Mt741ti-Attribute Procurement Auctions in the PresenceMtc

use procurement auctions to procure legal services, even for litigation (Edwards 2015). Recently, Indian Railways announced plans to implement procurement auctions with the aim of saving $1.4 billion in spending per year (Ians 2018).

Unlike sales auctions in which bids usually only involve price, bids in procurement auctions also include bidders' promise to deliver certain quality levels as well. This unique aspect creates multidimensional bids in this class of procurement auctions. Further, the uncertainty in buyer (dis)satisfaction also plays a significant role in procurement auctions. The *ex ante* uncertainty regarding satisfaction is governed by two endogenous decisions from the supplier's side: the promised quality and their unobservable effort during the project. Note that the "satisfaction risk" will only be realized after the service (or product) is delivered. As a consequence, the issue of satisfaction risk becomes imperative during the design of service procurement auctions. On the one hand, satisfaction is directly influenced by the promised quality of the winning supplier during the multidimensional auction. On the other hand, the supplier's effort also influences the final quality realized. Buyer satisfaction is commonly conceptualized as a function of the difference between proposed and delivered quality. Thus, the existence of satisfaction risk poses a critical research question: What is the best mechanism to overcome the problem of procuring multi-attribute services or goods when satisfaction risk is present?

In this study, we investigate the role of the satisfaction risk in the context of performance-based contracts (PBCs). PBCs have been widely adopted in operations management practice (Tan et al. 2017). For example, the construction industry has long suffered from low productivity, and PBCs are one of the most common mechanisms to mitigate satisfaction risk (Groves 2017). According to *Forbes* (Vitasek 2015), the U.S. Department of Transportation is moving toward a national performance-based approach. Transportation authorities in Canada, Finland, and New Zealand have already adopted scoring auctions combined with PBCs for road management and maintenance projects (Stankevich et al. 2005). For example, the New South Wales, Victoria, and Queensland road authorities in Australia applied a quality-based selection (QBS) method to select the winning bid during bidder evaluation and selection. QBS considers quality and price, and awards the contract to the bidder with the highest overall score. Then, during the project execution phase, payments for on-road works are made at a unit rate, and payments for off-road works are performance-based and paid on a lump-sum basis. Penalties are included in PBCs to address user literature on multi-attribute auctions without buyer satisfaction rewards and penalties, which shows that supplier quality and price can be determined separately (Che 1993). Also, we note that satisfaction risk can drive bidders to bid less (or more) aggressively on the quality dimension depending on the effect of promised quality on satisfaction, thus reducing or increasing the supplier's information rent. Second, our analysis highlights the importance of classifying the relationship between promised quality and effort (in particular, whether they are complements or substitutes) and how they influence the supplier's behavior. We find that less effort will be exerted in an optimal auction (i.e., buyer utility maximization) than in an efficient auction (i.e., social surplus maximization) when effort complements promised quality, while the opposite is true when effort substitutes for promised quality. Third, with respect to mechanism design, we find that an optimal reserve score is required to avoid a situation where undesirable bidders leave the buyer with a loss. A crucial implication here is that neither reserve quality nor reserve price alone is sufficient to exclude undesirable bidders that can create negative buyer surplus. Finally, to further explore the impact of uncertainty on our results, we analyze two classes of satisfaction functions (linear and nonlinear) under an additive relationship between bidders' behaviors and randomness. Interestingly, we find that uncertainty can actually benefit both supplier and buyer under certain conditions, resulting in a Pareto improvement.

The rest of the study is organized as follows. We first review the relevant literature and position of our study with respect to it in section 2. The model and

decreases the probability of achieving an exceeding *ex post* outcome (i.e., Δq). That is, the increase of promised quality q has two simultaneous effects in our model: to enhance satisfaction (i.e., increase $\tilde{q}$)[2] and to raise reference (i.e., increase the difficulty to reach a higher Δq). We define the first effect as the enhancement role and the second as the reference role in the remainder of our study. If $\Delta q_q \leq 0$, it indicates that the reference role dominates the enhancement role; if Δq_q

Lemma 3. *Expected buyer utility prior to bidding is* $E(U_b) = E_{\ (1)}\{W(q(\ _{(1)}), e(\ _{(1)})) - c\ (q(\ _{(1)}),\ _{(1)})\ F(\ _{(1)})/f(\ _{(1)})\}$ *where* $_{(1)} = min_i\{\ _i\}$, *i* = 1, 2, . . ., *n; c* $(q,\ )$ *is the partial derivative w.r.t.* , *and* $W(q(\ ),e(\ ))=V(q(\ ))-c(q(\ ),\ )+\Lambda(q(\ ),e(\ ))-g(e(\ ))$ *is the social surplus generated by the supplier of type* .

Note that the expected buyer utility can be characterized by two equivalent expressions: the direct form, and taking the difference between social surplus and information rent. Here we adopt the latter because of expositional convenience. In mechanism design theory, buyer utility is similar to the notion of "*virtual valuation.*" However, *virtual valuation* in our model involves both multidimensional bids and moral hazard. This generates a double uncertainty for the buyer.

Proposition 4. *Under the optimal mechanism,* = 1 *and* $s(q) = V(q) - D(q)$, *where* $D(q) = \int_l^q [F(q_0^{-1}(s))/f(q_0^{-1}(s))] \cdot c_q$

bid prices to achieve non-negative utility. In this case the buyer cannot exclude high-cost suppliers (i.e., $> \tilde{}$. If the buyer only sets a reserve price, all types of suppliers can participate. The intuition of this result is as follows. Any type of bidder, without violating the reserve price, can make a bid with sufficiently low promised quality to achieve a positive utility. The implication of this unique reserve score can be explained in two ways. First, a single-dimensional reserve (price or quality) in a multidimensional auction is insufficient; as a result, the buyer must impose a minimum requirement on both promised quality and bid price to exclude undesired types from the pool of potential suppliers. Second, the reserve score in a single-stage procurement auction works similarly to the pre-qualification process in multi-stage auctions, and ensures that only qualified bidders can participate in the subsequent bidding. To the best of our knowledge, this finding has not been emphasized in the previous procurement auction literature.

Recent developments in information technology have facilitated the implementation of multi-attribution auction. Buyers submit their needs through an electronic platform and solicit bids from the pre-qualified suppliers. When the buyer submits the specifications of the procurement, she also reports her valuation and/or scoring rules on the request items, which includes both price and non-price dimensions. To respond, the suppliers submit their bids, which include their promised quality and price. Further, we observe that many buyers in practice also set the minimum acceptable quality level and ceiling price together, which can be translated to a reserve score in our setting. Our results here provide practical guidance regarding how to design and implement procurement auctions when satisfaction concern is significant.

Corollary 2. *The quality distortion* $D(q)$ *of optimal mechanism under the scenario of dominant reference role in promised quality* (*i.e.,* $\Delta q_q \le 0$)*, is less than that under the scenario of dominant enhancement role* (*i.e.,* $\Delta q_q > 0$).

Corollary 2 provides an immediate insight for procurement managers. When promised quality involves an uncertain performance with a dominant reference role, bidders will submit lower bids because a high-promised quality decreases the possibility of fulfilling or exceeding the buyer's expectations upon completion of the project. Accordingly, the buyer deploys an optimal scoring rule with mild distortion. For the reverse case with a dominant enhancement role, the buyer should distort the promised quality more aggressively.

We denote $\hat{q}$ and $\hat{e}$ as promised quality and effort in *efficient mechanism*, respectively, and q^* and e^* as those in *optimal mechanism*. Comparing the bidder's behaviors in efficient and optimal mechanisms, we obtain the following proposition.

Proposition 6. *When the buyer is quality sensitive* (*i.e.,* $\Lambda_{qe} > 0$)*, both promised quality and effort are lower under optimal mechanism than under efficient mechanism* (*i.e.,* $\hat{q} > q^*$ *and* $\hat{e} > e^*$)*; when the buyer is effort sensitive* (*i.e.,* $\Lambda_{qe} < 0$)*, promised quality is lower under optimal mechanism than under efficient mechanism* (*i.e.,* $\hat{q} > q^*$)*, while the effort is higher under optimal mechanism than under efficient mechanism* (*i.e.,* $\hat{e} < e^*$

($k > 1$), the reference role dominates (is dominated by) the enhancement role. When $k = 1$, the enhancement role fully offsets the reference role.

Assume $\sim U[a, b]$ with $0 < a \leq b$. The stochastic factor applies to Δq additively. That is, $\Delta q(e, q, \ ) = re - (1 - k)q +$, and we label it as “additive uncertainty,” which appears widely in the supply chain literature (e.g., Agrawal and Sechadri 2000, Chen 2005, Chu and Lai 2013). In this section, we consider both linear and the more general nonlinear satisfaction functions and examine two types of uncertainties.[4]

the satisfaction function is quality sensitive or effort sensitive. When promised quality and effort complement with each other ($k < 1$), we observe that the promised quality decreases due to the increased negative contribution of promised quality on satisfaction (which is generated by decreased effort) as shown in Figure 3a; when the promised quality and effort substitute with each other ($k > 1$), the promised quality increases since the positive contribution of promised quality on satisfaction increases as shown in Figure 3b.

In this subsection, we focus on analyzing the impacts of and on buyer *ex ante* utility and the optimal mechanism design. The quality distortion $D(q)$, as the central point of the optimal mechanism, regulates q^* and e^* on the bidder's side; thus, setting the distortion appropriately is crucial in helping the buyer to maximize utility.

PROPOSITION 8. *Buyer's expected utility increases in , while it is independent of under linear* (Δq) *and increases (decreases) in under nonlinear* (Δq) *if* $\partial\Lambda(q, e, \ )/\partial \ > 0(<0)$.

Proposition 8 shows that the buyer's *ex ante* utility increases in under both linear and nonlinear (Δq) due to the fact that the mean of Δq increases in , which is illustrated in Figure 4a. In particular, the buyer's expected utility increases in at constant rate given linear (Δq), and increases at a decreasing rate given nonlinear $\lambda(\Delta q) = \ \cdot (1 - exp(-\Delta q))$. Under linear (Δq), the constant rate of buyer utility increase in implies that the increment of buyer utility is independent of q and e, and thus the degree of distortion is independent of . Under nonlinear (Δq), note that the marginal positive effect of on buyer utility $(dU_b(q, e)/d \ )$ always decreases in e, and increases (decreases) in q if $k < 1$ ($k > 1$). Therefore, a higher (lower) q under $k < 1$ ($k > 1$) and lower e boost the rate of increase of buyer utility. Consequently, the optimal mechanism imposes a more significant (milder) distortion.

In contrast to , under linear (Δq), the buyer's expected utility is independent of due to the constant mean of Δq, and thus the degree of distortion is also independent of . Interestingly, under nonlinear (Δq), the impact of on buyer utility depends on its impact on satisfaction $(\partial\Lambda(q, e, \ )/\partial \ )$. When satisfaction increases in , buyer benefits from the increase of uncertainty; the opposite is true if satisfaction decreases in . Similar to , the impact of on quality distortion in an optimal mechanism relies on the impact of on promised quality. Therefore, the buyer adopts different levels of distortion on the promised quality to respond to different effects of uncertainty. Figure 4b illustrates the impacts of on buyer utility under linear and nonlinear satisfaction. In particular, with nonlinear $\lambda(\Delta q) = \cdot (1 - \exp(-\Delta q))$, $\partial \Lambda(q, e, \ )$ $/\partial \ < 0$ always holds, which implies that the buyer's expected utility decreases in .

In summary, we analyze the impacts of two uncertainty types on the bidder's and buyer's behaviors. Under linear satisfaction, promised quality and effort remain unchanged with uncertainty, while the buyer's expected utility increases in

In the base model, we assume that the realized performance of the promised quality is stochastic. This is true in many practical scenarios. However, in some circumstances, the realization of promised quality can be achieved with certainty as well. To incorporate this

winning probability, $U_s(b(\ ), q(\ )| \ ) = [b - g(\ ^{-1}$
$(q), \ ) + \ \cdot$

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[1]For exposition, we use bidders and suppliers interchangeably in the remainder of the manuscript.

[2]This is because that the promised quality is of concrete input cost, a higher investment is more likely to achieve a higher performance.

[3]To illustrate the result of Proposition 4, consider $v(q) = q^{\frac{2}{3}}, c(\ , q) = \ \cdot q, \ \sim U$