Competition and Cost Overruns.

Optimal Misspecification of Procurement Contracts*

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Abstract

Most cases of cost overruns in public procurement are related to important changes in the initial project design. This paper deals with the problem of design specification in public procurement and provides a rationale for design misspecification. We propose a model in which the sponsor decides how much to invest in design specification and awards competitively the project to a contractor. After the project has been awarded the sponsor engages in bilateral renegotiation with the contractor, in order to accommodate changes in the initial project's design that new information makes desirable. When procurement takes place in the presence of horizontally differentiated contractors, the design's specification level is seen to affect the resulting degree of competition. The paper highlights this interaction between market competition and design specification and shows that the sponsor's optimal strategy, when facing an imperfectly competitive market supply, is to underinvest in design specification so as to make significant cost overruns likely. Since no such misspecification occurs in a perfectly competitive market, cost overruns are seen to arise as a consequence of lack of competition in the procurement market.

Keywords: Cost overruns, procurement contracts, strategic ignorance.

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"Lady Brandon treats her guests exactly as an auctioneer treats his objects. She either explains them entirely away, or tells one everything about them except what one wants to know" Oscar Wilde (1891) *The Picture of Dorian Gray*, reprint in Penguin Books, London, 1994, p. 14.

1 Introduction

Horror stories about public works projects frequently appear in the press. Most of the cases that catch the attention of the public eye are characterized by long delays and huge cost overruns, usually associated with changes of the initial design of the projects.[1] Accusations against the procuring agencies are focused on the issue of poor initial design. Agencies are portrayed as incompetent, or in some cases as corrupt, for not paying enough attention to the specification of projects before procuring them, thus resulting in renegotiation with the contractor over the projects.

This paper proposes a rationale behind this observed pattern. We show that it is in the interest of the procurer to underinvest in design specification. The intuition behind this result is that, by reducing the design specification, the sponsor reduces the comparative advantage of the most efficient firm in the awarding process. By making firms more homogeneous the sponsor intensifies competition and this results in a lower transfer. We also show that the more competitive the market, the better specified the initial design will be. In particular, in a perfectly competitive market, in which firms earn no rents, no design misspecification takes place.

The main goal of the paper is to use the analysis of the specification design problem to study the cost overruns in public works. We find that cost overruns are decreasing in the design specification level. Then, using the relationship between competitiveness and incentives to design specification, we show that when the procurement market is more competitive cost overruns are lower. For this reason, cost overruns are argued to be a consequence of the lack of competition in the procurement market.

[1] The Boston harbor tunnel in Boston, USA, and the new subway system in Athens, Greece, are two archetypical examples of public projects plagued with such problems.

We study a simple procurement problem in which a sponsor wants to undertake a single project. There exists a fixed number of horizontally differentiated potential contractors. Prior to the awarding process, the sponsor decides how much to invest

t) and this decision becomes public information. As a result of this learning process an initial design is specified. The

ormation about the optimal design is generated, and the awarded contractor and the sponsor engage in a bilateral renegotiation to change the initial design to accommodate the new information. Cost overruns, i.e., the difference between the final price and the price announced once the project is initially awarded, are a consequence of this renegotiation. As often claimed, a low investment in the initial design specification is likely to lead to negotiating significant changes and therefore to high cost overruns.[2]

Potential contractors in the procurement market are horizontally specialized in a specific design. As a consequence of this, the higher the investment in design specification, the higher the advantage of the contractor located closest to the initial design, and the larger its rents. From a different point of view, however, the higher the investment in initial design specification, the higher the probability that the awarded contractor will be the most efficient one, in the sense that the probability that the awarded contractor will be the closest to the final project design is higher. For this reason, when the sponsor decides how much to invest in design specification, he has to trade off optimally the reduction of procurement rents with the increase of the probability of choosing the most efficient firm.

This article is related to three different branches of the literature. First, the paper relates to the literature concerning to explain the cost overruns in public works. Lewis (1986) and Arvan and Leite (1989) study a framework in which: (a) procurement occurs over an extended period, (b) the sponsor and the contractor cannot credibly commit themselves to a long-term contract, (c) the

[2] Ganuza (1997), an empirical study of cost overruns in public works in Spain, tries to identify the magnitude and causes of cost overruns in larger public works. The largest 256 public work projects undertaken by the Spanish Administration during two years led to cost overruns 77 % of the cases, average cost overruns were 22 % of budgeted costs and 62,7% of cost overruns cases were related to changes in the projects' design during construction.

contractor has better information about the cost of completing the project, and (d) most benefits accrue-to the sponsor only after the project is completed. In this framework cost overruns occur because the opportunity cost of giving up the project increases. The price of each task depends on the credible threat of stopping the project. This threat is less credible for the later tasks that for the earlier ones. Thus the price that the sponsor pays increases over time, even when the expected cost of the all stages is the same. In the present model there is only one construction stage and, hence, we do not have this dynamic effect. Gaspar and Leite (1989) present a model in which the procurement mechanism induces an ex post downward bias on project cost and consequently cost overruns. In their model, the sponsor has to choose between n potential contractors after receiving a signal about the real cost of the project for each contractor. This signal is the sum of the idiosyncratic cost of the firm and a measurement error. The firm with the lowest signal is the firm with the lowest expected cost. In addition, the expected measurement error for this firm is negative, leading to underestimation of the true cost, and cost overruns. We are not considering this sort of cost uncertainty, and, hence, do not study this effect in our model.

The present work can also be regarded as a contribution to the literature that tries to endogenize the information structure in principal-agent relationships. In particular, the paper touches upon a line of research that investigates the strategic benefits of ignorance in principal agents problems. Cremer (1995) and Dewatripont and Maskin (1995) show how it can be in the interest of the principal to remain uninformed if the initial contract can be renegotiated. Ignorance in these models serves as a commitment device, because the principal wants to avoid taking actions in the renegotiation stage that can affect the incentives of the agent in the initial stage. Our contribution to this literature is to study the effect of the strategic ignorance of the sponsor in the procurement problem and to show how this strategic ignorance can lead to stronger competition among firms.

In terms of modeling choices our paper is closely related to Lewis and Sappington (1994) who focus on information acquisition by consumers in a monopoly market. The authors examine whether the monopolist should allow the consumers to acquire information about their tastes for his product. Improved private information enables the monopolist to charge higher prices to high-value buyers, but can also provide rents to the buyers. Most of their results are extreme, in the sense that the monopolist decides to provide all the information or none. Aside from differences in the information structures analyzed, our paper differs from Lewis and Sappington in that we analyze an procurement problem in which the price is set by an auction mechanism. In the same line of research, Bergemann and Välimaki (1997) study information acquisition by consumers in a duopolistic market in which one firm introduces a new product, whose value is learned by consumers through experimentation. The authors show that in equilibrium, the sales path of the new product induces levels of experimentation that differ from the efficient ones. The intuition is that both firms want to speed up the learning process in the early stages in order to obtain rents due to product differentiation. In this paper, the sponsor induces a suboptimal learning process to reduce firms' differentiation and consequently firms' rents.

Finally, this paper can also be related to the literature that studies the hold-up problem in contract theory.[3] This literature show that under incomplete contracting, when two parties need to invest before contracting, there can be underinvestment. This is due to the fact the parties can not appropriate the full benefits of an increase in their investment. Although we study a very specific framework, our main result seems to be close to this underinvestment result. In fact, the underinvestment in specification design comes from the fact that the sponsor cannot capture the full benefit of efficient matching. As will become clear later on, our result is, however, driven by a different cause: the renegotiation of the contract, which is crucial in the literature mentioned above is not relevant in our setting since the incumbent rents are discounted by potential contractors in the auction. In our case, the underinvestment result is due to the following effect: the more the sponsor invests in design specification, the more efficient is the matching (the larger is the total surplus), but the larger are the rents captured by the firms at the auction stage.

The remainder of the paper is organized as follows. In Section 2 the model is introduced while section 3 characterizes the efficient solution. Section 4 solves the model and presents the main

[3]See for example, Klein, Crawford and Alchian (1978) or Hart and Moore (1994).

results of the paper. In Section 5 we briefly consider the case in which the firms cannot observe the design specification level. Section 6 discusses the scope and implications of the model and presents conclusions. All proofs are all relegated to a technical appendix.

2 The model

Consider a sponsor that plans to undertake a project. The payoff to the sponsor depends on the project's design $d \in D$, where the design space D is a circle of perimeter one. Let $d^* \in D$ denote the optimal design for the sponsor and assume that the payoff to the sponsor from a project $d \in D$ is $V(d) = V - (d - d^*)^2$, where V is a given real number, so that the payoff is decreasing in the distance between d and d^*. The sponsor is initially uncertain about the exact location of the optimal design so that ex ante, d^* is distributed according to the uniform distribution on the design space.

There are N risk-neutral potential contractors $i = \{1, ..., N\}$. The location of each potential contractor d_i is uniformly distributed on the circle D. Each potential contractor specializes in one design, its location $d_i \in D$, and its cost of completing an arbitrary design d is $C_i(d) = C + \beta(d - d_i)^2$, where β is meant to capture the specialization level in the contractors' market.

We assume that the sponsor has to take two decisions related to the project design. In a specification stage, before contracting, the sponsor conducts research on the location of d^*, and specifies an initial design, denoted by $\widehat{d}$ by choosing a specification investment $\delta \in [0, \infty)$; the way in which the stochastic relationship between $\widehat{d}$ and d^* depends on δ is detailed below. Given $\widehat{d}$, the sponsor awards the project competitively to a potential contractor. During the realization of the project, new information about the optimal design arises and the sponsor may renegotiate the initial contract $\widehat{d}$ with the awarded contractor.

The initial design is partially correlated with the optimal design, in particular we assume it is a noisy signal of the optimal design, $\widehat{d} = d^* + \varepsilon$, where the noise ε is distributed over $\left[-\frac{1}{2}, \frac{1}{2}\right]$ according with the distribution function $G(\varepsilon|\delta)$. We make the following assumptions about this distribution:

Assumption 1 The density function associated to $G(\varepsilon|\delta)$ is symmetric and centered at 0.

Assumption 2 When $\delta = 0$, $G(\varepsilon|\delta)$ is equal to the uniform distribution on $[-\frac{1}{2}, \frac{1}{2}]$. When $\delta \to \infty$, $G(\varepsilon|\delta)$ converges to the Dirac delta function on 0 :

$$G(\varepsilon|\infty) = \begin{cases} 1 & \text{if } e \geq 0 \\ 0 & \text{otherwise} \end{cases}$$

Assumption 3 $G(\varepsilon|\delta)$ is differentiable and decreasing in δ for all ε lower than 0, $\frac{\partial G(\varepsilon|\delta)}{\partial \delta} < 0$ for all $\varepsilon \in (-\frac{1}{2}, 0)$, and $G(\varepsilon|\delta)$ is differentiable and increasing in δ for all ε greater than 0, $\frac{\partial G(\varepsilon|\delta)}{\partial \delta} > 0$ for all $\varepsilon \in (0, \frac{1}{2})$.[4]

[Figure 1 around here]

Given these assumptions $\widehat{d}$ is also distributed uniformly around the circle, and by assumption 1 it is an unbiased estimator of the optimal design. Assumption 2 implies that when $\delta = 0$ the initial design is not correlated with the optimal design, whereas when $\delta = \infty$ the initial design coincides with the optimal design. Assumption 3 implies that the variance of the noise decreases with δ.[5] Therefore, the greater the specification investment (the larger δ), the closer is in expected terms the initial design of the optimal one.

After the initial design has been specified and the specification level has become public information, the awarding process takes place. Notice that once the bidders observe $\widehat{d}$, the distribution

[4] The truncated normal distribution defined on the interval $[-\frac{1}{2}, \frac{1}{2}]$, when the underliying normal distribution has mean $\mu = 0$ and variance $\sigma = \frac{1}{\delta}$, is an example of distribution that is consistent with these three assumptions.

$$G(\varepsilon|\delta) = \frac{\int_{-\frac{1}{2}}^{\varepsilon} \exp\{-s^2\delta\}ds}{\int_{-\frac{1}{2}}^{\frac{1}{2}} \exp\{-s^2\delta\}ds}.$$

[5] An alternative assumption to Assumption 3 might be:
Assumption 3′ If $\delta > \delta'$, we can order the distribution functions $G(\varepsilon|\delta)$ and $G(\varepsilon|\delta')$ in the sense of first order stochastic dominance: $G(\varepsilon|\delta) \Box G(\varepsilon|\delta')$ $\forall \varepsilon \in [-\frac{1}{2}, 0]$, $G(\varepsilon|\delta) \geq G(\varepsilon|\delta')$ $\forall \varepsilon \in [0, \frac{1}{2}]$.

An example of a distribution that is consistent with this new assumption is the uniform distribution on an interval decreasing in δ, $[-\frac{1}{2(1+\delta)}, \frac{1}{2(1+\delta)}]$:

$$G(\varepsilon|\delta) = \begin{cases} 0 & \text{if} \quad \varepsilon < -\frac{1}{2(1+\delta)} \\ (1+\delta)\varepsilon + \frac{1}{2} & \text{if} \quad \varepsilon \in [-\frac{1}{2(1+\delta)}, \frac{1}{2(1+\delta)}] \\ 1 & \text{if} \quad \varepsilon > \frac{1}{2(1+\delta)} \end{cases}$$

Under this alternative assumption, using the techniques of Milgrom and Shanon (1994), we would obtain the same monotone comparative results. However, Assumption 3 allows us to obtain strictly monotonic results.

of d^* is no longer uniform. d^* is then distributed on the circle according to a posterior distribution $F(d|\delta)$ depending on the initial $\widehat{d}$ and the specification level δ.[6]Firms using $F(d|\delta)$ update their believes over the optimal design and submit their offers to the sponsor. All firms know the locations of their competitors and this information is verifiable by the sponsor.[7] The sponsor awards the public work to the most convenient firm (taking into account its bid and its location technology). The winning firm signs a contract to undertake the initial design. [8] During the construction of the project, the sponsor and the firm learn the optimal design, and change the initial contract using bilateral renegotiation that is represented by a Nash Bargaining procedure.

The sponsor's preferences over final outcomes are represented by the following utility function $U_S = V(d) - p - \delta$, where $V(d)$ is valuation of the project and p is the project's price. We want to characterize the sponsor's optimal investment in design specification, taking into account how this investment is going to affect the result of the auction process (the winning firm and the procurement price) as well as the contract's renegotiation. Summarizing, the time sequence of the model is as follows:

1. The sponsor, knowing the number of firms in the market, N, decides his expenditures on research, δ, and specifies an initial design $\widehat{d}$ for the project. The specification level δ becomes

[6]For notational convenience, we take the location of the public signal as the origin of the circle, and we define $F(d|\delta)$ on the interval $[\,\widehat{d} - \frac{1}{2}, \widehat{d} + \frac{1}{2}]$. Given the above assumptions over the noise distribution, $F(d|\delta)$ presents the following characteristics: (i) The density function associated to $F(d|\delta)$ is symmetric and centered at $\widehat{d}$. (ii) When $\delta = 0$, $F(d|\delta)$ is equal to the uniform distribution on $[\,\widehat{d} - \frac{1}{2}, \widehat{d} + \frac{1}{2}]$. When $\delta \to \infty$, $F(d|\delta)$ converges to the Dirac delta function on $\widehat{d}$ (iii) $F(d|\delta)$ is decreasing in δ for all d lower than $\widehat{d}$ and increasing in δ for all d greater than $\widehat{d}$.

[7]Therefore, firms compete in the procurement process like in standard Bertrand competition among heterogenous firms. The purpose of looking at such simplified setting is to avoid unnecessary complications in the presentation. We can show that introducing the assumption of asymmetric information over the firm's location does not change the results of the model as long as we do not consider contracts over realizations of d^*. If d^* is contractible we can commit to inefficient ex-post renegotiations of the optimal design in order to reduce the informational rents (See for example Che (1993)). We are assuming that d^* is not contractible and therefore we are not exploring this problem. However, our conjecture, is that the main results of the paper would still remain when d^* is contractible. Commiting to inefficient renegotiation of the contract and misspecifying the initial design are two ways to reduce firm rents, and we expect the sponsor would use both of them, if he could.

[8]Notice that procuring $\widehat{d}$ is a optimal strategy for the sponsor. He can not increase his profits by procuring another design since he does not know ex-ante the location of the firms and the firms are located according to a uniform distribution. In a related paper Ganuza and Pechivanos (1999) study a model in which the location of the firms and the optimal design are public knowledge (and there is no design renegotiation). In this model the optimal strategy for the sponsor is to procure a design different to the optimal one (between the optimal design and the location of the most disadvantaged firm), since by doing that he increases firm competition in the procurement process.

public information.[9]

2. The sponsor announces the initial design. Firms learn their location (with respect to $\widehat{d}$) and present their bids to the sponsor. The sponsor awards the public project to the firm that maximizes his expected utility considering its bids and its location technology.

3. The winning firm and the sponsor learn the optimal design d^* and, through a Nash bargaining procedure, decide the final design and the final price to be paid for the project.[10]

In the next section we study the benchmark case by characterizing the efficient solution. Section 4 provides the solution of the model.

3 Efficient solution

In this section, we consider the problem of a social planner, who chooses the design specification level δ^E, the winning firm d_w, and the final design d^E that maximize total surplus (the sum of sponsor's utility and the profits of the winning firm), $W = E\{U_S + \pi_w\} = E\{V(d) - C_w(d) - \delta\}$. In maximizing total surplus the planner faces the same informational constraints as the sponsor so that the timing of the efficient procurement process can be described as follows:

1. Given the number of firms in the market, N, the social planner decides research expenditure δ and specifies an initial design $\widehat{d}$ for the project.

2. Given $\widehat{d}$, the social planner learns the location of the firms and chooses the winning firm.

3. In the course of the construction of the project, the social planner learns the optimal design. Given the location of the winning firm and the optimal design, the social planner chooses a final design for the project.

[9]In Section 5, we relax the assumption of perfect information and we consider the case in which firms cannot observe the level of design specification.

[10]This model tries to capture the institutional framework which is used by public administrations to procure large public works. See Jofre-Bonet and Pesendorfer (2000) and Ganuza (1997) for description of the American and Spanish case, respectively.

We solve the model using backwards induction. The next subsection characterizes the final design given the winning firm and the optimal design. Subsection 3.2 will then select the optimal firm to undertake the project given the initial design, the locations of the firms and the design specification level. Lastly, subsection 3.3 studies the sponsor problem and provides the efficient design specification level.

3.1 Final design

In the construction stage, when the social planner learns the optimal design d^*, he chooses the final design of the project given this optimal design and the location of the winning firm d_w. Let d^E be the optimal final design which maximizes the total surplus of the project.

$$d^E \in \underset{d}{\operatorname{argmax}}\, V(d) - C_w(d)$$

Thus the optimal final design is

$$d^E = \frac{\beta d_w + d^*}{1+\beta}.$$

The optimal final design turns out to be an average between the location of the awarded firm and the optimal project design. The weight of the firm's location in the average depends on the technological parameter β. In particular, the larger the specialization of the market (the larger β) the closer is the final design to the location of the awarded firm. Notice that when $\beta = 0$, the case of homogenous firms, the cost does not depend on the design and the final design is the optimal one. On the contrary, when $\beta = \infty$, firms can only produce one design, and the final design is trivially the location of the winning firm.

3.2 The most efficient firm

In the awarding process the social planner has to choose a firm after learning all firms' locations, d_w, $i \in \{1, \ldots, N\}$. Given d^E, the expected surplus of the project depends on the location of the winning firm and on the specification level of the initial design. Let $S(d_i, \delta)$ be the expected surplus of the project if it assigned to a firm with location d_i when the design specification level is δ

$$S(d_i, \delta) = E_{d^*}\{V(d^E) - C_i(d^E)|\delta\}.$$

The following lemma shows how the expected surplus of the project depends on the firm's location.

Lemma 1 *If $\delta > 0$, then the expected surplus is decreasing in the distance between the initial design and the location of the firm. If $\delta = 0$, then the expected surplus does not depend on the distance between the initial design and the location of the firms.*

Let d_1 be the closest location to the initial design $\widehat{d}$. Then an immediate corollary of the previous Lemma characterizes the firm that maximizes the expected surplus.

Corollary 1 *The efficient winning firm is the closest firm to the initial design $d_w = d_1$.*

The intuition behind this result is the following. The expected surplus of the project will depend on the distance between the winning firm and the optimal design. Since the initial design is an unbiased estimator of the optimal design, the closest firm to the initial design is (in expected terms) the closest firm to the optimal one. Hence, the closest firm is the most efficient firm ex-ante. On the other hand, if the social planner does not invest in design specification, the optimal design can be with the same probability on any arbitrary place in the circle, implying that the expected surplus of any firm is the same. Notice, that the firm with location d_1 may turn out to be not the most efficient firm ex-post and that the probability of this event is decreasing in the design specification.[11]

3.3 Optimal design specification

In the specification stage, the social planner has to choose the investment in design specification knowing the number of firms. The expected surplus of the project is now only a function of the

[11]We do not consider the possibility of replacing the incumbent firm. As a matter of fact, the main results do not change when we introduce this possibility in the model, as long as the sponsor incurs in a positive cost to replace the incumbent firm.

design specification level.

$$S(\delta) = E_{d_1}\{S(d_1, \delta)\}.$$

The next result characterizes the relationship between the expected surplus of the project and the specification level of the design.

Lemma 2 *The expected surplus of the project is increasing in the specification level of design, δ.*

Lemma 2 rests on the fact that the larger is the investment in the project design specification, the better is the matching between the technology of the winning firm and the sponsor's preferences.

Given the above, the social planner has to choose the investment in design specification trading off increases in the expected surplus of the project against the cost of specifying the initial project. The optimal specification design level is the solution to this problem

$$\delta^E \in \underset{\delta}{\operatorname{argmax}}\, E_{d_1}\{S(d_1, \delta) - \delta\}. \tag{1}$$

First observe that given that $S(d_1, \delta)$ is bounded above, δ^E has to be finite. In the following we will assume that $\delta^E > 0$, an assumption which is justified if the cost of providing very basic information about the optimal design is sufficiently small. Then, we have:

Proposition 1 *The optimal design specification level δ^E is increasing in the number of firms N and the technological parameter β.*

The total procurement surplus depends on the distance between the location of the awarded firm and the optimal design. When the number of firms increases, the expected distance between the initial design and the awarded firm decreases, with the implication that the incentives to make this initial design closer to the optimal one also increase. Following a similar argument, if the technological parameter β increases, the incentives to reduce the distance between the awarded firm and the optimal design also increases (the match between the sponsor's preferences and the contractor's technology becomes most important). The only way for the sponsor to ensure an appropriate match is to reduce the distance between the optimal design and the initial one and this in turn can only be accomplished by increasing the investment in design specification.[12]

4 Competitive Solution

We solve the model using backwards induction. The next subsection characterizes the solution of the design's renegotiation. Subsection 4.2 provides the result of the competitive mechanism. Subsection 4.3 concludes the analysis of the model by studying what is the optimal design specification level.

4.1 Renegotiation of the initial design

When the awarded contractor and the sponsor learn the optimal design, they bargain over the final design d^C and the final price of the project p_F. At this renegotiation stage they know the initial design $\widehat{d}$, the procurement price p_p, and the location of the winning firm d_w . We assume that the outcome of the bargaining process is the solution of a generalized Nash bargaining problem.[13]

Let $\pi_S(d^C, p_F)$ denote the agreement payoff to the sponsor when the final design is d^C and the final price p_F and $\rho_S(\widehat{d}, p_p)$ his disagreement point. Let $\pi_F(d^C, p_F)$ denote the agreement payoff to the winning firm and $\rho_F(\widehat{d}, p_p)$ its disagreement point. The final design d^C and final price p_F will then be given by the solution to the following problem:

$$\max_{d^C,\, p_F} (\pi_S - \rho_S)^{1-\alpha} (\pi_F - \rho_F)^{\alpha}.$$

Where α is the firm's bargaining power. Payoff functions are defined as follows. The sponsor's final surplus is the utility of the final design minus the new price and the investment in design specification, $\pi_S(d^C, p_F) = V - (d^C - d^*)^2 - p_F - \delta$ and his disagreement point is given by the

[12]Notice that we did not impose assumptions on the convexity of the problem and therefore we cannot guarantee that the sponsor's problem is concave. We use the techniques of Edlin and Shannon (1998), that allow us to get comparative static results in non convex problems, as long as the cross derivatives' conditions are globally satisfied by the problem, a condition that is satisfied in our case.

[13]Notice that in contrast with other models, the assumption of Nash bargaining is not important in our model, since the negotiation rents of the awarded contractor are discounted in the auction. Different bargaining procedures can be shown to lead to the same results.

utility of the initial design minus the procurement price and the investment in design specification, $\rho_S(\widehat{d}, p_p) = V - (\widehat{d} - d^*)^2 - p_p - \delta$. The awarded firm's final profit is the new price minus the cost of the new design, $\pi_F(d^C, p_F) = p_F - C - \beta(d^C - d_w)^2$. Its disagreement point is the procurement price minus the cost of the initial design, $\rho_F(\widehat{d}, p_p) = p_p - C - \beta(\widehat{d} - d_w)^2$. Given these payoff functions, the Nash bargaining problem can be rewritten as follows

$$\max_{d^C, p_F} \left(-(d^C - d^*)^2 - p_F + (\widehat{d} - d^*)^2 + p_p\right)^{\alpha} \left(p_F - \beta(d^C - d_w)^2 - p_p + \beta(\widehat{d} - d_w)^2\right)^{1-\alpha}$$

and its solution is characterized in the next lemma.

Lemma 3 *The bargaining solution for the final design and the final price is given by:*

$$\begin{aligned} d^C &= \frac{\beta d_w + d^*}{1+\beta} \\ p_F &= p_p + \beta(d^C - d_w)^2 - \beta(\widehat{d} - d_w)^2 \\ &\quad + \alpha \left(-(d^C - d^*)^2 + (\widehat{d} - d^*)^2 - \beta(d^C - d_w)^2 + \beta(\widehat{d} - d_w)^2\right). \end{aligned}$$

We are assuming that in this stage the sponsor and the firm both learn the optimal design. It is easy to check that as long as the sponsor knows the location of the awarded firm, this assumption is not necessary. Suppose that only the awarded firm learns the optimal design and it has to report it to the sponsor. The firm will report the design that maximizes its expected rents, but given the result of the renegotiation, the expected rents are $\alpha(\pi_S + \pi_F - \rho_S - \rho_F)$, and the design that maximizes these rents is the optimal design.

Since the bargaining procedure is efficient, we obtain the same final design as in the efficient solution $d^C = d^E$. The final price can be seen to be equal to the procurement price, plus the cost to change from the initial design to the final one, plus a proportion α (bargaining power) of the surplus generated by the bargaining process: $p_F = p_p + C_w(d^C) - C_w(\widehat{d}) + \alpha(\pi_S + \pi_F - \rho_S - \rho_F)$.

4.2 Price Competition

Procurement proceeds in three steps. First, firms observe δ and $\widehat{d}$ and learn their location with respect to $\widehat{d}$. Second, each firm submits a bid, a location-price pair. Third, the sponsor, taking into account the location of the firms and the price, awards the project to the firm that submitted the bid that maximizes its expected utility U_S. The next proposition characterizes the solution at the procurement stage.

Lemma 4 *The closest firm wins the auction $d_w = d_1$, and the procurement price is*

$$p_p = C_1(\widehat{d}) - E_{d^*}\{\alpha\,(\pi_S + \pi_F - \rho_S - \rho_F)\,|\delta\} + S(d_1, \delta) - S(d_2, \delta),$$

where d_1 is the closest firm to the initial design and d_2 is the second closest firm.

The procurement price has three components: the cost of the initial project, the expected rents from future renegotiation (which are discounted), and the winning firm's expected profit $S(d_1, \delta) - S(d_2, \delta)$.

Proposition 2 *The expected profit of the winning firm is increasing in the specification level of the design δ.*

This is an important result for the paper: The higher is the specification level of the design, the higher is the market power of the winning firm, because the firm's location becomes more important. The implication of this result is that the sponsor can use the specification level of the design to control firms' rents.

4.3 Initial design optimal specification

The sponsor has to find the specification of initial design that maximizes its expected surplus δ^C, given the expectations on the procurement and renegotiation stages

$$\delta^C \in \underset{\delta}{\operatorname{argmax}}\, E_{d_1,d_2,d^*} U_S = \underset{\delta}{\operatorname{argmax}}\, E_{d_1,d_2,d^*}\{V(d^C) - p_F - \delta\}$$

Substituting the expression of the final price into the expected surplus we obtain

$$U_S = E_{d_1,d_2,d^*}\{V(d^C) - p_p + C_w(d^C) - C_w(\widehat{d}) + \alpha\,(\pi_S + \pi_F - \rho_S - \rho_F)\} - \delta.$$

and substituting the expected procurement price into this expression and simplifying we obtain

$$U_S = E_{d_1,d^*}\{V(d^C) - C_1(d^C)\} + E_{d_1,d_2}\{-S(d_1,\delta) + S(d_2,\delta)\} - \delta.$$

Since $E_{d_1,d^*}\{V(d^C) - C_1(d^C)\} = E_{d_1}\{S(d_1,\delta)\}$, we finally obtain that

$$U_S = E_{d_2}\left\{S(d_2,\delta) - \delta\right\}$$

and the initial design optimal specification is the solution to

$$\delta^C \in \operatorname*{argmax}_{\delta} E_{d_2}\{S(d_2,\delta) - \delta\}$$

Comparing this expression to 1 it is easy to see that the expected surplus of the sponsor does not depend on the location of the firm closest to the initial design, i.e., the winning firm (as is the case in the efficient solution) but depends on the location of the firm which is the second closest to the initial design. Apart from this fact, the problem is identical to the efficient one in 1 and the intuition of the results presented in the following Proposition is the same as in Proposition 1.

Proposition 3 *The optimal design specification level δ^C in the competitive case is increasing in the number of the firms N and the technological parameter β.*

The following proposition presents the main result of the paper.

Proposition 4 *The competitive specification level is less than the efficient design specification level, $\delta^C < \delta^E$. The difference between the efficient solution and the competitive solution converges to* 0 *as the number of firms goes to infinity*

As was remarked above, the sponsor's problem would be equivalent to the social planner's problem if in the latter we considered the second closest firm instead of the closest firm. Using this fact, it is easy to see the intuition of the proposition. From Proposition 1 we know that the larger the number of firms, the closer the winning firm to the initial design, and the larger the incentives to specify the initial design. Using the same argument, if we take the second closest firm instead of the closest firm, there should be less incentives to specify the initial design.

This proposition shows an important trade-off in design specification. Assume that the starting point is the competitive solution. If the sponsor increases the level of specification the total surplus of the procurement process goes up. This is due to the fact that the final design is closer in expected terms to the optimal one and the winning firm is the most likely to be the most efficient firm to undertake the final design, ex-post. On the other hand, the increase in design specification also increases the rents of the winning firm, and this effect turns out to compensate the first one.[14] Another way to see the intuition behind the result is that by reducing design specification, the comparative advantage of the closest firm in the awarding process decreases. In other words, the sponsor underinvests in the initial specification of the project to make potential contractors more homogeneous, with the underlying goal to intensify competition and reduce its expected transfer.[15]

Finally, when the number of firms goes to infinity, the rent of the closest firm converges to 0 because the expected distance with the second closest firm also converges to 0. In such case, the sponsor's trade off between reducing the firm rents and increasing the procurement surplus is eliminated as can be seen from the fact that $E_{d_1}\{S(d_1,\delta)\} - E_{d_2}\{S(d_2,\delta)\}$ goes to 0.

[14] Observe that in the realistic case in which a procurement agent manages the procurement process on behalf of a procurement principal, the renegotiation of the initial design can create room for collusion between the procurement agent and the awarded contractor. While we leave this case for future research, we conjecture that collusion increases the principal's incentives to specify the initial design and design misspecification would turn out to be lower than in the case we discuss in this paper.

[15] We start the paper with a quote from Oscar Wilde, in which he points out that the auctioneers are reluctant to provide good information about the goods they are selling. This observation can be explained using a similar argument to ours. Assume that an auctioneer wants to sell a good using a second price auction. There are two risk neutral bidders. Each bidder likes the good with probability $\frac{1}{2}$ (his valuation is high V_H) and with probability $\frac{1}{2}$ he does not like the good (his valuation is low V_L). Given the public information, they have a common expected valuation $\frac{1}{2}V_H + \frac{1}{2}V_L$. If the auctioneer discloses new information about the good, they learn their exact valuation, so they could have different valuations V_H or V_L. If the auctioneer discloses additional information about the good, he gets a low expected price $P_D = \frac{1}{4}V_H + \frac{3}{4}V_L$, the allocation of the good is efficient (the bidder with the highest valuation gets the good), and there are bidders' rents. If the auctioneer does not disclose any information about the good then: the expected price is higher $P_{ND} = \frac{1}{2}V_H + \frac{1}{2}V_L$, the bidder with the lowest valuation can get the good and there are no bidders' rents. As in our model, the lack of information about the good leads to fiercer competition between bidders although can produce inefficient allocations.

4.4 Cost overruns

In the introduction we mentioned the relationship existing between design misspecification and cost overruns. This subsection is devoted to formalize this relationship. Usually cost overruns are defined as the difference between the procurement price and the final price:

$$C_{CO} = p_F - p_p = C_1(d^C) - C_1(\widehat{d}) + \alpha\left(\pi_S + \pi_F - \rho_S - \rho_F\right).$$

The next result derives the relationship between expected cost overruns and the initial design specification.

Proposition 5 *Expected cost overruns of the project are decreasing in the design specification level,* δ

In other words, since cost overruns are due to reforms of the initial design, the better the initial design, the fewer reforms of the design will be needed and this implies lower expected cost overruns. An immediate Corollary characterizes the important relationship between competition and cost overruns.

Corollary 2 *Expected cost overruns of the project are decreasing in the number of the firms* N*.*

In other words, the more competitive the procurement market, the lower expected cost overruns will be. This might be an important result since it shows that any policy devoted to promote competition in the procurement market, may have the positive effect of reducing cost overruns.

4.5 Endogenous market supply

In this section we report the consequences of introducing an endogenous market supply in the model. That is, instead of assuming a fixed number of firms, we introduce a new stage in the game in which firms decide whether to enter into the market (paying a fixed cost) or not.

The result of this extension is quite surprising, as endogenizing the number of firms in the market might lead to multiplicity of equilibria with the following intuition. Firms decide to enter into the market when their expected profits at least compensate the entry cost. On the other hand, expected profits of any one firm depend positively on the specification level of the design. Yet we know that the specification level of the design depends positively on the number of firms. Therefore, there may exist equilibria, with few firms, low expected profits, and a low specification level and equilibria with many firms, high expected profit and a high level of design specification.

This multiplicity of equilibria may be a source of inefficiency since, from the point of view of the sponsor, it is always better to have many firms. Yet, due to a coordination failure, he may be stuck with a narrow market and a high level of cost overruns.

5 Imperfect Information

In this section we briefly consider the case in which firms cannot observe the level of design specification. The timing and structure of the game are the same as in the previous section.

1. The sponsor, knowing the number of firms in the market, N, decides his expenditures on research, δ, and specifies an initial design $\widehat{d}$ for the project. The firms can not observe δ but they have a common expectation δ' over it.

2. The sponsor announces the initial design. Firms learn their location (with respect to $\widehat{d}$) and given their expectations, present their bids to the sponsor. The sponsor awards the public project to the firm that maximizes his expected utility considering the firm's bid and its location technology.

3. The winning firm and the sponsor learn the optimal design d^* and, through a Nash bargaining procedure, decide the final design and the final price to be paid for the project.

We solve the model using backwards induction.

5.1 *Renegotiation of the initial design*

The renegotiation process between the sponsor and the winning firm has the same solution that in the previous game (when the awarded contractor learns d^* the specification level does not play any role). Therefore, given the optimal design d^* and the winning firm d_w, the final design and the final price are the same than in the previous section

$$\begin{aligned} d^{II} &= \frac{\beta d_w + d^*}{1+\beta} \\ p_{_F}^{II} &= p_{_p}^{II} + \beta(d^{II} - d_w)^2 - \beta(\widehat{d} - d_w)^2 \\ &\quad + \alpha\left(-(d^{II} - d^*)^2 + (\widehat{d} - d^*)^2 - \beta(d^{II} - d_w)^2 + \beta(\widehat{d} - d_w)^2\right). \end{aligned}$$

As a consequence, the focus is on the procurement stage and the design specification problem.

5.2 *Price competition*

The procurement proceeds as in the previous section. In order to solve the problem we have assumed that the firms have common expectation regarding the project's specification level δ'. Given this expectation, we obtain similar results to those in the previous section: the closest firm to the initial design wins the auction $d_w = d_1$, the procurement price will be

$$p_{_p}^{II} = C_1(\widehat{d}) - E_{d^*}\{\alpha\left(\pi_S + \pi_F - \rho_S - \rho_F\right)|\delta'\} + S(d_1, \delta') - S(d_2, \delta').$$

5.3 *Initial design optimal specification*

Given the above, the sponsor's ex ante payoff is

$$E_{d_1,d_2,d^*}\{U_S\} = E_{d_1,d_2,d^*}\{V(d^{II}) - p_{_F}^{II} - \delta\}.$$

and substituting the final price we get

$$\begin{aligned} E_{d_1,d_2,d^*}\{U_S\} &= E_{d_1,d_2,d^*}\{V(d^{II}) - C_1(d^{II}) - \alpha\left(\pi_S + \pi_F - \rho_S - \rho_F\right)\} \\ &\quad + E_{d_1,d^*}\{\alpha\left(\pi_S + \pi_F - \rho_S - \rho_F\right)|\delta'\} + E_{d_1,d_2}\{-S(d_1, \delta') + S(d_2, \delta')\} - \delta. \end{aligned}$$

Notice that, when unobserved, the specification level chosen by the sponsor cannot affect firms' expectation δ' so that the term

$$E_{d_1,d^*}\{\alpha\,(\pi_S+\pi_F-\rho_S-\rho_F)\,|\delta'\}+E_{d_1,d_2}\{-S(d_1,\delta')+S(d_2,\delta')\}$$

does not depend on δ. Given this the sponsor's problem is equivalent to the following problem

$$\delta^{II}\in\underset{\delta}{\operatorname{argmax}}\,E_{d_1}\{S(d_1,\delta)\}-E_{d_1,d^*}\{\alpha\,(\pi_S+\pi_F-\rho_S-\rho_F)\}-\delta$$

and we have the following result.

Proposition 6 *If the winning firm has some bargaining power $\alpha>0$, the competitive specification level with imperfect information is higher than the efficient design specification level $\delta^{II}>\delta^E$. If the sponsor has all the bargaining power $\alpha=0$, in the ex post renegotiation of the contract, then the solution is the efficient solution.*

Observe that the sponsor knows that firms discounts design renegotiation rents in their bids but is unable to affect these discounts. For this reason, he tries to reduce firms' ex post rents by overinvesting in design specification. The higher the investment in design's specification, the lower the rents of the winning firm during the renegotiation process.

In order to calculate the sponsor's total surplus note that the sponsor has a dominant strategy δ^{II} given that he can not affect firms' expectations. Although this is not important to derive the equilibrium design specification level (as δ^{II} turns out to be a dominant strategy, given the continuation game) in a Nash equilibrium firms correctly forecast the sponsor's strategy, so that $\delta'=\delta^{II}$. Using this fact, the next corollary shows that the sponsor is worse off than in the case in which firms can observe the design specification level.

Corollary 3 *Under unobservability of design specification level, the Nash equilibrium payoff for the sponsor is*

$$U_S=E_{d_2}\{S(d_2,\delta^{II})-\delta^{II}\}$$

and is lower than the Nash equilibrium payoff of the case with observable design specification level

Corollary 3 provides a reasonable result. When comparing a Stackelberg game (the case in which firms can observe δ) with the case in which firms cannot observe such δ, the sponsor's profits are larger in the former case. An important implication of this corollary is that the sponsor has incentives to make the specification level observable. In the case of public works there are two ways in which the sponsor can make δ observable:

- The sponsor can commit to an observable design specification by delegating an independent firm the task of specifying the initial design.
- Given information on the value of δ can be inferred ex-post, a sponsor that cares about future payoffs may want to establish a reputation for underinvesting in the specification of the initial design to intensify competition among contractors.

6 Conclusions

Since public procurement accounts for a significant fraction of economic activity and since it is not unusual that public project end up with a final cost several times higher than the initial estimates, cost overruns are a very important issue for economists, politicians and the public.

The first goal of this paper was to provide an explanation for cost overruns in public procurement. We have developed a model in which cost overruns arise as a consequence of the renegotiation of an initial contract. Given existing uncertainty on the project's optimal design, the sponsor can devote resources to provide an initial estimate. Since this is costly, the sponsor is likely to provide a description of the project that, while an unbiased estimate of the optimal location will differ from it in all probability. Given this, as the project's optimal location is learned in the realization stage, the awarded contractor and the sponsor are likely to have strong incentives to engage in a bilateral renegotiation to modify the initial design of the project. Cost overruns arise as a consequence of this design renegotiation.

Our results show that in equilibrium the sponsor has incentives to invest less in the design's specification than would be efficient (keeping into account only the cost of the initial design specification). The intuition of the result is that by reducing design specification, the sponsor promotes fiercer competition among contractors: Lowering the initial design specification, homogenizes horizontally differentiated potential contractors and in particular decreases the comparative advantage of the most efficient firm.

This paper sheds light on one trade off in public procurement. While a more accurate specification of an initial design increases the probability to award the project to the most efficient firm, it also increases the rents of the latter. Since under perfect competition there no design misspecification takes place (as rents are eliminated) the above mentioned trade off disappears and the initial design specification is the efficient one. Given this cost overruns can be seem as a consequence of lack of competition in the procurement market and we can conclude that public policies promoting competition in procurement markets are also likely to reduce cost overruns in public works.

A Appendix

As a convention and without loss of generality we are going to consider in the appendix that $\widehat{d} = 0$ and $d_i, d_1, d_2 \in [0, \frac{1}{2}]$. We need to state some preliminary facts before we start with the proofs of the results.

Let $G_{d_1}(d, N)$ and $G_{d_i}(d, N)$ be the distributions of the expected distance between the initial design $\widehat{d}$ and the closest firm d_1 and the firm which is the firm i closest to $\widehat{d}$, respectively. These distributions do not depend on the initial design and it can be shown that $\frac{\partial G_{d_1}(d,N)}{\partial N} < 0$ $\forall d \in (0, \frac{1}{2})$. These distributions are ordered in a strict first order stochastic dominance sense, $G_{d_1}(d, N) > G_{d_i}(d, N)$, for all $d \in (0, \frac{1}{2})$.

Proof of lemma 1: The expected surplus of an arbitrary firm d_i given that the initial design is $\widehat{d} = 0$ and the specification level is δ, is

$$\begin{aligned} S(d_i, \delta) &= E_{d^*}\{V(d^E) - C_i(d^E)|\delta\} \\ &= E_{d^*}\{V - C - (d^E - d^*)^2 - \beta(d^E - d_i)^2|\delta\}. \end{aligned}$$

By plugging $d^E = \frac{\beta d_i + d^*}{1+\beta}$ into the expression and then factorizing, we get

$$S(d_i, \delta) = E_{d^*}\{V - C - \frac{\beta}{1+\beta}(d_i - d^*)^2 | \delta\}.$$

Since d^* is distributed on $[-\frac{1}{2}, \frac{1}{2}]$ according to $F(d|\delta)$, this expectation is

$$S(d_i, \delta) = V - C - \int_{-\frac{1}{2}}^{\frac{1}{2}} \frac{\beta}{1+\beta} \min\{(d_i - s)^2, (1 - |d_i - s|)^2\} f(s|\delta) ds.$$

Notice that, due to the fact that the design space is a circle, there are two distances between d_i and d^* and we have to consider only the shortest length arc.

$$\begin{aligned} S(d_i, \delta) &= V - C - \int_0^{\frac{1}{2}-d_i} \frac{\beta}{1+\beta}(d_i - s)^2 f(s|\delta) ds - \int_{\frac{1}{2}-d_i}^{\frac{1}{2}} \frac{\beta}{1+\beta}(d_i - s)^2 f(s|\delta) ds - \\ & - \int_{-\frac{1}{2}+d_i}^{0} \frac{\beta}{1+\beta}(d_i - s)^2 f(s|\delta) ds - \int_{-\frac{1}{2}}^{-\frac{1}{2}+d_i} \frac{\beta}{1+\beta}(1 - d_i + s)^2 f(s|\delta) ds. \end{aligned}$$

By using the symmetry of $F(d|\delta)$ we get

$$\begin{aligned} S(d_i, \delta) &= V - C - \int_0^{\frac{1}{2}-d_i} \frac{\beta}{1+\beta}((d_i - s)^2 + (d_i + s)^2) f(s|\delta) ds \\ & - \int_{\frac{1}{2}-d_i}^{\frac{1}{2}} \frac{\beta}{1+\beta}((d_i - s)^2 + (1 - d_i - s)^2) f(s|\delta) ds \\ S(d_i, \delta) &= V - C - \int_0^{\frac{1}{2}} \frac{2\beta}{1+\beta}({d_i}^2 + s^2) f(s|\delta) ds - \int_{\frac{1}{2}-d_i}^{\frac{1}{2}} \frac{\beta}{1+\beta}(1 - 2(d_i + s)) f(s|\delta) ds. \end{aligned}$$

Integrating by parts the second term we get

$$S(d_i, \delta) = V - C - \frac{\beta}{1+\beta}\left({d_i}^2 + \int_0^{\frac{1}{2}} 2s^2 f(s|\delta) ds - 2d_i + \int_{\frac{1}{2}-d_i}^{\frac{1}{2}} 2F(s|\delta) ds\right).$$

It is interesting to see the special cases $\delta = 0$ and $\delta = \infty$. We have that

$$S(d_i, 0) = V - C - \frac{\beta}{1+\beta}\int_0^{\frac{1}{2}} 2s^2 ds.$$

If there is no investment in design specification, the expected surplus does not depend on the location of the firm. On the other hand

$$S(d_i, \infty) = V - C - \frac{\beta}{1+\beta}{d_i}^2,$$

when the initial design is the optimal one, case $\delta = \infty$, the expected surplus only depends on the location of the firm. For interior cases, we differentiate $S(d_i, \delta)$ with respect to d_i

$$\frac{\partial S(d_i, \delta)}{\partial d_i} = -\frac{\beta}{1+\beta}\left(2d_i - 2 + 2F(\frac{1}{2} - d_i|\delta)\right).$$

By using that $F(\frac{1}{2}-d_i|\delta)$ is increasing in δ, and $\frac{\partial S(d_i,0)}{\partial d_i}=0$, we can conclude that given the firm's location d_i, this expression is negative for $\delta>0$. Then the surplus is decreasing in the distance between the initial design and the firm's location.

Proof of lemma 2: The expected procurement surplus, given that the winning firm is the closest firm to the initial design, is

$$S(\delta)=E_{d_1}\{S(d_1,\delta)\}=E_{d^*,d_1}\{V-C-\frac{\beta}{1+\beta}(d_1-d^*)^2|\delta\}$$

Therefore, to prove the lemma we have to show that $E_{d^*,d_1}\{(\ d^*-d_1)^2|\delta\}$ is decreasing on δ. First, we analyze the sum of the expected quadratic distance between the optimal design and all the firms. Let A_i be the expected quadratic distance between the optimal design and the firms which is firm i closest to the initial design.

$$\begin{aligned}\sum_{i=1}^{N}A_i &= E_{d^*,d_1}\{(d^*-d_1)^2|\delta\}\\ &\quad +E_{d^*,d_2}\{(d^*-d_2)^2|\delta\}+\cdots+E_{d^*,d_N}\{(d^*-d_N)^2|\delta\}.\end{aligned}$$

Rearranging terms we get

$$\sum_{i=1}^{N}A_i=NA_1+\sum_{i=2}^{N}A_i-A_1.$$

It is clear that this sum does not depend on δ since the relative position of the firms is not important when we are adding all the distances. Therefore, the derivative of this sum respect to δ has to be 0,

$$N\frac{\partial A_1}{\partial\delta}+\sum_{i=2}^{N}\frac{\partial(A_i-A_1)}{\partial\delta}=0.$$

The next step is to show that $\frac{\partial A_i-A_1}{\partial\delta}>0$ for every $i\neq 1$. Using similar computations to those in the proof of Lemma 1 we get[16]

$$A_i-A_1=\int_0^{\frac{1}{2}}\left(z^2-2z+\int_{\frac{1}{2}-z}^{\frac{1}{2}}2F(s|\delta)ds\right)(g_{d_i}(z,N)-g_{d_1}(z,N))dz.$$

Integrating by parts

$$\begin{aligned}A_i-A_1 &= \left[\left(z^2-2z+\int_{\frac{1}{2}-z}^{\frac{1}{2}}2F(s|\delta)ds\right)(G_{d_i}(z,N)-G_{d_1}(z,N))\right]_0^{\frac{1}{2}}+\\ &\quad -\int_0^{\frac{1}{2}}\left(2z-2+2F(\frac{1}{2}-z|\delta)\right)(G_{d_i}(z,N)-G_{d_1}(z,N))dz.\end{aligned}$$

[16]Notice, that d_X and d^o are independent variables, and we do not need to specify the joint distribution.

Finally, taking the derivatives respect to δ

$$\frac{\partial A_i - A_1}{\partial \delta} = -\int_0^{\frac{1}{2}} 2\frac{\partial F(\frac{1}{2}-z|\delta)}{\partial \delta}(G_{d_i}(z,N) - G_{d_1}(z,N))dz > 0.$$

Since $\frac{\partial F(s|\delta)}{\partial \delta} > 0$ and $G_{d_1}(z,N) > G_{d_i}(z,N)\ \forall z \in (0,\frac{1}{2})$. But given that the derivative of the sum is 0, and given that $\frac{\partial(A_i - A_1)}{\partial \delta} > 0$ for every $i \neq 1$, this implies that $\frac{\partial A_1}{\partial \delta} < 0$, which concludes the proof.

Proof of proposition 1: We are going to use a result of Edlin and Shannon (1998), that allows us to obtain strictly monotonic static comparative results without making assumptions on the concavity of the distribution functions.

Theorem 1 (Edlin and Shannon (1998)) *Let $S \subset \Re$, $f : \Re \times \Re \to \Re$, $x^* \in \operatorname{argmax}_{x \in S} f(x,t^*)$ and $x' \in \operatorname{argmax}_{x \in S} f(x,t')$. Suppose that f is C^1 and has increasing marginal returns, and that $x^* \in int\ S$. Then $x' > x^*$ if $t' > t^*$, and $x' < x^*$ if $t' < t^*$.*

We have to check that we can apply this theorem to our decision problem. Our problem is:

$$\max_{\delta} E_{d_1}\{S(d_1,\delta) - \delta\}$$
$$= \int_0^{\frac{1}{2}} \left(V - C - \frac{\beta}{1+\beta}\left(z^2 + \int_0^{\frac{1}{2}} 2s^2 f(s|\delta)ds - 2z + \int_{\frac{1}{2}-z}^{\frac{1}{2}} 2F(s|\delta)ds\right)\right) \times g_{d_1}(z,N)dz - \delta.$$

We define the objective function $f(x,t)$ as

$$f(\delta,N) = \int_0^{\frac{1}{2}} \left(V - C - \frac{\beta}{1+\beta}\left(z^2 + \int_0^{\frac{1}{2}} 2s^2 f(s|\delta)ds - 2z + \int_{\frac{1}{2}-z}^{\frac{1}{2}} 2F(s|\delta)ds\right)\right) \times g_{d_1}(z,N)dz - \delta.$$

Where, $x = \delta, t = N$,and $S = \Re^+ \cup 0$. Therefore the only condition that we have to check is that $f(x,t)$ has increasing marginal returns, so that $\frac{\partial f}{\partial t}$ is increasing in t.

To verify this condition, we compute the cross derivative $\frac{\partial^2 f}{\partial N \partial \delta}$. First, from differentiating with respect to δ, we get

$$\frac{\partial f}{\partial \delta} = -\frac{\beta}{1+\beta}\int_0^{\frac{1}{2}} \left(\int_0^{\frac{1}{2}} 2s^2 \frac{\partial f(s|\delta)}{\partial \delta} ds + \int_{\frac{1}{2}-z}^{\frac{1}{2}} 2(\frac{\partial F(s|\delta)}{\partial \delta})ds\right) g_{d_1}(z,N)dz - 1.$$

Integrating by parts $\frac{\partial f}{\partial \delta}$ and differentiating with respect to N we get

$$\frac{\partial^2 f}{\partial N \partial \delta} = \frac{\beta}{1+\beta} \int_0^{\frac{1}{2}} 2(\frac{\partial F(\frac{1}{2} - z|\delta)}{\partial \delta})(\frac{\partial G_{d_1}(z,N)}{\partial N})dz.$$

Since $\frac{\partial F(\frac{1}{2}-z|\delta)}{\partial \delta} > 0$ and $\frac{\partial G_{d_1}(z,N)}{\partial N} > 0$ we get that the whole expresion is positive, and $f(\delta, N)$ has increasing marginal returns. Therefore, applying Theorem 1, we conclude that the optimal design specification level δ^E is increasing in the number of firms N.

We use the same argument for β. Then, we compute the cross derivative,

$$\frac{\partial^2 f}{\partial \beta \partial \delta} = -\frac{1}{(1+\beta)^2} \int_0^{\frac{1}{2}} \left(\int_0^{\frac{1}{2}} 2s^2 \frac{\partial f(s|\delta)}{\partial \delta} ds + \int_{\frac{1}{2}-z}^{\frac{1}{2}} 2(\frac{\partial F(s|\delta)}{\partial \delta})ds \right) g_{d_1}(z,N)dz$$

This expresion is positive, since by lemma 2 we know that $E_{d_1}\{S(d_1, \delta)\}$ is increasing in δ, and this implies that

$$\int_0^{\frac{1}{2}} \left(\int_0^{\frac{1}{2}} 2s^2 \frac{\partial f(s|\delta)}{\partial \delta} ds + \int_{\frac{1}{2}-z}^{\frac{1}{2}} 2(\frac{\partial F(s|\delta)}{\partial \delta})ds \right) g_{d_1}(z,N)dz$$

is negative. Then, applying theorem 1, we conclude that the optimal design specification level δ^E is increasing in the technological parameter β.

Proof of lemma 3: The bargaining problem between the winning firm and the sponsor is

$$\max_{d^C, p_F} (-(d^C - d^*)^2 - p_F + (\widehat{d} - d^*)^2 + p_p)^\alpha \left(p_F - \beta(d^C - d_w)^2 - p_p + \beta(\widehat{d} - d_w)^2\right)^{1-\alpha}.$$

From totally differentiating with respect to d^C and p_F we get the two first order conditions. After simplifying we get

$$-(d^C - d^*) - \beta(d^C - d_w) = 0$$

and

$$(1-\alpha)\left(-(d^C - d^*)^2 - p_F + (\widehat{d} - d^*)^2 + p_p\right) = \alpha\left(p_F - \beta(d^C - d_w)^2 - p_p + \beta(\widehat{d} - d_w)^2\right).$$

The solution of this system is

$$\begin{aligned} d^C &= \frac{\beta d_w + d^*}{1+\beta} \\ p_F &= p_p + \beta(d^C - d_w)^2 - \beta(\widehat{d} - d_w)^2 \\ &\quad +\alpha\left(-(d^C - d^*)^2 + (\widehat{d} - d^*)^2 - \beta(d^C - d_w)^2 + \beta(\widehat{d} - d_w)^2\right). \end{aligned}$$

which concludes the proof.

Proof of lemma 4: First, we recall two previous results that we will use for the proof. By Lemma 3 we know that the negotiation is efficient and that given δ and the winning firm, the competitive mechanism produces the same surplus as in the efficient solution. By Lemma 1 we know that given $\delta > 0$ the closest firm is the firm that produces the largest expected surplus.

Second we are going to normalize the bids in the auction. Assume that the bids are

$$b_i = C_i(\widehat{d}) - E_{d^*}\{\alpha\left(\pi_S + \pi_F - \rho_S - \rho_F\right)|\delta\} + \pi_i.$$

With this normalization, we can see that π_i is the expected profit of the firm i when it presents the bid b_i. Using this normalization, when the sponsor grants the project to firm i his expected surplus is

$$U^S = S(d_i, \delta) - \pi_i - \delta.$$

Suppose that the firm $d_j \neq d_1$ is winning the project. Since, by individual rationality $\pi_j \geq 0$, the sponsor surplus must be lower than or equal to $S(d_j, \delta) - \delta$. But, in this case the closest firm d_I can offer a better bid, with a profit $\pi_1 = S(d_1, \delta) - S(d_j, \delta) - \epsilon$, with $\epsilon > 0$. The sponsor obtains a higher surplus with this offer $(S(d_j, \delta) - \delta + \epsilon)$ and the closest firm obtains positive profits. Therefore, the winning firm must be the closest firm to the initial design $d_w = d_1$.

Using the same argument, we conclude that the procurement price must be

$$b_1 = C_1(\widehat{d}) - E_{d^*}\{\alpha\left(\pi_S + \pi_F - \rho_S - \rho_F\right)|\delta\} + S(d_1, \delta) - S(d_2, \delta)$$

It is easy to check that the closest firm can not increase this offer. This is because the second closest firm could get the project with a bid equal to $b_2 = C_2(\ \widehat{d}) - E_{d^*}\{\alpha\left(\pi_S + \pi_F - \rho_S - \rho_F\right)|\delta\}$.

Proof of Proposition 2: By Lemma 3 we know the expected profit of the winning firm is the difference between the expected surplus with its location and the expected surplus with the location of the second closest firm to the initial design.

$$\begin{aligned}\Pi(\delta) &= E_{d_1}\{S(d_1, \delta)\} - E_{d_2}\{S(d_2, \delta)\} \\ &= \int_0^{\frac{1}{2}} -\frac{\beta}{1+\beta}\left(z^2 - 2z + \int_{\frac{1}{2}-z}^{\frac{1}{2}} 2F(s|\delta)ds\right)(g_{d_1}(z, N) - g_{d_2}(z, N))dz\end{aligned}$$

We integrate by parts this expression to get

$$\left[-\frac{\beta}{1+\beta}\left(z^2-2z+\int_{\frac{1}{2}-z}^{\frac{1}{2}}2F(s|\delta)ds\right)(G_{d_1}(z,N)-G_{d_2}(z,N))\right]_0^{\frac{1}{2}}$$
$$+\int_0^{\frac{1}{2}}\left(\frac{\beta}{1+\beta}(2z-2+2F(\frac{1}{2}-z|\delta)\right)(G_{d_1}(z,N)-G_{d_2}(z,N))dz$$

Differentiating with respect to δ we get

$$\frac{\partial\Pi(\delta)}{\partial\delta}=\int_0^{\frac{1}{2}}\left(\frac{2\beta}{1+\beta}\frac{\partial F(\frac{1}{2}-z|\delta)}{\partial\delta}\right)(G_{d_1}(z,N)-G_{d_2}(z,N))dz$$

This expression is positive, since by Assumption 3 $\frac{\partial F(\frac{1}{2}-z|\delta)}{\partial\delta}>0$, and $G_{d_1}(z,N)>G_{d_2}(z,N)$ for all $z\in(0,\frac{1}{2})$.

Proof of Proposition 3: We follow the same argument that we have used in the proof of Proposition 1.

Proof of Proposition 4: The competitive problem is

$$\delta^C\in\underset{\delta}{\operatorname{argmax}}\,E_{d_2}\{S(d_2,\delta)-\delta\}$$

This problem is equivalent to

$$\delta^C\in\underset{\delta}{\operatorname{argmax}}\,E_{d_1,d_2}\{S(d_1,\delta)-\Pi(\delta)-\delta\}$$

Where $\Pi(\delta)=E_{d_1}\{S(d_1,\delta)\}-E_{d_2}\{S(d_2,\delta)\}$ is the expected profit of the winning firm. By Lemma 2 we know that $\frac{\partial\Pi(\delta)}{\partial\delta}>0$. In order to show the result we will show that $\delta^C>\delta^E$ and $\delta^C=\delta^E$ are not possible.

- *Case 1*: $\delta^C>\delta^E$. This is not possible, since in this case δ^E provides more surplus to the sponsor than δ^C.

  $$E_{d_2,d_1}\{S(d_1,\delta^E)-\Pi(\delta^E)-\delta^E\}>E_{d_2,d_1}\{S(d_1,\delta^C)-\Pi(\delta^C)-\delta^C\}$$

  This inequality follows from $\delta^E\in\text{argmax}\{E_{d_1,d^*}\{S(d_1,\delta)-\delta\}\}$ and $\Pi(\ \delta^E)<\Pi(\ \delta^C)$.

- *Case 2*: $\delta^C=\delta^E$. It is not possible since $\delta^E\in\text{argmax}\{E_{d_1,d^*}\{S(d_1,\delta)-\delta\}\}$ and $\frac{\partial\Pi(\delta)}{\partial\delta}>0$ implies than $\delta^C=\delta^E$ cannot satisfies the first order condition of the problem.

Proof of proposition 5: The expected cost overruns are

$$C_{CO} = E_{d_1,d^*}\{C_1(d^C) - C_1(\widehat{d}) + \alpha\left(\pi_S + \pi_F - \rho_S - \rho_F\right)|\delta\}$$

Since $C_1(\ \widehat{d})$ does not depend on δ, in order to show that the cost overruns are decreasing in δ, we only need to show that $E_{d_1,d^*}\{C_1(d^C)|\delta\}$ and $E_{d_1,d^*}\{\alpha\left(\pi_S + \pi_F - \rho_S - \rho_F\right)|\delta\}$ are decreasing in δ.

By plugging the expression of the optimal design $d^C = \frac{\beta d_1 + d^*}{(1+\beta}$ into $E_{d_1,d^*}\{C_1(d^C)|\delta\}$, and then factorizing, we get

$$E_{d_1,d^*}\{C_1(d^C)|\delta\} = E_{d_1,d^*}\{C + \beta(d^C - d_1)^2|\delta\} = E_{d_1,d^*}\{C + \frac{\beta}{(1+\beta)^2}(d^* - d_1)^2|\delta\}.$$

Therefore we need to show that $E_{d_1,d^*}\{(\ d^* - d_1)^2|\delta\}$ is decreasing on δ. But this was proved in the proof of Lemma 2.

We denote by $R(\delta)$ the rent of the awarded firm in the renegotiation of the design.

$$\begin{aligned} R(\delta) &= E_{d_1,d^*}\{\alpha\left(\pi_S + \pi_F - \rho_S - \rho_F\right)|\delta\} \\ R(\delta) &= E_{d_1,d^*}\{\alpha\left(-(d^C - d^*)^2 + (\widehat{d} - d^*)^2 - \beta(d^C - d_1)^2 + \beta(\widehat{d} - d_1)^2\right)|\delta\} \end{aligned}$$

Rearranging terms and using straightforward calculations we get

$$R(\delta) = E_{d_1,d^*}\{\frac{-\alpha\beta}{(1+\beta)}(d^* - d_1)^2|\delta\} + E_{d_1}\{\alpha\beta(\widehat{d} - d_1)^2\} + E_{d^*}\{\alpha(\widehat{d} - d^*)^2|\delta\}$$

We can use the computation of the proof of lemma 1 to simplify again the equation as

$$\begin{aligned} R(\delta) &= E_{d_1}\{\frac{-\beta\alpha}{(1+\beta)}\left({d_1}^2 + \int_0^{\frac{1}{2}} 2s^2 f(s|\delta)ds - 2d_1 + \int_{\frac{1}{2}-d_1}^{\frac{1}{2}} 2F(s|\delta)ds\right)\} \\ &\quad + E_{d_1}\{\alpha\beta(\widehat{d} - d_1)^2\} + \alpha\int_0^{\frac{1}{2}} 2s^2 f(s|\delta)ds. \end{aligned}$$

Rearranging terms we get

$$\begin{aligned} R(\delta) &= \frac{\alpha}{1+\beta}\int_0^{\frac{1}{2}} 2s^2 f(s|\delta)ds - E_{d_1}\{\frac{\beta\alpha}{(1+\beta)}\left(\int_{\frac{1}{2}-d_1}^{\frac{1}{2}} 2F(s|\delta)ds\right)\} \\ &\quad E_{d_1}\{\alpha\beta(\widehat{d} - d_1)^2\} - E_{d_1}\{\frac{\beta\alpha}{(1+\beta)}\left(d_1^2 - 2d_1\right)\}. \end{aligned}$$

The whole expression is decreasing in δ. The first term is decreasing in δ, since $\int_0^{\frac{1}{2}} 2s^2 f(s|\delta)ds$ is the variance of d^*. The second term is decreasing in δ, since by assumption 3 $F(d|\delta)$ is increasing in δ, $\forall d \in [\ \widehat{d},\ \widehat{d}+\frac{1}{2}]$. Finally, the third and fourth terms do not depend on δ. The whole argument implies that $R(\delta)$ is decreasing on δ and this concludes the proof.

Proof of corollary 2: Immediate from propositions 3 and 5.

Proof of proposition 6: By the same argument of the proof of Proposition 1, given that $\delta^E \in \text{argmax}\{E_{d_1,d^*}\{S(d_1,\delta) - \delta\}\}$ and $\delta^{II} \in \text{argmax}\{E_{d_1,d^*}\{S(d_1,\delta) - \delta - R(\delta)\}\}$, in order to prove $\delta^E < \delta^{II}$, we only need to show that $R(\delta)$ is decreasing in δ. But this was proven in Proposition 5.

Proof of corollary 3: Notice that

$$E_{d_2,d^*}\{S(d_2,\delta^C) - \delta^C\} > E_{d_2,d^*}\{S(d_2,\delta^{II}) - \delta^{II}\}$$

is immediate because $\delta^C \in \text{argmax}\{E_{d_2,d^*}\{S(d_2,\delta) - \delta\}\}$, and $\delta^C \neq \delta^{II}$ ($\delta^E \,\square\, \delta^{II}$ and $\delta^E > \delta^C$).

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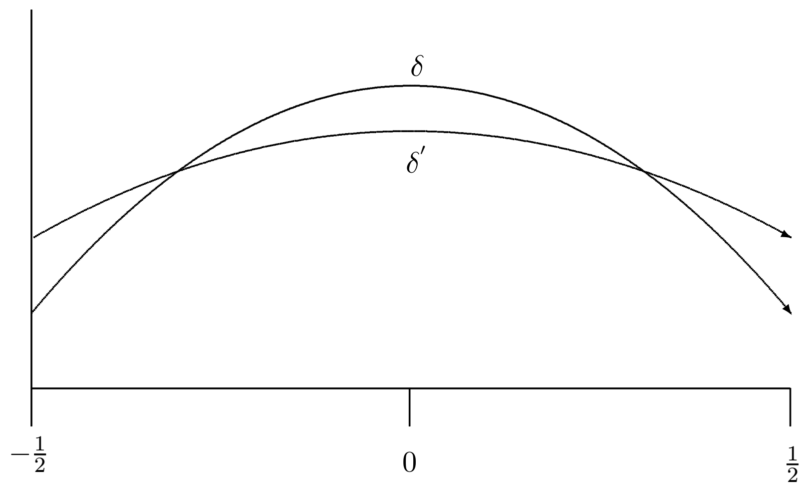

Figure 1: Two arbitrary density functions of e where $\delta > \delta'$.