

Quantity Choice in Unit Price Contract Procurements

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Abstract

A common approach for procuring large construction projects is through Unit Price Contracts. By the means of a simple model, we study the optimal quantity to procure under uncertainty regarding the actual required quantity given that the procurer strives to minimize expected total costs. The model shows that the quantity to procure in optimum follows from a trade-off between the risk of having to pay for more units than actually necessary and of having to conduct costly renegotiations. The optimal quantity increases in costs associated with possible renegotiations, decreases in expected per unit price, and, if a renegotiation does not increase per unit price too much, decreases in the uncertainty surrounding the actual quantity required.

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Introduction

Large constructions, e.g., infrastructure projects, may be procured in a series of different ways. In many countries, the prevailing approach in practice seems to be through Unit Price Contracts (UPC)¹. In a UPC, the procurer, e.g. a national road administrator, specifies the amounts of each activity, e.g., the amount of gravel to be removed, and lets the agents bid on unit prices. Typically, the agent with the lowest total bid – summing over all amounts times the bidding prices – wins the procurement.

This paper addresses the optimal behavior of the procurer, henceforth the principal, in UPC procurements. In particular, it addresses what amount of an activity to procure in a setting where the actual amount required is uncertain. Previous work dealing with UPC more or less implicitly assumes that the principal will procure the estimated amount of each activity. For instance, Ewerhart and Fiesler (2003) states that in a UPC “*the buyer estimates the quantities of the respective input factors that will be needed to accomplish the task. Then the buyer publicly announces her estimates [...]*”. We will, by the means of a simple model, show that this notion is not correct. Rather, there are cases in which the principal should – in order to minimize her expected total costs – procure a quantity exceeding the estimated or expected one and other cases in which the procured quantity should be lower. More importantly, the model will provide us with an intuitive understanding for the mechanisms at work.

This paper is akin to a literature focusing on optimal behavior among bidders in UPC procurement. In particular, that literature addresses strategic bidding behavior under which the bidding agents have superior information. The agent may exploit their information advantage by skewing their bids. This behavior is often referred to as unbalanced bidding. The underlying information asymmetry may be that the agent is better informed about the actual, *ex post*, amounts of individual tasks. This case is investigated by Atey and Levin (2001) and Bajari et.al. (2007). A similar situation may occur when the agent is better informed about her own type, e.g., skill, as studied in the aforementioned Ewerhart and Fieseler (2003). These papers model the bidding agents’ behavior in UPC auctions while the present paper models

¹UPC can be viewed as a subgroup of Design-Bid-Build. Love (2002) notes that “traditional lump sum” procurements (to which UPC belongs) dominate in many commonwealth countries. In Sweden, ~ 90% of the road investments between 2000 and 2009 were procured under UPC, Mandell and Nilsson (2010).

the procurer's behavior. Thus, the present paper is a step towards a unified model which allows for strategic behavior of both procurer and bidders.

As noted, a central outcome of our model is that the quantity to procure may deviate, upwards or downwards, from the expected quantity actually required. Consequently, our model adds to the literature on cost overruns. That cost overruns are frequently occurring in infrastructure projects seems to be an established fact in the literature, Flyvbjerg et.al. (2003) and Odeck (2004). According to Priemus et al (2008), cost overruns for large infrastructure projects of between 50 and 100 per cent are common. Furthermore, the forecasts of costs have not improved over the last 70 years.

Priemus et.al. also provide a couple of plausible explanations for systematic miscalculation of costs leading to cost underestimation; bad forecasting due to technical problems and calculation problem, that the project change shape during the construction phase, and that planners, instead of getting the forecast right, perform a forecast to support an already decided project. Our model suggests one additional reason. Namely that the procurer, in some situations, contracts on a low quantity knowing that the required quantity with a large probability will be larger than the contracted one and, thus, that total costs *ex post* most probably will exceed the contracted sum. The interesting – and perhaps somewhat paradoxical – result is that this behaviour is optimal since it keeps the *expected* total costs at a minimum.

Ganuza (2007) and Gaspar and Leite (1989/90) are related to the present paper as both develop models on procurement in which cost-overruns are likely to occur in optimum. These studies focus on different aspects of procurement than our model. The former shows that the procurer, in optimum, should underinvest in design specification. The reason is that an exact design will decrease competition among bidders, which results in that a large share of the rents will be captured by the winning bidder. The latter provides a model in which each bidder has an imperfect signal about the cost of finalizing the project. As the lowest bid will win, a selection bias problem emerges. This results in a high risk for cost-overruns.

It should be noted that there are different definitions of the concept cost-overrun. The definition here, as in Ganuza (2007) and, to some extent, Gaspar and Leite (1989/90), would be actual total costs minus contracted sum. Priemus et al. (2008, page 125) states the definition as “*Actual cost minus forecasted cost*” where forecasted cost is defined as “*the*

estimate made at the time of decision to build, or as close to this as possible if no estimate was available for the decision to build". The contract sum is probably not a good approximation of the latter.

The remaining paper is structured as follows: The next section introduces the model and leads up to a first-order condition. The characteristics of this condition is analysed in section 3. The model relies on a series of assumption. Possible consequences of relaxing some of the more restrictive assumptions are discussed in section 4. Section 5 concludes.

The model

We will not model the bidding procedures. Rather, we assume that the winning bid covers the agent's marginal cost associated with each activity with some margin. Consequently, the agent always gains from conducting one extra unit of the activity and the agent has no incentive to carry out less of an activity than what is specified in the contract. Given this, the amounts specified in the contract serve as a lower threshold².

For the sake of this presentation it suffices to focus on one activity. Let us denote the amount of this activity required to complete the project by Q . It is easy to expand the model to include several activities, but it will not add to the understanding of the problem. In the procurement stage, i.e., *ex ante*, Q is not fully known³. However, it seems reasonable that the principal, i.e. the procurer, has a prior but uncertain estimate of Q . For simplicity, let us assume that $Q \sim U(Q_{low}, Q_{high})$. This assumption of a uniform distribution is not very realistic, but it greatly simplifies the presentation.

Given this information, the principal specifies an amount in the UPC. Let us denote this amount q , which is the central variable in the model as it is the only variable the principal controls. The bidding process yields a winning per unit price for q , which we denote p .

² For this to be true there must be nothing else to gain from conducting less of an activity than the contract states. In particular, there may be no reputational effects. That is, the agent's behaviour in this contractual relationship must not influence the probability of winning future contracts.

³ This may, for instance, be due the exact characteristics of the rock may be unobservable prior to the project has started.

Clearly, when deciding what amount to procure the resulting price is not known. Intuitively, and as will be shown subsequently, the principal's belief about the emerging per unit price will influence his choice of q . To capture this, we assume that the principal knows that the emerging price will be in the uniform⁴ interval (p_{low}, p_{high}) . Again, the uniform distribution is probably not very realistic but a simple way to capture uncertainty.

Due to the uncertainty regarding required quantity, it may be the case that q is not sufficient to produce the project, *i.e.*, it may be the case that $q < Q$. Whether or not this situation occurs is not known at the procurement stage, but becomes evident to the agent during the construction phase. It is of minor concern exactly when (after the procurement) the information about the true Q is revealed. Here, we assume that it is revealed once q has been conducted.

If it turns out to be the case that $q < Q$ the principal and the agent must renegotiate the contract in order to finalize the project. This may be associated with a renegotiation cost, denoted R . We restrict our attention to $R \geq 0$ and $R \leq (Q_{high} - Q_{low}) p$. The former limit is uncontroversial. If the latter limit is not fulfilled, the cost of renegotiating the contract will exceed the entire possible gain from renegotiating⁵. The result of the renegotiation is a price per unit for the remaining amount of the activity required to finalize the project, $p_R \geq p$.⁶ Let p_R be equal to $p + \gamma$. For simplicity, we assume that at the renegotiation stage the true Q is observable for both parties. That is, there will only be one renegotiation as it is then known (with certainty) that the remaining amount is $Q - q$.

Figure 1 summarizes the timing of the model as described above. In the first stage, the principal decides on how many units to procure, q . This is followed by the procurement,

⁴ The crucial assumption is that the distribution is symmetric around its expected value. The use of a uniform distribution is motivated by it being used for the quantity (where the exact distribution, as will be discussed in section 4, will influence the outcome).

⁵ Then, it is obviously better to procure the maximal amount of the activity, *i.e.*, $q = Q_{high}$, and thereby setting the probability of having to renegotiate to zero.

⁶ That is, we disregard the case where the renegotiated price is less than the initial one. The rationale for this is that it seems unlikely that the principal would receive a better deal once locked into an agreement with a given agent.

which will establish the winning per unit price. The next step is the construction phase under which the true Q will be revealed to the agent. If q is sufficient, i.e., $q \geq Q$, payments are made according to the contract and the game ends. If not, renegotiations are needed.

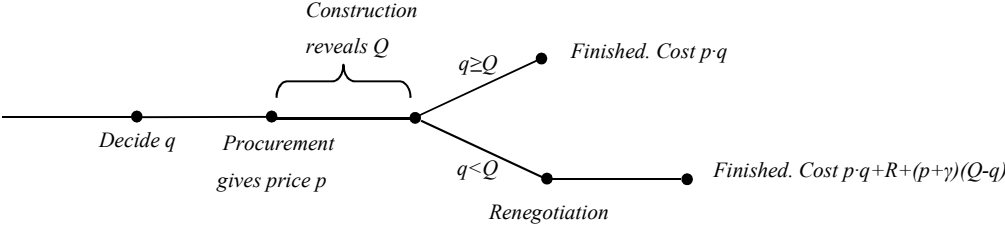


Figure 1. The sequence of the game.

Using the assumptions above, the principal’s total cost, TC , will be

$$TC = \begin{cases} p \cdot q & \text{when } q \geq Q \\ (p \cdot q) + R + (p + \gamma)(Q - q) & \text{when } q < Q \end{cases}$$

Figure 2 shows TC for different realizations of Q . One key factor is that for realizations below q ; TC always equals $p \cdot q$. The principal thus, most likely, pays for q units even though the project could have been carried through using only $Q < q$ units. Note that for these realizations; the principal only knows that Q is weakly less than q as he may not observe Q . The other key factor is the cost of renegotiations. In figure 2 these costs show up in two different ways; first through a shift in the TC -curve at q , due to the renegotiation cost, and, second, through the slope of the TC -curve above q . If there is a mark-up in per unit price due to the renegotiation, this will result in a steeper TC -curve.

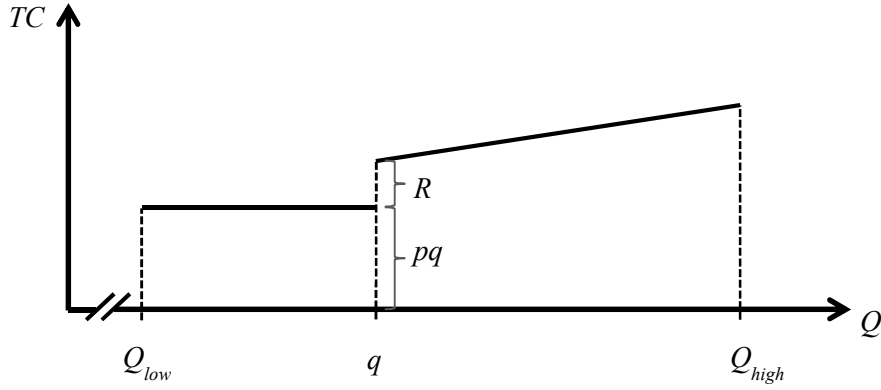


Figure 2. Total cost over realization of Q .

Neither party knows the actual TC prior to the construction phase. Rather, the principal strives to minimize the *expected* total cost, which may be written as

$$E\{TC\} = \frac{1}{p_{high} - p_{low}} \int_{p_{low}}^{p_{high}} \left(\frac{1}{Q_{high} - Q_{low}} \left(\int_{Q_{low}}^q pq \, dq + \int_q^{Q_{high}} (pq + R + (p + \gamma)(Q - q)) \, dq \right) \right) dp$$

The first integral is due to the uncertainty in emerging price prior to conducting the procurement. The first integral inside the brackets captures realizations under which q is sufficient and the second integral captures those where additional activity is required. The expression may be rewritten as

$$E\{TC\} = \frac{(p_{high} + p_{low})(q^2 - 2qQ_{low} + Q_{high}^2) + 2(q - Q_{high})(\gamma(q - Q_{high}) - 2R)}{4(Q_{high} - Q_{low})} \quad (1)$$

The principal's optimization problem amounts to choosing q to minimize $E\{TC\}$. From (1) we may derive the following first order condition

$$q^* = \frac{Q_{low}(p_{high} + p_{low}) + 2(Q_{high}\gamma + R)}{p_{high} + p_{low} + 2\gamma} \quad (2)$$

Taking account for that the symmetry we have assumed regarding the distribution around the expected price implies that $p_{low} + p_{high} = 2\bar{p}$, where \bar{p} denotes the expected price, we reach

$$q^* = \frac{\bar{p}Q_{low} + \gamma Q_{high} + R}{\bar{p} + \gamma} \quad (3)$$

The next section contains a closer analysis of the characteristics of this optimal quantity to procure. For now, we only note that the uncertainty surrounding the price does not enter into the expression as long as it, as is assumed here, is symmetrically distributed around the expected value.

Analysis

From (3) it is evident that the optimal quantity to procure is influenced by several variables; the expected price, the renegotiation cost, the possible mark-up in price following a renegotiation and the range of the uncertainty in required quantity. The aim of this section is to analyze how these variables affect the optimal quantity as well as to provide an intuitive understanding of these dependencies.

We start with the influence from the renegotiation cost. Differentiating (3) with respect to R yields:

$$\frac{\partial q^*}{\partial R} = \frac{1}{\bar{p} + \gamma} > 0 \quad (4)$$

The denominator of (4) is the expected price after the renegotiation. Even if we would allow for a negative price mark-up, we do not allow for this price to be negative. Thus, (4) is positive and the optimal quantity increases (linearly) in the renegotiation cost, see Figure 3a. This makes intuitive sense. By increasing the procured quantity, the risk of ending up in a situation where this quantity is insufficient, i.e., $q < Q$, becomes smaller. On the other hand, by increasing q , the cost incurred when q turns out to be sufficient, i.e., $q \geq Q$, becomes larger. This illustrates the fundamental trade-off faced by the principal; a larger q reduces the risk for costly renegotiations, but also increases the costs for outcomes where renegotiations are not needed. What (4) shows is that if the renegotiation costs are higher, then the principal is willing to increase the costs incurred when $q \geq Q$ to reduce the risk of renegotiations.

Applying the same logic on the price mark-up, γ , would suggest that the optimal procured quantity should increase if the mark-up is increased. To see this, we differentiate (3) with respect to γ , which yields

$$\frac{\partial q^*}{\partial \gamma} = \frac{\bar{p}(Q_{high} - Q_{low}) - R}{(\bar{p} + \gamma)^2} > 0 \quad (5)$$

Equation (7) is indeed positive⁷. Thus, if the price mark-up increases, the principal increases the contracted quantity and thereby reduces the risk of having to pay the higher renegotiated price, see Figure 3b.

If the expected per unit price increases, the principal will reduce the procured quantity, as seen from differentiating (3) with respect to \bar{p} which yields

$$\frac{\partial q^*}{\partial \bar{p}} = -\frac{R+(Q_{high}-Q_{low})\gamma}{(\bar{p}+\gamma)^2} < 0 \quad (6)$$

This too makes intuitive sense in the light of the fundamental trade-off described above. The principal may reduce the risk of a costly renegotiation by increasing the procured quantity, but that increases the probability of having to pay $p \cdot q$ for a job that actually required less than q units of input. The higher the p , the higher the cost in these outcomes. Consequently, if the expected per unit price increases, the principal will reduce the procured quantity as a renegotiation has become relatively (but not absolutely) less costly, see Figure 3d.

The optimal quantity to procure depends, in addition to the variables discussed above, on the lower and upper limit of the distribution of Q , i.e., the minimum and maximum amount of the input required respectively. Differentiating (3) with respect to Q_{low} and Q_{high} respectively yields

$$\frac{\partial q^*}{\partial Q_{low}} = \frac{\bar{p}}{(\bar{p}+\gamma)} > 0 \quad (7)$$

$$\frac{\partial q^*}{\partial Q_{high}} = \frac{\gamma}{(\bar{p}+\gamma)} > 0 \quad (8)$$

From (7) we see that if the lowest possible quantity required increases, the optimal quantity to procure must increase. As seen from (8), the same applies for the highest possible required amount. Neither of these is surprising in the light of our previous discussion. Increasing the upper boundary increases the probability of having to conduct costly renegotiations. The same

⁷This is true as long as $R \leq (Q_{high}-Q_{low}) \bar{p}$ which must be the case otherwise the contractor will put $q = Q_{High}$ and thereby ruling out any risk for renegotiation

applies for the lower boundary as increasing this will shift some probability mass to outcomes where $q < Q$ and a renegotiation is required.

Equations (7) and (8) also say something about the optimal response from a change in uncertainty. For the uncertainty surrounding a given expected Q to increase it must be the case that Q_{low} decreases at the same time as Q_{high} increases at the same rate. From (7) we know that the former implies a decrease in q^* , while, from (8), the latter implies an increase in q^* . The outcome is determined by the relative strength between (7) and (8), which depends on the relation between the expected price (being in the numerator of (7)) and the price mark-up (the numerator of (8)). We have no theoretical prediction of this. However, as long as the mark-up is less than the expected price, (7) will outweigh (8) implying that the optimal quantity to procure decreases when the uncertainty increases (also see Figure 3c).

The results above are summarized in Figure 3, which illustrates – by the means of a numerical example – the optimal quantity and resulting expected total cost as a function of the renegotiation cost, R , the price mark-up, γ , the quantity range, $Q_{high}-Q_{low}$, and the expected price, \bar{p} . Note that the quantity is measured on the left axis and expected cost on the right and that the scale for the expected cost is different in the expected price graph.

Figure 3 hints towards some other findings, in addition to those discussed above. For instance it seems as q^* asymptotically approaches Q_{high} when the price mark-up increases, and Q_{low} when the expected price increases. That these observations are not artifacts of this particular numerical example is easily verified by studying (3). There is also an intuitive explanation. As the price mark-up becomes very high, risking a renegotiation becomes prohibitively costly. Hence, to avoid renegotiations the principal procures an amount equal (or, in the limit, very close to) to Q_{high} . A similar logic applies for the expected price. When this is very large (relative to R and γ), the principal faces great incentives to avoid paying for more units than are actually required. This is achieved by procuring an amount close to Q_{low} . The principal knows that this implies a large risk for a renegotiation, but the cost this incurs is relatively small.

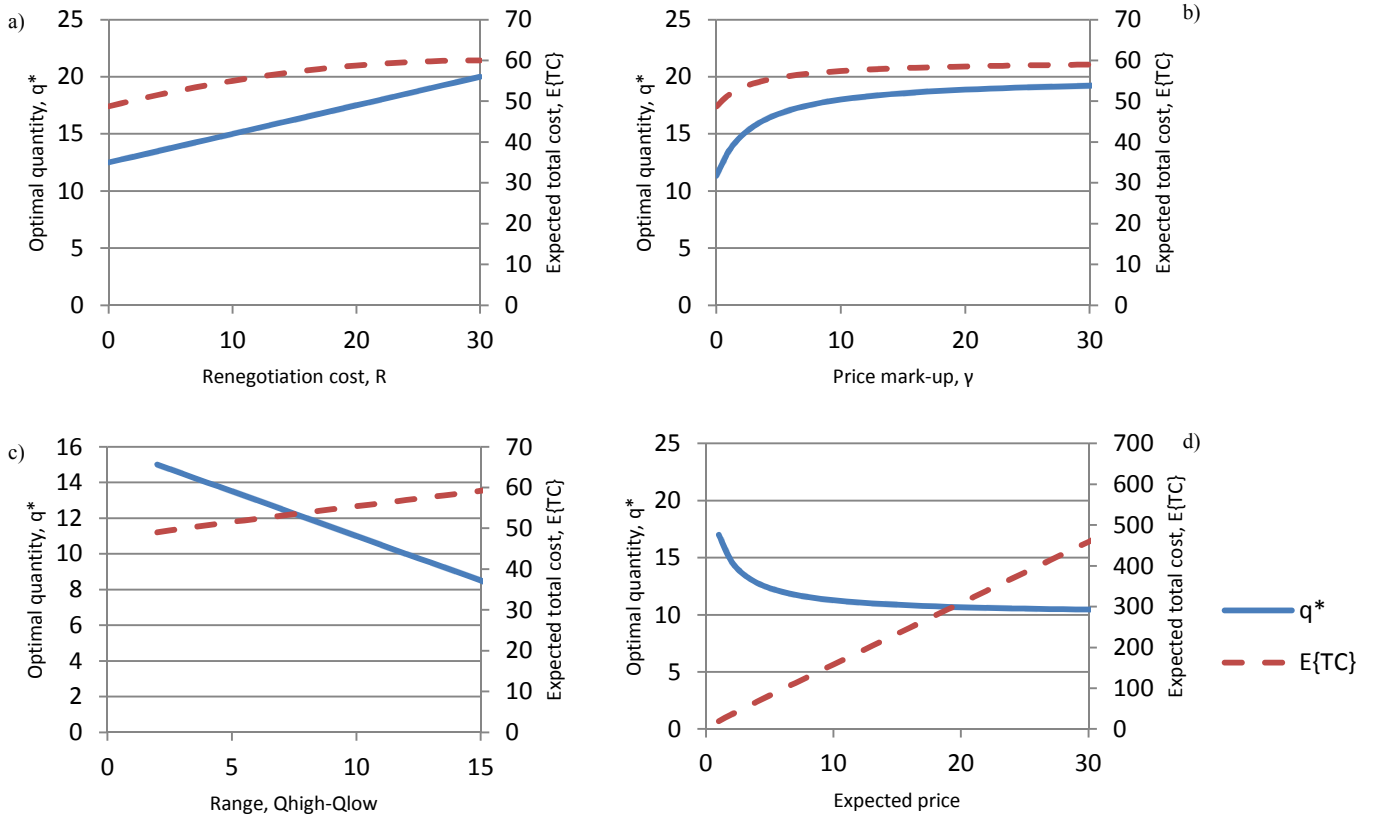


Figure 3, optimal quantity to procure (left axis) and resulting expected total cost (right axis) as a function of R , γ , $Q_{high}-Q_{low}$ and \bar{p} , respectively. The base case of this numerical example is $p_{low}=2$, $p_{high}=4$, $Q_{low}=10$, $Q_{high}=20$, $R=4$, and $\gamma=1$.

Also note that when the range of the uncertainty surrounding Q decreases, q tends to the expected value of Q (15 in the numerical example)⁸. This must be the case as in a setting without uncertainty; the principal clearly should procure the certain amount.

Finally, as seen from Figure 3a, when R tends to zero the amount to procure is close to Q_{low} . This provides a good illustration of the fundamental trade-off the principal faces. The reason for a $q > Q_{low}$ when $R = 0$ in Figure 3a is that there is a positive mark-up in price in the base case of the numerical example. From (3) it is easily seen that if both R and γ equal zero, the optimal quantity to procure is exactly Q_{low} . In the light of the discussion above, this is expected. In this setting there are no costs associated with a renegotiation and, thus, the trade-

⁸The range in Figure 3C starts at 2. A lower value on the range would violate the upper limit of R , $((Q_{high}-Q_{low})\bar{p})$.

off breaks down to the corner solution of procuring Q_{low} , conducting the (costless) renegotiation at which the true Q becomes known to both the agent and the principal. By this the principal will only have to pay for units actually required.

Discussion regarding relaxing assumptions

The model and analysis above build on a series of assumptions. To a large extent these are chosen as to facilitate the presentation, rather than because they are realistic. This section contains a brief discussion about likely consequences of relaxing these assumptions. We pay particular attention to the assumptions regarding q operating as a lower limit, and the use of uniform distributions. We also briefly address the assumptions stating that both the mark-up in price after a renegotiation and the renegotiation cost itself are known with certainty prior to the renegotiation.

That q operates as a lower limit follows from an assumption of that the price will cover marginal cost with some margin together with the assumption that only the agent may observe Q prior to a renegotiation. The former implies that it is always profitable for the agent to conduct one extra unit of the activity. By allowing for an increasing marginal cost function there may be situations when the agent does not conduct q units, if these are not necessary for finalizing the project. However, even in this case it may, depending on the marginal cost structure, be that more than amount actually required is conducted. Thus, the basic problem still remains.

Another question is whether the agent may conduct less than q units even though the price exceeds the marginal cost. For this to be the case there must be something else to gain for the agent. A plausible explanation would be reputation. By delivering the project at a lower cost than contracted upon may result in it being easier to win future procurements. For this to be the case it seems that the winner in the (future) procurement process must be elected not only on lowest total price, but also on past records.

Related to this discussion is the issue about the principal's ability to observe the actual quantities prior to a renegotiation. In the model it is assumed that only the agent may observe these. It seems plausible that the principal could adopt some kind of (potentially costly) monitoring that would relax this assumption. If the quantities were perfectly observable for the principal, the problem addressed would disappear. In that case the principal would procure

the maximum possible quantity, but only pay for units actually required. This points towards another problem that entails a trade-off between the problem we address here and the cost of monitoring. This question is left for future research. More interesting from the present paper's perspective is if the principal may observe actual quantities, but that the observation is imperfect, i.e., it contains noise. To really capture the outcome of such a situation would require a different model.

However, the model in its current form hints towards a possible outcome. Partial observability should result in that the total cost at low realizations is lower than at higher ones (still less or equal than q). Even if the total cost is lower for low realization, it is – due to imperfect monitoring – larger than the cost under perfect observability. Graphically, this would imply that the horizontal section of Figure 2 is sloping upward at a rate lower than the unit price. Consequently, the basic mechanism in the current model is still present in that the principal for low realizations risks paying more than would have been necessary under perfect monitoring. This is still weighed towards the risk of a costly renegotiation. However, as the cost of the former is less under partial observability, the optimal quantity to procure must be higher than predicted by our model since the renegotiation is now *relatively* more costly.

Regarding the uniform distribution surrounding the expected price, this assumption is easily relaxed. As seen from (2), what matters for the principal's choice of q is that the distribution is symmetric around the expected value. As long as this is the case, it would seem to have no impact on q^* which distribution is chosen. Thus, this assumption is not very restrictive.

The assumption of a uniform distribution around the expected required quantity has a larger impact on the outcome. Without data it is difficult to say much about the shape of a realistic assumption. A starting point would be a more bell-shaped distribution having the same upper and lower bound as the uniform distribution currently used. As this puts more probability on outcomes close to $E\{Q\}$ it will have a similar impact on the result as decreasing the range of the uniform distribution. As shown above this would typically (when the price mark-up is less than the expected price) call for a higher q in optimum.

Flyvbjerg et.al. (2002) examine the difference between *ex post* total cost and planned budget for 258 transportation infrastructure projects. They find a distribution that is skewed towards cost overruns. A similar pattern is reported by Berechman and Chen (2011) for 163 highway

investments in Vancouver Island. Both these studies differ from ours in that we compare *ex post* outcomes with what is contracted (not planned). Even so, they point towards that a likely distribution of Q should be skewed to the right. Still keeping the same upper and lower bound, this would shift probability mass towards lower outcomes and thus, using the same logic as above, would call for a lower q^* than under the assumptions of a uniform distribution.

Given that there is no risk-aversion involved, there is little reason to suspect that uncertainty in renegotiation cost and price mark-up at the procurement stage will have any impact on the optimal q . The principal would simply have to base his decision on the expected values. Of course, this may change if, for instance, the variables are correlated with Q .

Conclusions

In this paper we have, by the means of a simple model, studied the optimal quantity to procure when unit price contracts are used and there is uncertainty around what the actual required quantity will be. The model shows that the optimal quantity to procure, i.e., the one that minimizes the procurer's expected total cost, is determined by a fundamental trade-off between (1) the risk of having to pay for more units than actually necessary and (2) the risk of having to conduct costly renegotiations. In optimum, the procured quantity will increase in costs associated with a possible renegotiation. It will decrease in the expected per unit price. Typically, if the renegotiation does not result in too large mark-up in per unit price, the procured quantity decreases in the uncertainty surrounding the actual quantity required. These results have all been shown mathematically and the intuition behind them is discussed in the main text.

When the procured quantity is low compared to the expected amount required the risk that the final amount exceeds the procured one is obviously large. This implies that the actual total cost, with high probability, will exceed the total sum agreed upon in the contract. If we allow ourselves to define this as being a measure of cost-overflow, this leads to an interesting conclusion. Namely that not only is it rational and optimal to allow for cost-overruns. It is actually more likely, in optimum, to see cost-overruns in projects that are expected to run smoothly in the sense that the costs of renegotiations are expected to be low. That is, if one observes cost-overruns defined as actual costs minus contract sum, this does not necessarily be an indication of any miscalculation or other error – intentional or not – on behalf of the

procurer. Rather, it may serve as an indicator that the relationship between principal and agent was expected to run smoothly with low costs associated with any possible renegotiation of the initial contract.

Let us conclude this paper by pointing at an area for future research. The literature on unbalanced bidding predicts that a rational informed agent will exploit her superior information in the bidding process. In particular, she will post high per unit bids on activities that she believes are underspecified by the procurer. That is, the optimal procurement strategy described above, may invoke strategic responses from the bidding agents. Understanding the implications of such strategic responses requires a unified model capable of handling both procurer and agent behavior.

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