + J_M, \mu_\Delta + J_{M+1}, \ldots, \mu_\Delta + J_N\}]$. Hence adding a constant τ, to either random variable Δ or c (and consequently to J), would not change $EAV(M)$.

Proof of Proposition 4. Note that the proofs of Propositions 1-3 hold for any generic $M \leq N$. Hence, they directly apply when the buyer assesses $M < N$ suppliers.

Note that the proof of Proposition 1 shows that $d_M^{(1)} = EAV(M+1) - EAV(M) \geq 0$. Now, let us consider the second increment $d_M^{(2)}$ (for $M+2 \leq N$):

$$\begin{aligned} d_M^{(2)} &= EAV(M+2) - EAV(M+1) - (EAV(M+1) - EAV(M)), \\ &= -\int_0^{c_0} (1-H(x))^{N-M-2}(1-H_a(x))^M (H_a(x) - H(x))^2 dx. \end{aligned}$$

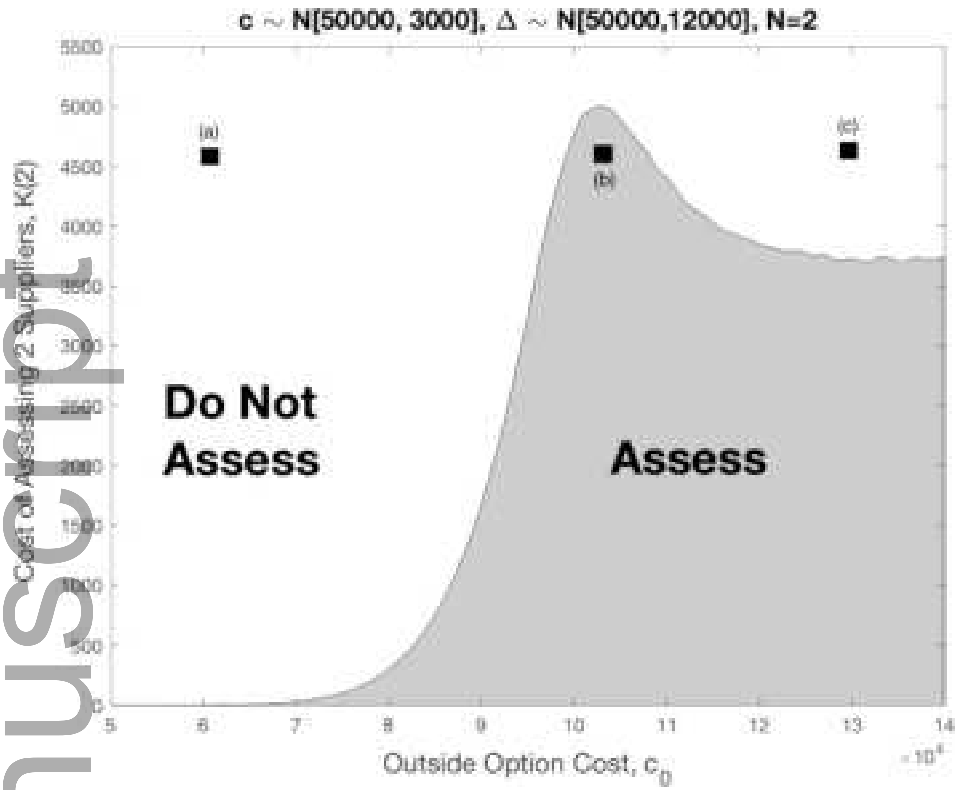
Note that the integrand $(1-H(x))^{N-M-2}(1-H_a(x))^M(H_a(x)-H(x))^2 \geq 0$, $\forall x$. Hence, the second increment is negative, and, $EAV(M)$ is concave increasing in the number of assessed suppliers M. Since $K(M)$ is weakly convex increasing in M, then $EAV(M) - K(M)$ is concave, and the optimal M^* is given by the first order condition as characterized in Proposition 4.

Note that $\frac{\partial EAV(M+1) - EAV(M)}{\partial c_0} = (1-H(c_0))^{N-M-1}(1-H_a(c_0))^M(H_a(c_0) - H(c_0))$. Per the proof of Proposition 1, there exists a x_1 such that $H(x) \leq H_a(x)$ for $x < x_1$, and $H(x) \geq H_a(x)$ for $x > x_1$. Hence, $\frac{\partial EAV(M+1) - EAV(M)}{\partial c_0} \geq (\leq) 0$ for $c_0 < (>) x_1$. Consequently, the benefit from assessing one more supplier, and hence M^*, increases in c_0 for $c_0 < x_1$, and decreases in c_0 for $c_0 > x_1$.

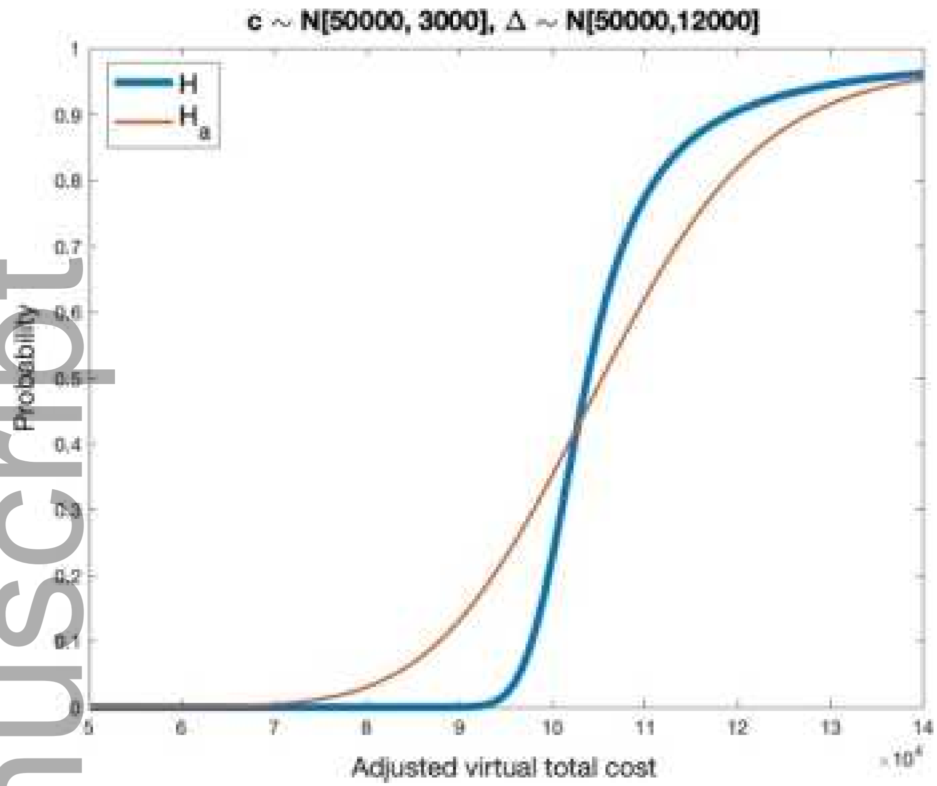
Now, consider the change in EAV by assessing the $(M+1)$st supplier when facing a pool of $N+1$ suppliers:

$$\begin{aligned} d_M^{(1)}(N+1) &= EAV(M+1, N+1) - EAV(M, N+1), \\ &= \int_0^{c_0} (1-H(x))^{N+1-M}(1-H_a(x))^M dx - \int_0^{c_0} (1-H(x))^{N-M}(1-H_a(x))^{M+1} dx, \\ &= \int_0^{c_0} (1-H(x))^{N-M}(1-H_a(x))^M (H_a(x) - H(x)) dx. \end{aligned}$$

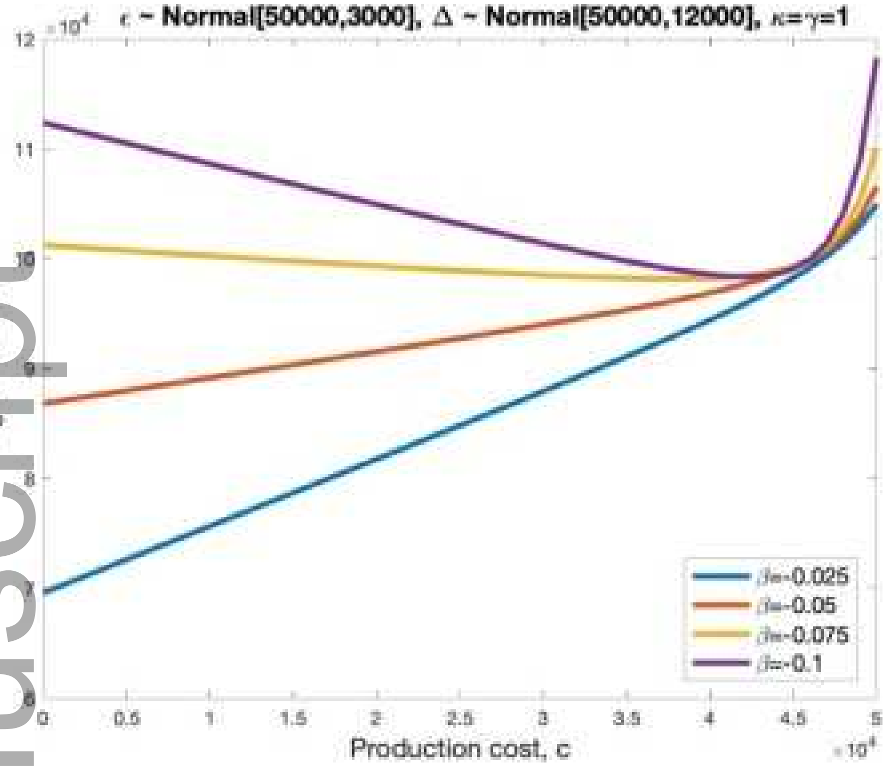
Then, $d_M^{(1)}(N+1) - d_M^{(1)}(N) = -\int_0^{c_0}(1-H(x))^{N-M-1}(1-H_a(x))^M(H_a(x)-H(x))H(x)dx$. Note that for $c_0 < x_1$, $(H_a(x) - H(x)) \geq 0 \; \forall x \leq c_0$ due to mean-preserving spread. Hence, $d_M^{(1)}(N+1) - d_M^{(1)}(N)$ is negative, i.e., the incremental benefit from increasing the number of assessed suppliers decreases in the supply base size. Consequently, if $0 < M^*(N) < N$ for some N, then $M^*(N+1) \leq M^*(N)$, for $c_0 < x_1$.



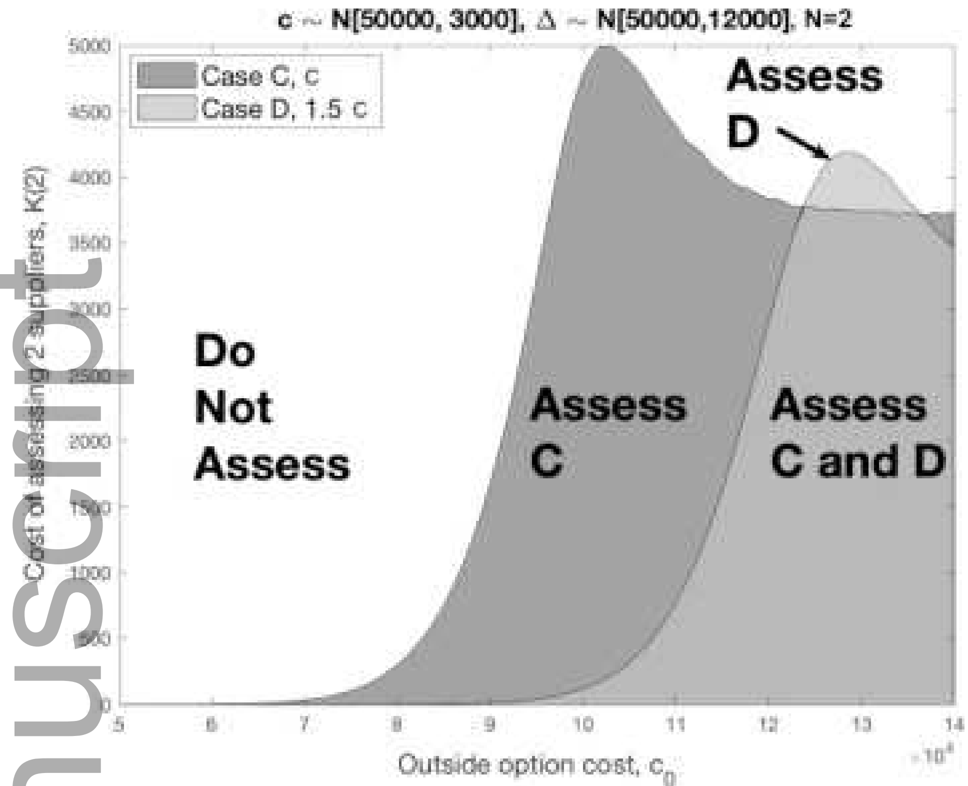
poms_13284_f1.png



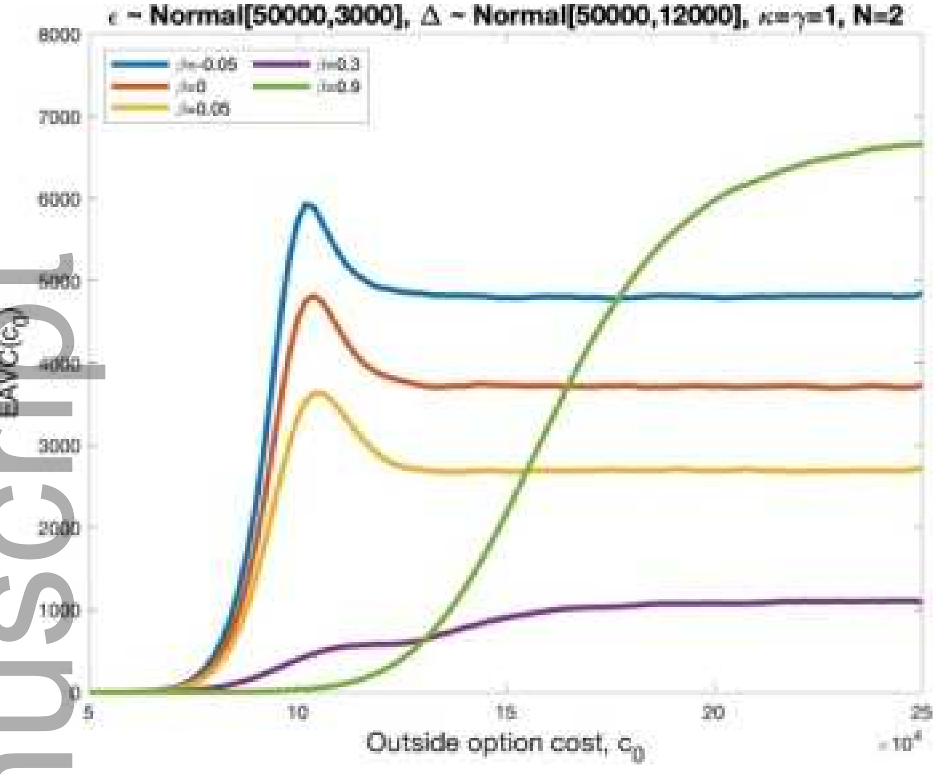
poms_13284_f2.png



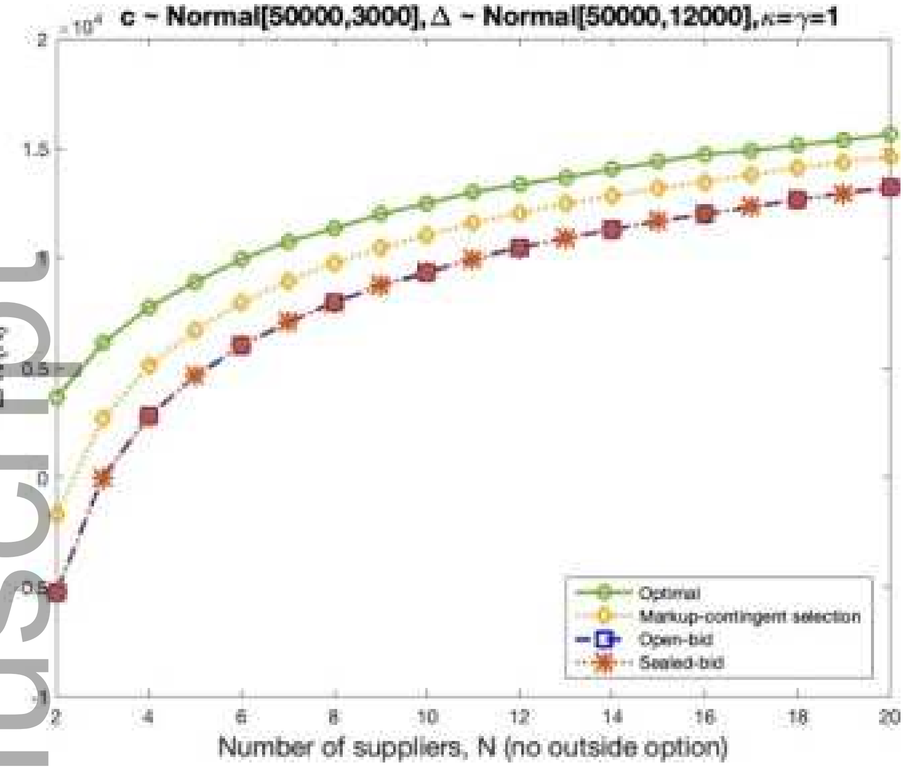
poms_13284_f3.png



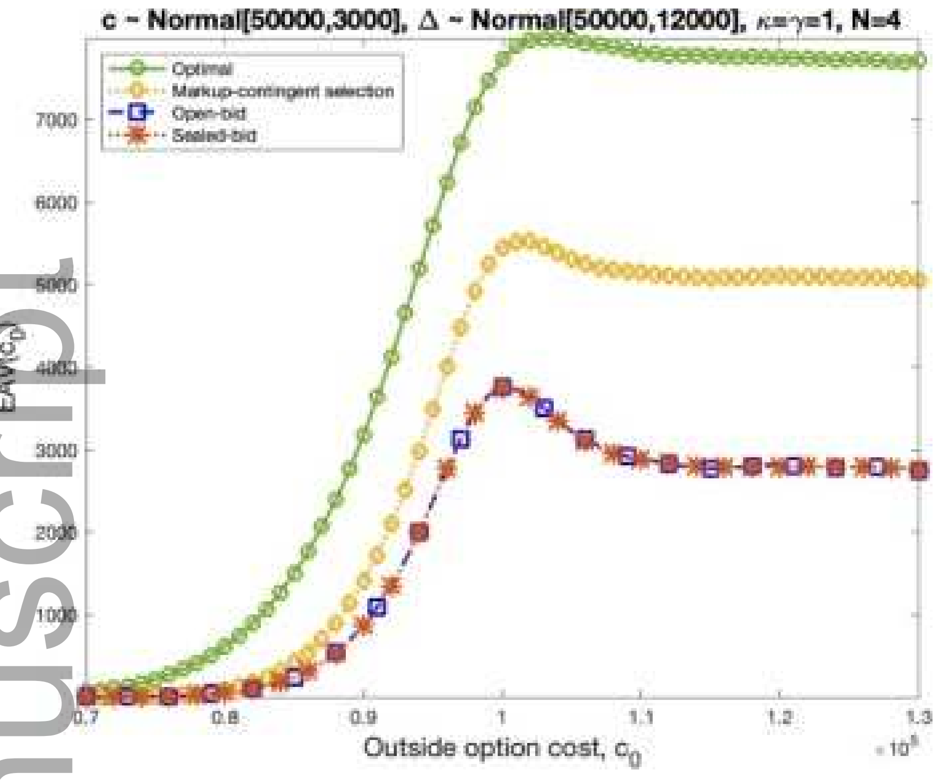
poms_13284_f4.png



poms_13284_f5.png



poms_13284_f6.png



poms_13284_f7.png