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Abstract

We consider a repeated contract game between a sponsor (principal) and a contractor (agent) concerning a large scale project, where the project requires a number of tasks to be completed before the benefit from the project can be realized. There is cost uncertainty and the contractor has private, task specific information which is relevant in cost determination. Thus, the sponsor must resolve an adverse selection problem in designing the remuneration scheme offered to the contractor. We focus on the case where the sponsor cannot precommit to compensation per task and where the contractor is not bound to complete the project. We demonstrate that the contractor does not achieve cost minimization in equilibrium and that both the distribution of cost per task, given that the task is completed, and the compensation scheme rise as the project nears completion, giving the appearance of cost overruns towards the tail end of the project. We also consider the possibility of project delay as an alternative screening device.

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Cost Overruns in Long Term Projects

I. Introduction

This paper deals with the phenomenon popularly known as cost overruns, particularly in regard to large scale, government sponsored procurement. Though there has been considerable recent theoretical work on procurement, e.g., Riordan (1986) and Tirole (1986), there has been little written on the cost overruns issue per se. Yet it is this issue which seems to occupy the public's eye. Indeed, the 'horror stories' abound and frequently receive extensive media coverage.¹

Lewis (1986) is the one article we are aware of that is explicitly devoted to an analysis of cost overruns. He considers a model where the project sponsor learns about cost when the project requires completion of many tasks, tasks are performed sequentially, and there is uncertainty about the cost involved in task completion. The history of cost realizations provides information to the sponsor in estimating a parameter, known by the contractor, which governs the cost distribution. This setup is complicated by assuming that when the cost distribution is unfavorable the contractor can exert cost reducing effort, unobserved by the sponsor, to improve the cost distribution. In sequential equilibrium, the contractor with the unfavorable cost distribution initially exerts substantial effort, but reduces effort as the project nears completion. Thus, the cost distribution for a task at the end of the project dominates the cost distribution for a task at the beginning of the project, in the sense of first order stochastic dominance. This effect can be interpreted as cost overruns.

Though we find Lewis' results intriguing, we think it inappropriate to conceive of cost overruns as merely this stochastic dominance property in cost per task. In government sponsored procurement, for example, it often seems that the public is more concerned with

¹ A sampling of one month of the *Wall Street Journal* has provided two examples of such horror stories: The stealth bomber program (February 25, 1988 p.3) and the Comanche Peak nuclear power plant (February 16, 1988, p.7)

the tax burden than with the economic cost entailed in seeing a project to completion. Naturally, there is no difference between the two when the sponsor (and public) can readily observe cost, the contractor minimizes cost, and the remuneration is cost plus. But we doubt that it is valid to treat government outlays and economic costs as equivalent in procurement. In our view, cost overruns are better thought of as a combination of a stochastic dominance property in cost per task, a lack of economic cost minimization on the part of the contractor, and an excessive variability in contractor remuneration.

Lewis' model does capture all of these elements and, consequently, his results accord well with intuition. However, his model is weak in that he assumes the compensation scheme is given exogenously. One may wonder whether his results would be sustained if the compensation were determined endogenously, since in his model the incentive to exert cost reducing effort is provided by expected future rents and it is not clear from his article why these rents should be present. This question motivated our paper.

We develop a model where the sponsor sets the compensation scheme. This, coupled with the assumption that a disproportionate amount of the benefit from the project is obtained only after project completion, is sufficient to generate a stochastic dominance result. Towards the end of the project the sponsor is 'locked in,' the costs associated with contractor remuneration for already completed tasks are sunk and the sponsor will fund the project henceforth, regardless of the remaining costs. When there are many tasks remaining, the sponsor cancels the project if the current task proves to be very expensive. Thus, conditional on the sponsor allowing the project to continue, the cost distribution for a task near the end of the project dominates the cost distribution for a task at the beginning of the project. Note that all that is needed for this result is some randomness in cost per task.

Thus, a model of complete information, where the sponsor is able to directly observe cost per task, is capable of providing a stochastic dominance result. But under complete information, it is optimal for the sponsor to use cost plus pricing and for the contractor to minimize economic costs. Hence, a model of complete cost information is

insufficient to produce the other features we associated with cost overruns. Some information asymmetry is necessary to obtain these other features.

In our model the contractor is taken to be the more informed party. At the start of each task, the contractor observes some private information, relevant in determining cost. When the task is completed, the sponsor observes some, but not all, of the contractor's cost. The unobserved component of cost and, hence, the total cost are functions of the observed component and the private information. The compensation scheme is a function of the observed component. The problem which determines the optimal compensation scheme is very similar to the optimal regulation problem studied by Baron and Myerson (1982), Baron and Besanko (1984a) and (1987), Laffont and Tirole (1986), et. al. As in these other articles, the rent earned by the contractor in our model emerges as an inducement to the contractor to reveal her private information. Moreover, the optimal compensation scheme does not induce cost minimization, since a scheme that did induce cost minimization would make the sponsor pay excessive informational rents.

The above mentioned articles deal with the optimal regulation problem in a static context. We are explicitly concerned with a dynamic analysis, since we would like to understand the time pattern of costs and payments.² Recently, the optimal regulation literature has begun to consider dynamic issues. For example, Baron and Besanko (1984b) consider a two period optimal regulation problem which has elements of both adverse selection and moral hazard and, in addition, allows for serial correlation in the costs. One important result which they get is that the informational rents expected to be earned in the last period are extracted by the regulator in the previous period via a reduction in the transfer payment the regulator makes to the monopolist.

Analogous results concerning the time path of payments have been obtained in the labor contracts literature. For example, in an analysis of implicit contracts which include

² In our model, this time pattern is not driven by the sponsor learning about cost. We had to rule out learning to make our model tractable.

random reservation wages, Harris and Holmstrom (1982) and Holmstrom (1983) argue that insurance premiums are front end loaded into the implicit contract via a reduction of the first period wage. The effect is to create a 'tilting' in the employee compensation scheme, i.e., the wage-earnings profile is steeper than the reservation wage profile, whereby rent accruing to the employee is increasing in seniority. Lazear (1979) and (1981) obtains a similar result when the problem is the employee effort rather than the employee quit moral hazard.³

In these dynamic labor contract models, it is assumed that the firm can credibly commit to the entire lifetime compensation scheme of its employees. In fact most of the labor contracting literature has adopted this asymmetric approach where the firm has total precommitment power while workers have no precommitment power.⁴ Baron and Besanko (1984b) also assume perfect precommitment on the part of the regulator. Consequently, they get the result that the regulator induces the first best outcome in the last period. Though inducing the first best outcome is not optimal for the regulator in a static model, it is optimal for the regulator to induce this outcome in any but the initial period of a multiperiod model, because then the informational rents can be extracted via transfers in previous periods.

This observation applies just as well to our approach. In the equilibrium of our type of model with sponsor precommitment to the remuneration scheme, the contractor will minimize cost and, in fact, remuneration in any period will be independent of reported cost. Thus, such a model is no more capable of explaining cost overruns than is a full information model. However, in a model where neither the sponsor nor the contractor has a precommitment capability, all the features associated with cost overruns emerge. That is, time dependence in the sponsor's attitude towards project completion, private cost

³ Other authors have explained tilting in the employee compensation scheme as a consequence of the firm's desire to screen workers for specific attributes. For example see Salop and Salop (1976).

⁴ However, see Macleod and Malcomson (1989) for a noteworthy exception.

information on the part of the contractor, and a lack of commitment towards the compensation scheme per task are together sufficient to produce cost overruns.

It is not necessary to consider sponsor learning about project cost to achieve these results. Moreover, if one were to consider learning it would still be necessary to assume that the sponsor cannot precommit to the time path of the remuneration scheme, because, as Baron and Besanko show, the optimal precommitment contract entails the sponsor promising to not revise the compensation scheme on the basis of its observation of the cost history. Furthermore, the introduction of learning seriously complicates the approach, because, as is suggested by Laffont and Tirole (1987), equilibrium contracting is likely to entail substantial pooling in all but the ultimate period.

Our approach, which combines the sponsor's lack of contractual precommitment with the sponsor's need to elicit the contractor's private cost information, is also capable of explaining the possibility of project delay as an equilibrium outcome. Since one often associates delays with cost overruns, it is gratifying that our modelling approach provides a coherent way of looking at both phenomena. We provide a rationale for delay as an *involuntary* screening device, functioning in complement with the compensation scheme. We demonstrate why the sponsor prefers cancellation of the project to delay, if the sponsor can commit to cancellation. We also show the effect that delay has on the shape of the compensation scheme and consider when in the course of the project delay is likely to occur. We argue that delay is more likely to occur early in the project.

The remainder of the paper is organized as follows. In the next section we present the basic structure. Section III is devoted to an analysis of equilibrium in a simplified one period game, to highlight the informational issues. Section IV considers the full dynamic game and contrasts the solution to the case of perfect sponsor precommitment. Section V offers an extension of the one task model by allowing for discounting and delay in project completion. Finally, we provide a brief conclusion in section VI.

II. The Basic Setup

We consider the relationship between a sponsor and a contractor over the construction of a large scale project. We assume that the bulk of the benefit from undertaking the project is obtained by the sponsor when the project is completed. This assumption is made primarily to reflect indivisibilities inherent in procurement and also to account for costs of second sourcing. Let B denote the benefit accruing to the sponsor in the event the project is completed. For simplicity, it is assumed that the benefit to the sponsor is 0 in the event that the project is not completed, i.e., we assume that second sourcing is impossible. B is taken to be common knowledge.

We assume that the project requires a large number of tasks, N , for completion. Assume that the tasks must be performed in a pre-specified order and that each task requires one period. Consequently, we can refer to a particular task by the period in which it is undertaken. Assume that in each period the contractor could earn π elsewhere, if the contractor were not working on the project. For simplicity take $\pi = 0$.

Each task is characterized by an idiosyncratic cost component. The task specific component in period t , c^t , is learned fully by the contractor at the start of period t but is not observed by the sponsor. We wish to rule out time dependency in the distribution of costs as an explanation for the time path of payments and realized costs. For example, we don't allow learning by doing on the part of the contractor. This is done by assuming that for $t \neq \tau$, c^t and c^τ have the same marginal distribution.

We also wish to rule out the possibility that the sponsor uses the cost history to learn about the private cost information. Though such learning by the sponsor is probably realistic, formally including sponsor learning into our model would necessitate a revamping of our approach. Below, we consider the separating equilibrium of our contracting game by invoking revelation principle arguments that are by now standard. But, as Laffont and Tirole (1987) show, this approach is not valid under serial correlation in the cost and no precommitment by the sponsor, when the contractor can quit. Moreover, in the general

framework the optimal contract problem becomes extremely messy, when full pooling is not optimal.

For these reasons, we assume that for $t \neq \tau$, c^t and c^τ are i.i.d. random variables with distribution, F , and associated density function, f . Assume $\text{supp } F = [\underline{c}, \bar{c}]$. These assumptions imply that the sponsor and the contractor are equally uninformed about future cost realizations, though the contractor has superior information as to current cost.

For the contractor to complete task t , the contractor must send the sponsor a signal of task cost, s^t , $s^t \in \mathfrak{R}_+$. When the idiosyncratic cost component is c^t and the contractor signals s^t , the total cost incurred by the contractor in completing the task is $C(s^t, c^t)$. Observe that C itself does not have t as an argument.

We offer two distinct interpretations of this formulation. First, we allow for a standard principal-agent interpretation, where the contractor supplies a vector of inputs, e , that are unobserved by the sponsor. The sponsor only observes the cost of the other inputs used in task completion. Observed inputs and unobserved inputs are partial substitutes. Then, $s^t = s(e^t, c^t)$ and $C(s^t, c^t) = s(e^t, c^t) + e^t$. Second, we allow for the possibility that the contractor is currently engaged in projects with other procurors. There are joint costs of production and joint cost allocation is problematic. Suppose the cost allocation problem has been resolved by a prespecified accounting convention. Then, the economic cost minimizing technology, which depends on a parameter unknown to the sponsor, may allocate only a small amount of the joint cost to the project under consideration, but inferior technologies may exist which allocate a larger share of the joint cost to the project under consideration. In this second interpretation, s^t is the cost allocated to the project under consideration and $C(s^t, c^t)$ is the cost of all the projects in which the contractor is engaged.

The sponsor can only base the contractor's compensation in period t on s^t . Thus, regardless of the interpretation, the contractor has incentive to load cost into its signalled component, in order to get greater remuneration. This type of strategic behavior by the

contractor is what we were referring to in the introduction when we discussed the idea that cost overruns are, in part, lack of cost minimization .

After nature has determined c^t in period t the sponsor announces the compensation function, $P^t, P^t : \mathfrak{R}_+ \rightarrow \mathfrak{R}_+$. The contractor then chooses an indicator variable, Q^t , $Q^t \in \{0,1\}$, such that if $Q^t = 1$ the contractor has decided to complete task t while if $Q^t = 0$ the contractor has decided to quit and drop out of the project. The contractor sends the signal s^t only if $Q^t = 1$. In this case the contractor incurs the cost $C(s^t, c^t)$, the sponsor pays the contractor $P^t(s^t)$, and the game proceeds into the next period. The game ends if $Q^t = 0$. In this case task t is not performed and no additional payment is made from the sponsor to the contractor.

We assume that C is twice continuously differentiable and satisfies the following properties.

- (1) (a) $C_{11} > 0$,⁵
 (b) $C_2 > 0$ and $C_{12} < 0$, and
 (c) $c = \min_s C(s, c)$.

In (1a) we assume strict convexity of C in the signal to assure that $C(\cdot, c)$ has a unique minimizer. We restrict attention to P that are continuous and increasing. Then, (1b) is sufficient to guarantee that contractor isoprofit curves in signal-compensation space satisfy the single crossing property. (1c) is made primarily for convenience. This assumption implies that the parameter c is the true cost when the contractor has minimized cost. To make our problem economically meaningful, assume $0 < \underline{c} < \frac{B}{N}$.

We wish to analyze the sequential equilibrium of this contract game. In the next section we consider a simplified one task game which highlights the informational issues. Then in section IV we consider the full dynamic game.

⁵ Note that subscripts refer to partial derivatives.

III. Equilibrium in a One Period Model

The model presented in this section is really an optimal nonlinear price problem, where it is the buyer, rather than the seller, setting the price schedule and where signalled cost, rather than quantity, is determined in conjunction with price. We consider the extensive form game explicitly because it simplifies the presentation of the dynamic model. For notational ease, we drop the time superscript in this section.

We solve for sequential equilibrium of the model via backward induction. First, consider the choice of signal decision of the contractor given the pre-specified compensation scheme, P , and given that the contractor has chosen to complete the project. Then, the contractor with cost parameter c chooses $s(P,c)$, where

$$(2) \quad s(P,c) \in \operatorname{argmax}_s P(s) - C(s,c).^6$$

Assuming that P is differentiable and that $s(P,c) > 0$, the first order necessary condition is given by

$$(3) \quad P'(s(P,c)) = C_1(s(P,c),c).$$

Next, consider the contractor's choice to complete the project, or not, given the compensation scheme, P , and given knowledge of how the signal would be chosen if the project were completed. This decision is determined by $Q(P,c)$, where

$$(4) \quad \begin{aligned} Q(P,c) &= 0 \text{ if } P(s(P,c)) - C(s(P,c),c) < 0 \text{ and} \\ Q(P,c) &= 1 \text{ if } P(s(P,c)) - C(s(P,c),c) > 0.^7 \end{aligned}$$

Observe that the contractor only completes the project if it is individually rational to do so.

We turn to the choice of the sponsor's compensation scheme. The sponsor chooses the compensation scheme to solve

⁶ Note that existence of a solution is guaranteed by taking P to be continuous and bounded.

⁷ Since the set of contractor types which are indifferent to quitting or completing the task are of measure zero, it is irrelevant whether such types quit or stay.

$$(5) \quad \underset{P}{\text{maximize}} \int_{\underline{c}}^{\bar{c}} [B - P(s(P,c))]Q(P,c)f(c)dc \quad \text{subject to: (2) and (4).}$$

From (1b) it is evident that for any given compensation function, P , there exists $\hat{c}(P)$ such that $Q(P,c) = 1$ if $c < \hat{c}(P)$ and $Q(P,c) = 0$ if $c > \hat{c}(P)$. Hence (5) can be rewritten as

$$(5') \quad \underset{P}{\text{maximize}} \int_{\underline{c}}^{\hat{c}(P)} [B - P(s(P,c))]f(c)dc \quad \text{subject to: (2).}$$

It is convenient to transform the problem given in (5'), where the compensation is the control, to an alternate problem, where the signal sent by the contractor is the control. Then, the compensation scheme which implements this signal can be readily constructed. From the optimal incentives literature,⁸ it is well known that $s(\cdot)$ defined on $[\underline{c}, \hat{c}]$ can be implemented if and only if $s' \geq 0$, in which case the compensation function which implements $s(\cdot)$ is given by

$$(6) \quad P(s(c)) = C(s(c),c) + \int_{\underline{c}}^{\hat{c}} C_2(s(x),x)dx.$$

Note that when P satisfies (6), (3) is also satisfied. The interpretation of (6) is that a contractor with cost realization c is paid both to cover actual cost and to induce the contractor to signal $s(c)$. The second term in (6) is an informational rent which accrues to a contractor with cost realization c . Observe that this informational rent is increasing in \hat{c} , since $C_2 > 0$ by assumption. Consequently, the sponsor has some incentive to limit the set of cost realizations for which the contractor will desire to complete the project. By shrinking this set, the informational rent paid is lessened.

By substituting (6) into (5') we can rewrite the sponsor's problem as

⁸ For example, see Maskin and Riley (1984).

$$(7) \quad \underset{s(\cdot), \hat{c}}{\text{maximize}} \int_{\underline{c}}^{\hat{c}} \left[B - C(s(c), c) - \int_c^{\hat{c}} C_2(s(x), x) dx \right] f(c) dc \quad \text{subject to: } s' \geq 0.$$

Finally, by changing the order of integration in the third term, (7) can be rewritten as

$$(8) \quad \underset{s(\cdot), \hat{c}}{\text{maximize}} \int_{\underline{c}}^{\hat{c}} \left[B - C(s(c), c) - \frac{C_2(s(c), c)F(c)}{f(c)} \right] f(c) dc \quad \text{subject to: } s' \geq 0.$$

In the remainder of this section we describe some of the properties that a solution to (8) possesses. First, we consider comparative statics of this solution with respect to the sponsor's benefit from project completion, B . Intuitively, \hat{c} should be nondecreasing in B . That is, as the sponsor's gain from project completion increases, the sponsor should be willing to tolerate paying somewhat higher informational rents in order to increase the chance that the project is completed. Indeed, this intuition is correct as is shown in the following proposition. (All proofs are provided in the appendix.)

Proposition 1: Let $(s(\cdot, B), \hat{c}(B))$ denote a solution to (8) when the sponsor's benefit is B . Then $\hat{c}(B_1) \geq \hat{c}(B_2)$ if $B_1 > B_2$.

By the same sort of intuition, one might suspect that the compensation function is nondecreasing in B . Unfortunately, this may not be the case when the monotonicity constraint on $s(\cdot)$ binds in (8), in which case the solution will involve bunching, i.e., over an interval of cost realizations the contractor will choose to send the same signal.⁹ As our primary objective is to elucidate the multiperiod version of this model, we make the following additional assumptions to rule out the possibility that the monotonicity constraint binds.

⁹ Actually, the difficulty occurs only when there is bunching over an interval bounded above by $\hat{c}(B)$ and the common signal sent is decreasing in B .

$$(9) \quad C_{112}, C_{22} \geq 0.$$

$$(10) \quad \frac{F}{f} \text{ is nondecreasing in } c.^{10}$$

When (1) and (9) are satisfied, $B - C(s,c) - \frac{C_2(s,c)F(c)}{f(c)}$ is strictly concave in s for all c and, hence, has a unique maximizer which we denote by $s^*(c)$. Then (1), (9), and (10) together imply $s^* > 0$. Under these additional assumptions, the compensation scheme is monotonic in B as is shown in the next proposition.

Proposition 2: Assume (1), (9), and (10) hold. Then, the sponsor's optimal compensation scheme is $P(B,c) = C(s^*(c),c) + \int_c^{\hat{c}(B)} C_2(s^*(x),x)dx$ for $c \in [c, \hat{c}(B)]$. Moreover, (i) $P(B_1,c) \geq P(B_2,c)$ if $B_1 > B_2$. In addition, if $\hat{c}(B_1)$ or $\hat{c}(B_2) \in (c, \bar{c})$, then (ii) $\hat{c}(B_1) > \hat{c}(B_2)$ and (iii) $P(B_1,c) > P(B_2,c)$. Furthermore, (iv) $B > C(s^*(\hat{c}(B)), \hat{c}(B))$.

We close this section by comparing the solution of (8), assuming that (9) and (10) hold, to the full information optimum. The first order condition which determines $s^*(c)$ is given by

$$(11) \quad -C_1(s^*(c),c) - \frac{C_{12}(s^*(c),c)F(c)}{f(c)} = 0.$$

Let $s_*(c)$, the efficient cost signal, be implicitly defined by $C_1(s_*(c),c) = 0$. Thus, $s^*(c) = s_*(c)$ since $F(c) = 0$ and $s^*(c) > s_*(c)$ for $c > \underline{c}$, since $C_{12} < 0$. In other words, for all but the lowest cost realization, the contractor does not cost minimize. Thus, this one period model of procurement gives rise to three distinct forms of inefficiency relative to the first best, full information case. First, the cost signal is excessive relative to the cost minimizing signal. Second, the sponsor must pay an informational rent to the contractor in order to

¹⁰ (10) implies that the hazard rate, $\frac{f}{F}$, is nonincreasing. This assumption is common in the nonlinear pricing literature.

elicit the desired cost signal. Third, when $\hat{c}(B) \in (\underline{c}, \bar{c})$ the project is not undertaken sufficiently often, i.e., $\hat{c}(B) < \min(\bar{c}, B)$, so that ex post the project may be cancelled though benefits exceed cost.

IV. Multiperiod Equilibrium

We turn to the N period model. The play in each period occurs in four stages, similar to the four stages described in the one period model. We assume that both the sponsor and the contractor are risk neutral and, in this section, we also assume there is no discounting. The essential differences between this multiperiod formulation and the one period formulation is that the sponsor's benefit is only realized if and when all the tasks are completed and, in making the third stage decision whether or not to complete the task, the contractor bases the decision on expected future rents from continuing in the project as well as on current compensation. These differences are relatively minor. Consequently, most of the insights obtained in the previous section continue to hold. For the purpose of illustration, it suffices to consider the case $N = 2$. The results for the general, multiperiod formulation are then readily obtained via a straightforward extension.

Since the model is solved by backward induction it is convenient to take the time index in reverse time. That is, t refers to the number of tasks remaining; when $t = 1$ the project is in the last period, when $t = 2$ the project is in the penultimate period, etc. The period 1 equilibrium is identical to the equilibrium described in the one period model. Thus, we proceed to describe the equilibrium play in period 2. Throughout the analysis we assume that (1), (9), and (10) hold.

Let R^1 denote the expected future rents earned by the contractor from continuing play into period 1.

$$(12) \quad R^1 = \int_{\underline{c}}^{\hat{c}^1(B)} C_2(s^*(c), c) F(c) dc.$$

Similarly, let V^1 denote the expected benefit net of contractor compensation gained by the sponsor from continuing play into period 1.

$$(13) \quad V^1 = \int_{\underline{c}}^{\hat{c}^1(B)} \left[B - C(s^*(c), c) - C_2(s^*(c), c) \frac{F(c)}{f(c)} \right] f(c) dc.$$

Therefore, the expected net social benefit from continuing the project into period 1, W^1 , is given by

$$(14) \quad W^1 = R^1 + V^1 = \int_{\underline{c}}^{\hat{c}^1(B)} [B - C(s^*(c), c)] f(c) dc.$$

In stage four, the choice of the signal by the contractor depends on P^2 but not on R^1 , as the equilibrium play in period 1 is independent of the period 2 play.¹¹ That is, from the point of view of play in the last period, the previous cost signal and contractor compensation is sunk. Hence, this period 2 signal, $s(P^2, c^2)$ is given by (2). The quit-complete the project decision made in stage three does depend on R^1 , because the contractor expects to earn R^1 on average if the contractor continues the project. Hence,

$$(15) \quad \begin{aligned} Q^2(P^2, c^2) &= 0 \text{ if } P^2(s(P^2, c^2)) - C(s(P^2, c^2), c^2) + R^1 < 0 \text{ and} \\ Q^2(P^2, c^2) &= 1 \text{ if } P^2(s(P^2, c^2)) - C(s(P^2, c^2), c^2) + R^1 > 0. \end{aligned}$$

The upshot of (15) is that to implement the signal function $s(\cdot)$ in period 2, the sponsor offers the same compensation function that would implement $s(\cdot)$ in period 1, less the expected rent R^1 . With this observation and the realization that the sponsor expects to earn V^1 from continuing play into period 1, the optimal compensation function problem for the sponsor is given by

¹¹ This is where our assumption ruling out sponsor learning plays a crucial role.

$$(16) \quad \begin{aligned} & \underset{\underline{c}}{\hat{c}^2} \text{ maximize } \int_{\underline{c}}^{\hat{c}^2} \left[V^1 - C(s^*(c), c) - \frac{C_2(s^*(c), c)F(c)}{f(c)} + R^1 \right] f(c) dc \text{ or} \\ & \underset{\underline{c}}{\hat{c}^2} \text{ maximize } \int_{\underline{c}}^{\hat{c}^2} \left[W^1 - C(s^*(c), c) - \frac{C_2(s^*(c), c)F(c)}{f(c)} \right] f(c) dc. \end{aligned}$$

Therefore, $\hat{c}^2(B) = \hat{c}^1(W^1) \leq \hat{c}^1(B)$, where the inequality follows by Proposition 1, since $W^1 < B$. Moreover, this inequality is strict if either $\hat{c}^2(B)$ or $\hat{c}^1(B) \in (\underline{c}, \bar{c})$, by Proposition 2. In other words, there is a tendency for the distribution of cost, conditional on continuation of the project, to be concentrated over low cost realizations during the initial project tasks and to be more evenly distributed over the entire range of cost realizations during the final project tasks. This point can be made more emphatically by considering the optimal compensation function problem in period t .

$$(17) \quad \underset{\underline{c}}{\hat{c}^t} \text{ maximize } \int_{\underline{c}}^{\hat{c}^t} \left[W^{t-1} - C(s^*(c), c) - \frac{C_2(s^*(c), c)F(c)}{f(c)} \right] f(c) dc \text{ where}$$

$$(18) \quad \begin{aligned} W^t &= \int_{\underline{c}}^{\hat{c}^t} [W^{t-1} - C(s^*(c), c)] f(c) dc \\ &= B \prod_{i=1}^t F(\hat{c}^i) - \sum_{i=1}^t \left[\prod_{h=i}^t F(\hat{c}^h) \right] \int_{\underline{c}}^{\hat{c}^i} C(s^*(c), c) f(c) dc. \end{aligned}$$

From (18), it is evident that W^t is decreasing in t .

We refer to the case where B is sufficiently large that $\hat{c}^t(B) = \bar{c}$ as sponsor lock-in. When the sponsor is locked in, the sponsor will fund the project regardless of the cost realization. If the sponsor is locked in during period t then the sponsor is necessarily locked in during period τ for all $\tau < t$. During lock-in, the distribution of cost, conditional on continuation of the project, is constant. Prior to lock-in, the expected cost, conditional

on continuation of the project, is increasing as the number of remaining tasks decreases. This shift in the cost distribution over time offers one possible explanation for cost overruns. Note that this explanation does not depend at all on a change in behavior on the part of the contractor with regard to the choice of signal. As long as (9) and (10) hold, the choice of signal is independent of the number of tasks which remain. Rather, this explanation hinges on increasing sponsor aversion to project cancellation as the project nears completion.

It is interesting to consider how the compensation function varies over time. From (6) and (15), P^2 is given by

$$(19) \quad P^2(s^*(c)) = C(s^*(c), c) + \int_c^{\hat{c}^2(B)} C_2(s^*(x), x) dx - R^1.$$

Similarly, the formula for P^t for arbitrary t is given by

$$(20) \quad P^t(s^*(c)) = C(s^*(c), c) + \int_c^{\hat{c}^t(B)} C_2(s^*(x), x) dx - R^{t-1}, \text{ where}$$

$$(21) \quad R^{t-1} = \int_c^{\hat{c}^{t-1}(B)} C_2(s^*(c), c) F(c) dc \text{ for } t \geq 2 \text{ and } R^0 = 0.$$

Observe that the second term in (20), the current informational rent earned by the contractor with cost realization c in period t , is decreasing in c and is small for c near to but less than $\hat{c}^t(B)$. Thus, for c near to but less than $\hat{c}^t(B)$ the contractor makes a loss in period t but nevertheless continues in the project, because the contractor expects to earn rents in the future sufficient to offset the current loss.

From (20) and (21) it is evident that the compensation function is highest when there is only one task remaining, both because the current informational rent is at a maximum, the second term in (20) is nonincreasing in t , and because there is no

subsequent expected rent to be extracted. During all periods of lock-in excluding period 1, payments are constant across time and equal to P^L , where

$$(22) \quad P^L(s^*(c)) = C(s^*(c), c) + \int_{\underline{c}}^{\bar{c}} C_2(s^*(x), x)[1 - F(x)]dx - \int_{\underline{c}}^c C_2(s^*(x), x)F(x)dx.$$

These lock-in payments are higher than the pre-lock-in payments. To see this note that if t is sufficiently large that the sponsor is not locked in then

$$(23) \quad \begin{aligned} P^I(s^*(c)) &< C(s^*(c), c) + \int_{\underline{c}}^{\hat{c}^{t-1}(B)} C_2(s^*(x), x)dx - R^{t-1} \\ &= C(s^*(c), c) + \int_{\underline{c}}^{\hat{c}^{t-1}(B)} C_2(s^*(x), x)[1 - F(x)]dx - \int_{\underline{c}}^c C_2(s^*(x), x)F(x)dx \\ &\leq P^L(s^*(c)). \end{aligned}$$

This shift in the payments over time offers a second possible explanation for cost overruns.¹² Note that in this case the notion of cost is from the sponsor's viewpoint rather than from the social viewpoint. For a given cost signal, tasks become more expensive to the sponsor as the project nears completion because the sponsor is required to pay an increased informational rent to the contractor. Though the sponsor also gets to extract greater future informational rents on average, the increase in current informational rent more than offsets the increase in future expected informational rents which can be extracted.

Observe that there is a tendency for expected payments from sponsor to contractor to rise as the project continues until lock-in, since the shift in the distribution of cost, conditional on project continuation, and the shift in the compensation function complement each other. This form of time dependency is also a consequence of the sponsor's

¹² Prior to lock-in, the compensation function may or may not be monotonic in t .

increasing sponsor aversion to project cancellation as the project nears completion. But the variability in per period compensation is a consequence of the sponsor's lack of precommitment as is the excessive cost signaling and the degree to which costs and compensation rise. We demonstrate why this is the case below.

Consider a world where the sponsor can both observe the contractor's cost and precommit to a compensation scheme over the duration of the project. Then, the sponsor can capture the entire expected net social benefit from the project, U^N , where for each t

$$(24) \quad U^t = \int_{\underline{c}}^{c^{*t}(B)} [U^{t-1} - c]f(c)dc$$

$$= B \prod_{i=1}^t F(c^{*i}(B)) - \sum_{i=1}^t \left[\prod_{h=i}^t F(c^{*h}(B)) \right] \int_{\underline{c}}^{c^{*i}(B)} cf(c)dc,$$

and where $c^{*t}(B) = \min [U^{t-1}, \bar{c}]$ and $U^0 = B$. Note that $c^{*t}(B) \geq \hat{c}^t(B)$ and $U^t > W^t$ for all $t = 1, \dots, N$. This latter inequality holds, as can be seen by considering (18) and (24), because there is no distortion due to excessive cost signals nor is there underproduction in U^t . We show that the sponsor can implement the entire net social benefit function under precommitment, even when the contractor has private cost information.

Consider the compensation function P^{*t} given by

$$(25) \quad P^{*t}(s_*(c)) = C(s_*(c), c) + \int_{\underline{c}}^{c^{*t}(B)} C_2(s_*(x), x)dx.$$

Observe that in the static model, P^{*t} implements $s(c) = s_*(c)$ for $c \in [\underline{c}, c^{*t}(B)]$. In fact, P^{*t} is a constant function. Intuitively, if the sponsor pays a constant amount, independent of the contractor's signal, then the contractor is a residual claimant and, hence, will minimize cost. This result can also be seen by differentiating both the right and left hand sides of (25) with respect to c , noting that $C_1(s_*(c), c) = 0$. The expected rent that the contractor earns under P^{*t} , R^{*t} , is given by

$$(26) \quad R^{*t} = \int_{\underline{c}}^{c^{*t}(B)} C_2(s_*(c), c) F(c) dc.$$

Then by setting $P^1 = P^{*1}$, $P^t = P^{*t} - R^{*t-1}$ for $t = 2, \dots, N$ and by charging the contractor a pre-construction fee equal to R^{*N} , the sponsor can obtain an expected payoff equal to U^N .^{13 14} Thus, under precommitment, compensation is invariant to cost conditions but is monotonic in the number of tasks remaining till project completion.

This lack of sensitivity in compensation to observed cost distinguishes the precommitment and no precommitment solutions. Also note that the lock-in period is at least as long under precommitment as under no precommitment, because $U^t > W^t$.

During lock-in, but excluding the ultimate period, the maximum payment under no

precommitment, $C(s^*(\bar{c}), \bar{c}) - \int_{\underline{c}}^{\bar{c}} C_2(s^*(x), x) F(x) dx$, is greater than the precommitment

payment, $\bar{c} - \int_{\underline{c}}^{\bar{c}} C_2(s_*(x), x) F(x) dx$, because $C_{12} < 0$. The minimum payment under no

precommitment, $\underline{c} + \int_{\underline{c}}^{\bar{c}} C_2(s^*(x), x) [1 - F(x)] dx$, is less than the precommitment payment,

$\underline{c} + \int_{\underline{c}}^{\bar{c}} C_2(s_*(x), x) [1 - F(x)] dx$. Indeed, it is straightforward to show that prior to lock-in

the minimum payment under no precommitment is also less than the payment under precommitment associated with the same task. But the maximum payment under no precommitment cannot be ranked against the payment under precommitment, because under precommitment there are both greater expected future rents to extract and a greater range of current costs which are allowed and these two effects are offsetting. It appears that

¹³ The purpose of the pre-construction fee is to extract informational rents obtained in the initial period of construction. In the absence of an ability to set a pre-construction fee, the precommitment solution we have outlined is only approximately optimal. Also note that we could have included a pre-construction fee into the no precommitment model. Such a fee would have no effect on the equilibrium we have described because it is sunk once the initial task is underway.

¹⁴ Baron and Besanko (1984b) obtain a similar result in their Theorem 2.

expected compensation per task increases more dramatically under no precommitment as a consequence of the range of current costs increasing more dramatically. Certainly, the variability in compensation increases more dramatically under no precommitment. It appears that even relative to a standard given by the precommitment solution, the no precommitment solution gives rise to all the properties we ascribe to cost overruns.

V. Discounting and Project Delay

Heretofore we have considered the model in the absence of impatience on the part of either the sponsor or the contractor. It is well understood that when parties in a long term relationship are impatient and there is bilateral monopoly, with substantial specific capital, delays often result as a consequence of opportunism on the part of either party in an attempt to gain a greater share of the quasirents. Grossman and Perry (1986) provide an elegant formalization of this idea in an alternating offers bargaining model. Our model is better characterized as monopsony than bilateral monopoly, since the sponsor makes a take it or leave it offer.¹⁵ Moreover, our model differs from Grossman and Perry in the assumption that the contractor's cost depends on the cost signal as well as the private cost information. Nevertheless, we show that the introduction of discounting leads to the possibility that project delay will be utilized as an involuntary screening device.

Reconsider the model where the project only requires one task for completion but now suppose that both parties discount the future, with common discount factor equal to δ . Suppose the game is altered to allow for the possibility of a one period delay. That is, there is no change in the game if the contractor decides to complete the project in stage three. But, if the contractor decides not to complete the project in stage three, the game does not end. Instead, the project is delayed. In this case the compensation scheme already announced, P^N , is void and the game proceeds as if stage two had been reached for a

¹⁵ Contractor opportunism is also ruled out by the assumption that B is common knowledge. Were B also private information, the contractor could demand very high payment for completing the project currently, forcing the project to be delayed to make the sponsor 'prove' that B is not so high.

second time. Subsequent play follows as in the basic model. If the project is completed after the delay, contractor compensation is based on the post-delay compensation scheme, P^D . The payoffs to both parties are then as in the basic model but are discounted by δ .

To get an intuition for how delay works, suppose for the moment that $P^N = P^D - k$, for some $k > 0$. That is, both schedules implement the same signal function, $s(\cdot)$. Let \tilde{c} be such that $P^N(s(\tilde{c})) - C(s(\tilde{c}), \tilde{c}) = \delta[P^D(s(\tilde{c})) - C(s(\tilde{c}), \tilde{c})]$. Then, it is not hard to show that $P^N(s(c)) - C(s(c), c) \geq \delta[P^D(s(c)) - C(s(c), c)]$ as $\tilde{c} \geq c$. In other words, the contractor will choose to complete the project immediately if the cost realization is sufficiently low and delay the project otherwise. For this reason, it may seem sensible to view delay as a device where the sponsor is able to appropriate some of the informational rent accruing to the contractor when the cost realization is low. However, this view of delay is incorrect for two reasons.

First, the appropriation of rents is relative to what the contractor could obtain after the delay. Since the sponsor cannot precommit to hold down the post-delay compensation scheme, it is quite conceivable that the pre-delay payments are actually higher than they would be were the sponsor able to commit to cancellation of the project, in the event that the project was not completed immediately.

Second, the post-delay compensation scheme will not be a vertical translation of the pre-delay compensation scheme. Instead, the sponsor will interpret the contractor's choice to delay the project as an imperfect signal of the contractor's type. After observing this signal, the sponsor will revise her beliefs as to the contractor type. In sequential equilibrium, this revision of beliefs must be consistent with the contractor's strategy. The post-delay compensation scheme must be optimal for the sponsor given these revised beliefs.

We restrict attention to revision of beliefs that are generated by the following class of conjectures. There is some critical contractor type, \tilde{c} , such that for all c less than \tilde{c} the contractor chooses to complete the project without delay and for all c greater than \tilde{c} the

contractor chooses to delay the project. \tilde{c} should be thought of as a function of the pre-delay compensation scheme. Note that while this restriction of beliefs may appear to be reasonable, there is a rather serious technical issue concerning existence of an equilibrium to sustain these beliefs. For now we ignore this issue. Below, we highlight the problem and provide a necessary and sufficient condition for consistency of these beliefs.

Given this type of conjecture, the sponsor's post-delay beliefs will be given by the distribution $F(\cdot | c \geq \tilde{c})$. Therefore, the equilibrium play, once delay has occurred, is described by the solution to the basic model with the distribution $F(\cdot | c \geq \tilde{c})$ replacing the distribution F . Since $\frac{F(c | c \geq \tilde{c})}{f(c | c \geq \tilde{c})} = \frac{F(c) - F(\tilde{c})}{f(c)}$, it follows that if F satisfies (10), then $F(\cdot | c \geq \tilde{c})$ satisfies (10) as well.¹⁶ Hence, as long as F satisfies (10) there is a unique post-delay equilibrium, by the same argument as was given in the proof of proposition 2. Denote the post-delay signal function by $s(\cdot, \tilde{c})$ and the maximum cost type which will complete the project by $\hat{c}(B, \tilde{c})$. Then the post-delay compensation scheme, $P^D(\cdot, \tilde{c})$, is given by

$$(27) \quad P^D(s(c, \tilde{c}), \tilde{c}) = C(s(c, \tilde{c}), c) + \int_c^{\hat{c}(B, \tilde{c})} C_2(s(x, \tilde{c}), x) dx$$

It follows from (9) and (10) that $s(\cdot, \tilde{c})$ is nonincreasing in \tilde{c} .¹⁷ In other words, an increase in \tilde{c} leads to less distortion in the cost signal. Similarly, from an examination of (**) in the proof of Proposition 2, it follows that $\hat{c}(B, \tilde{c})$ is nondecreasing in \tilde{c} . Thus, the informational rent that a type c contractor earns after delay, $R(c, \tilde{c})$, the second term in the right hand of (27), is increasing in \tilde{c} , since $C_{12} < 0$.

$$16 \quad \frac{d}{dc} \left[\frac{F(c | c \geq \tilde{c})}{f(c | c \geq \tilde{c})} \right] / dc = \frac{f(c)^2 - f(c)[F(c) - F(\tilde{c})]}{f(c)^2}. \text{ This is clearly positive when } f(c) \leq 0. \text{ When } f(c) < 0,$$

$$\frac{d}{dc} \left[\frac{F(c | c \geq \tilde{c})}{f(c | c \geq \tilde{c})} \right] / dc < \frac{f(c)^2 - f(c)F(c)}{f(c)^2} = \frac{d}{dc} \left[\frac{F(c)}{f(c)} \right] / dc \geq 0.$$

¹⁷ We can, without loss of generality, extend the domain of $s(\cdot, \tilde{c})$ from $[\tilde{c}, \tilde{c}]$ to $[\underline{c}, \tilde{c}]$ by setting $s(c, \tilde{c}) = s_*(c)$ for all $c \in [\underline{c}, \tilde{c}]$ to make the previous sentence more precise.

We turn to the sponsor's choice of the pre-delay compensation scheme. Suppose the sponsor wishes to implement the signal function $s(\cdot)$ defined on $[\underline{c}, \bar{c}]$ prior to delay. We claim that the pre-delay compensation scheme, P^N , will implement $s(\cdot)$, where

$$(28) \quad P^N(s(c)) = C(s(c), c) + \int_c^{\bar{c}} C_2(s(x), x) dx + \delta R(\bar{c}, \bar{c}),$$

provided that some additional conditions, discussed below, are met. Observe that under P^N a type \bar{c} contractor is indifferent to producing immediately or choosing to delay. The sponsor's expected net benefit from implementing $s(\cdot)$ is given by

$$(29) \quad V(s(\cdot), \bar{c}) = \int_{\underline{c}}^{\bar{c}} \left[B - C(s(c), c) - C_2(s(c), c) \frac{F(c)}{f(c)} - \delta R(\bar{c}, \bar{c}) \right] f(c) dc + \\ \delta \int_{\bar{c}}^{\hat{c}(B, \bar{c})} \left[B - C(s(c, \bar{c}), c) - C_2(s(c, \bar{c}), c) \frac{F(c) - F(\bar{c})}{f(c)} \right] f(c) dc.$$

The sponsor is assumed to choose $s(\cdot)$ and \bar{c} to maximize V . For given \bar{c} , the integrand in the first term on the right hand side of (29) is the same integrand as in the basic model, minus a fixed cost. Consequently it will be optimal to set $s(\cdot) = s^*$ prior to delay. Therefore, we can think of the sponsor's problem as being given by

$$(30) \quad \begin{aligned} & \underset{\underline{c}}{\text{maximize}} \int_{\underline{c}}^{\bar{c}} \left[B - C(s^*(c), c) - C_2(s^*(c), c) \frac{F(c)}{f(c)} - \delta R(\bar{c}, \bar{c}) \right] f(c) dc + \\ & \quad \hat{c}(B, \bar{c}) \\ & \quad \delta \int_{\bar{c}}^{\hat{c}(B, \bar{c})} \left[B - C(s(c, \bar{c}), c) - C_2(s(c, \bar{c}), c) \frac{F(c) - F(\bar{c})}{f(c)} \right] f(c) dc \end{aligned}$$

or

$$\begin{aligned} & \underset{\underline{c}}{\text{maximize}} \int_{\underline{c}}^{\bar{c}} \left[B - C(s^*(c), c) - C_2(s^*(c), c) \frac{F(c)}{f(c)} \right] f(c) dc + \\ & \quad \hat{c}(B, \bar{c}) \\ & \quad \delta \int_{\bar{c}}^{\hat{c}(B, \bar{c})} \left[B - C(s(c, \bar{c}), c) - C_2(s(c, \bar{c}), c) \frac{F(c)}{f(c)} \right] f(c) dc. \end{aligned}$$

This second formulation of the sponsor's problem highlights the involuntary nature of delay, as is shown in the following proposition.

Proposition 3: The payoff to the sponsor when delay is possible is never greater than the payoff to the sponsor when delay is ruled out a priori.

Since the sponsor is free to set $\bar{c} = \bar{c}$ in (30), the following corollary is immediate.

Corollary: If the sponsor is locked in when delay is ruled out a priori, then the sponsor will set the compensation sufficiently high to avoid delay when delay is possible.

In other words, delay occurs only when, in the equilibrium developed in section III, there is a positive probability of project cancellation. In this case, the sponsor would prefer to commit to cancelling the project if it is not immediately completed. Being unable to do so, the sponsor is forced to raise the compensation for completing the project immediately. In fact, this effect may be sufficiently strong to rule out delay altogether,

giving the appearance that the sponsor is locked in, though lock-in would not occur if the sponsor could credibly commit to project cancellation.

We turn to the issue of the consistency of the sponsor's beliefs, to justify this formulation. It is convenient to think of the pre-delay payment as coming from the family,

$$(31) \quad P^N(s^*(c), k) = C(s^*(c), c) + \int_c^{\bar{c}} C_2(s^*(x), x) dx - k,$$

for arbitrary k . This allows us to take the domain of P^N to be the entire support of F and to view k as the choice variable which shifts the pre-delay compensation scheme up or down in a vertical fashion.¹⁸ Similarly, it will be convenient to think of the discounted post-delay payment as coming from the family

$$(32) \quad \delta P^D(s(c, \bar{c}), \bar{c}, h) = \delta [C(s(c, \bar{c}), c) + \int_c^{\bar{c}} C_2(s(x, \bar{c}), x) dx - h]$$

for arbitrary \bar{c} and h . This allows us to view the domain of P^D to be the entire support of F .

Definition: The family of pre-delay payments, P^N , and discounted post-delay payments, δP^D , satisfy the single crossing property if

- (i) $\int_c^{\bar{c}} C_2(s^*(x), x) dx - k = \delta [\int_c^{\bar{c}} C_2(s(x, \bar{c}), x) dx - h]$ implies
- (ii) $C_2(s^*(c), c) > \delta C_2(s(c, \bar{c}), c)$

for all k , \bar{c} and h .

¹⁸ To make (31) compatible with (27) take $k = - \int_c^{\bar{c}} C_2(s^*(x), x) dx + \delta R(\bar{c}, \bar{c})$.

Evidently, this single crossing property is sufficient to sustain the consistency of the sponsor's beliefs. The left hand side of (i) is the informational rent for the contractor from taking the pre-delay payment when the cost realization is c . The right hand side of (i) is the discounted informational rent from taking the post-delay payment. The definition says that any time the contractor is indifferent to delaying the project or completing it immediately, the contractor would prefer to delay, if the cost realization were slightly higher, and would prefer to complete the project immediately, if the cost realization were slightly lower. This implies that there can be at most one cost realization for which the contractor is indifferent between choosing to delay or not. Observe that for P^N and δP^D to satisfy the single crossing property it is necessary that

$$(33) \quad C_2(s^*(c),c) > \delta C_2(s_*(c),c) \text{ for all } c \in [\underline{c}, \bar{c}].$$

Also note that by taking $c = \bar{c}$ in (33), it is evident from (27) that (33) is necessary for the sponsor's beliefs to be consistent.

Proposition 4: Suppose (33) holds. Then P^N and δP^D satisfy the single crossing property.

Thus, (33) is a necessary and sufficient condition for the consistency of the sponsor's beliefs. Hence, our analysis is valid as long as the discount factor is not too large. That is,

$$(34) \quad \delta < \max_c \left[\frac{C_2(s^*(c),c)}{C_2(s_*(c),c)} \right].$$

(33) also implies that there is a one to one relationship between the height of the pre-delay payment, k , and the set of cost realizations over which the contractor chooses to complete the project immediately, determined by \bar{c} . To see this note that we have demonstrated that

$R_1(\bar{c}, \bar{c}) > 0$. Since $R_2(\bar{c}, \bar{c}) = -C_2(\bar{c}, \bar{c})$, (33) also implies that the pre-delay payment is increasing in \bar{c} , as can be seen by differentiating (28) with respect to \bar{c} .

We consider how the choice of \bar{c} depends on B . Intuitively, \bar{c} should be nondecreasing in B , since delay imposes a cost on the sponsor and this cost is increasing in B . In fact, this appears to be necessary only when the sponsor is locked in after the delay, as is shown in the following proposition.

Proposition 5: $[1 - \delta]F(\bar{c}(B)) + \delta F(\hat{c}(B, \bar{c}(B)))$ is nondecreasing in B . If $\hat{c}(B, \bar{c}(B)) = \bar{c}$, then $\bar{c}(B)$ is nondecreasing in B .

We have already shown that $\hat{c}(B, \bar{c})$ is increasing in \bar{c} when $\hat{c}(B, \bar{c}) < \bar{c}$. Thus, for $\bar{c}(B)$ to be decreasing in B over some interval it would appear from Proposition 4 that $\hat{c}(B, \bar{c})$ would have to be fairly elastic in B over that same interval. In other words, this lack of monotonicity in the likelihood of delay occurs only when the post-delay informational rents are highly elastic in the sponsor's benefit. Then, delay is less attractive to the sponsor, since the sponsor can't precommit to limit these post-delay rents and since the pre-delay payments must be high when the post-delay rents are high to induce self-selection. With the exception of this extraordinary case, Proposition 4 supports the intuition that delay is more likely when the benefits from project completion are not so large.

We have restricted attention to a model where there is at most one period of delay. This restriction was made to simplify the analysis. One might be able to extend our approach in a more realistic, albeit more complicated, manner by allowing for an arbitrary number of periods of delay. Finally, note that this approach to project delay could also be extended to allow for a multiplicity of tasks, performed sequentially, just as the one task model in section III was extended to allow for a multiplicity of tasks in section IV. Then it would appear, from proposition 5 and the corollary to proposition 3, that delay is more likely early into the project, when the sponsor's discounted expected net benefit is not so large.

VI. Conclusion

We have argued in this paper that a satisfactory explanation of cost overruns can be provided simply by assuming that the sponsor cannot precommit to the compensation paid to the contractor when the contractor has some private cost information. We do not want to create the impression that this is the sole explanation of cost overruns. Undeniably, sponsor learning about project costs and bargaining over the split of quasirents are also important determinants of cost overruns and project delays. We suspect that a model which included these other elements would only amplify our results.

From a normative perspective, our model suggests that it would be beneficial for the sponsor to search for up front investments which have the effect of tying the sponsor's hands in making decisions during the course of the project. Perhaps the prevalence of cost overruns and project delays is evidence that such investments are not readily available and, consequently, that such inefficiencies are an unavoidable consequence in procurement.

References

- Baron, D.P., 1988, "Information, Incentives, and Commitment in Regulatory Mechanisms: Regulatory Innovation in Telecommunications," mimeo.
- Baron, D.P. and D. Besanko, 1984a, "Regulation, Asymmetric Information, and Auditing," *Rand Journal of Economics*, 447-470.
- _____, 1984b, "Regulation and Information in a Continuing Relationship," *Information Economics and Policy*, 267-302.
- _____, 1987, "Monitoring, Moral Hazard, Asymmetric Information, and Risk Sharing in Procurement Contracting," *Rand Journal of Economics*, 509-532.
- Baron, D.P. and R.B. Myerson, 1982, "Regulating a Monopolist with Unknown Costs," *Econometrica*, 911-930.
- Grossman, S. J. and M. Perry, 1986, "Sequential Bargaining under Asymmetric Information," *Journal of Economic Theory*, 120-154.
- Harris, M. and B. Holmstrom, 1982, "A Theory of Wage Dynamics," *Review of Economic Studies*, 315-333.
- Lazear, E.P., 1979, "Why is there Mandatory Retirement?" *Journal of Political Economy*, 1261-1284.
- _____, 1981, "Agency, Earnings Profiles, Productivity and Hours Restrictions," *American Economic Review*, 606-620.
- Laffont, J.J. and J. Tirole, 1986, "Using Cost Observation to Regulate Firms," *Journal of Political Economy*, 614-641.
- _____, 1987, "The Dynamics of Incentive Contracts," *Econometrica*, 1153-1175.
- Lewis, T.R., 1986, "Reputation and Contractual Performance in Long-Term Projects," *Rand Journal of Economics*, 141-157.
- Macleod, W.B., and Malcolmson, J.M., 1989, "Implicit Contracts, Incentive Compatibility, and Involuntary Unemployment," *Econometrica*, 447-480.
- Maskin, E. and J. Riley, 1984, "Monopoly with Incomplete Information," *Rand Journal of Economics*, 171-196.
- Riordan, M.H., 1986, "A Note on Optimal Procurement Contracts," *Information Economics and Policy*, 211-219.
- Salop, J. and S. Salop, 1976, "Self-Selection and Turnover in the Labor Market," *Quarterly Journal of Economics*, 619-627.
- Tirole, J., 1986, "Procurement and Renegotiation," *Journal of Political Economy*, 235-259.

Appendix

Proof of Proposition 1:

$$\int_{\underline{c}}^{\hat{c}(B_1)} \left[B_1 - C(s(B_1, c), c) - \frac{C_2(s(B_1, c), c)F(c)}{f(c)} \right] f(c) dc \geq$$

$$\int_{\underline{c}}^{\hat{c}(B_2)} \left[B_1 - C(s(B_2, c), c) - \frac{C_2(s(B_2, c), c)F(c)}{f(c)} \right] f(c) dc \text{ and}$$

$$\int_{\underline{c}}^{\hat{c}(B_2)} \left[B_2 - C(s(B_2, c), c) - \frac{C_2(s(B_2, c), c)F(c)}{f(c)} \right] f(c) dc \geq$$

$$\int_{\underline{c}}^{\hat{c}(B_1)} \left[B_2 - C(s(B_1, c), c) - \frac{C_2(s(B_1, c), c)F(c)}{f(c)} \right] f(c) dc.$$

Adding these inequalities together and then rearranging terms yields

$$\int_{\hat{c}(B_2)}^{\hat{c}(B_1)} [B_1 - B_2] f(c) dc \geq 0. \bullet$$

Proof of Proposition 2: In this case $s(B, c) = s^*(c)$ for all B . It follows from (6) that

$$(*) \quad P(B, c) = C(s^*(c), c) + \int_{\underline{c}}^{\hat{c}(B)} C_2(s^*(x), x) dx.$$

(i) follows immediately from (*), $C_2 > 0$, and Proposition 1. For $s(\cdot) = s^*$, the objective function in (8) is strictly concave in \hat{c} given (1), (9), and (10). When there is an interior optimum, the first order necessary condition which determines $\hat{c}(B)$ is

$$(**) \quad B - C(s^*(\hat{c}(B)), \hat{c}(B)) - \frac{C_2(s^*(\hat{c}(B)), \hat{c}(B))F(\hat{c}(B))}{f(\hat{c}(B))} = 0.$$

(ii) is then obtained by implicitly differentiating (**) with respect to B . (iii) follows from (*) and (ii). Since $\hat{c}(B) > \underline{c}$, the left hand side of (**) is greater than or equal zero, even at a corner solution. Then, (iv) follows because $C_2 > 0$. •

$$\begin{aligned}
 \text{Proof of Proposition 3: } & \delta \int_{\underline{c}}^{\hat{c}(B, \bar{c})} \left[B - C(s(c, \bar{c}), c) - C_2(s(c, \bar{c}), c) \frac{F(c)}{f(c)} \right] f(c) dc \\
 & \leq \delta \int_{\underline{c}}^{\hat{c}(B, \bar{c})} \left[B - C(s^*(c), c) - C_2(s^*(c), c) \frac{F(c)}{f(c)} \right] f(c) dc \\
 & \leq \int_{\underline{c}}^{\max[\hat{c}(B), \bar{c}]} \left[B - C(s^*(c), c) - C_2(s^*(c), c) \frac{F(c)}{f(c)} \right] f(c) dc.
 \end{aligned}$$

Thus, the objective function in (30) is dominated by

$$\int_{\underline{c}}^{\hat{c}(B)} \left[B - C(s^*(c), c) - C_2(s^*(c), c) \frac{F(c)}{f(c)} \right] f(c) dc. \bullet$$

Proof of Proposition 4: We will show that (33) implies $C_2(s^*(c), c) > \delta C_2(s(c, \bar{c}), c)$ for all $c, \bar{c} \in [\underline{c}, \bar{c}]$. This is immediate for $c \leq \bar{c}$ since $s(c, \bar{c}) = s_*(c)$ in this case. For $c > \bar{c}$ observe that $\delta C_2(s_*(c), c) > \delta C_2(s(c, \bar{c}), c)$ since $s(c, \bar{c}) > s_*(c)$ and $C_{12} < 0$. The result is also straightforward in this case. •

Proof: The first part of the proposition follows from the same type of argument as was given in the proof of Proposition 1 and is not repeated here. It implies that over any sufficiently small interval in B , either $\bar{c}(B)$ or $\hat{c}(B, \bar{c}(B))$ is nondecreasing and if one is

decreasing the other must be increasing. The second part of the proposition follows from the observation that $\bar{c}(B)$ can't be decreasing when $\hat{c}(B, \bar{c}(B)) = \bar{c}$. •