ESSAYS ON ASYMMETRIC INFORMATION IN GOVERNMENT CONTRACTING

by

Stephanie Anne West

Dissertation submitted to the Faculty of the

Virginia Polytechnic Institute and State University

in partial fulfillment of the requirements for the degree of

DOCTOR OF PHILOSOPHY

in

Economics

APPROVED

Mark A. Loewenstein

M. Loewenstein, Chairman

Richard Cothren

R. Cothren

H. Cremer

Bruno Parigi

B. Parigi

William T. Smith II

B. Smith

July 1992
Blacksburg, Virginia

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(ABSTRACT)

The dissertation consists of a set of essays which investigate optimal contracting policies in the presence of asymmetric information and uncertainty. The first essay studies how risk aversion and a sunk investment by the firm influence the contracting outcome. The government contracts with a single, risk-averse supplier for the production of output. Both the government and the firm face uncertainty with respect to the marginal production cost of the item. Prior to full-scale production, the firm performs start-up work, during which it may make a costly investment which lowers the marginal cost of production. This cost-reducing effort is not observable by the government. At the end of the start-up phase, the firm privately learns its production cost. It then reports to the government concerning this cost, and production takes place according to the terms of the contract.

The primary result concerns the effect that the firm's investment has on the private information problem. Specifically, the investment by the firm in the start-up phase reduces the firm's incentive to misrepresent (overstate) its cost to the government later on. From this, it follows that the firm provides a strictly smaller investment than the government would prefer under the optimal contract.

The second essay examines the optimal incentive contract to offer to bidders with independent private values when it is costly for the principal to monitor the agent's cost performance ex post. Cost sharing reduces the winner's informational rents when the bidders

possess heterogeneous private cost information but also discourages the agent from providing effort to reduce cost. In addition, if cost observation is costly for the principal, cost sharing gives the agent an incentive to pad his cost ex post. The essay investigates the consequences of this ex post adverse selection problem for the optimal incentive contract.

The principle results of the analysis are as follows. First, it is demonstrated that when monitoring is costly, a low cost agent will overreport his realized cost with positive probability in equilibrium. Depending upon the cost sharing parameter, the equilibrium cost reporting and monitoring strategies may either involve pooling or a mixed strategy solution.

Second, we show that the optimal contract with costly monitoring generally differs from the contract which is optimal when monitoring is costless. Depending upon the characteristics of the contracting environment, the optimal contract may induce either pooling or a mixed strategy outcome ex post. If the optimal contract involves pooling, the 'costly monitoring' cost sharing parameter is weakly smaller than the optimal cost sharing parameter with costless monitoring. If the optimal contract induces a mixed strategy equilibrium, the optimal level of cost sharing is strictly higher than the optimal cost sharing parameter when monitoring is costless. Finally, our model predicts that, other things equal, the level of cost sharing should be higher, the smaller the number of bidders and the more diffuse the bidder's expected costs.

Acknowledgements

I am very grateful to Mark Loewenstein for his expert and thoughtful guidance and for providing ideas and insights that have contributed substantially to these essays.

For their helpful comments on the second chapter, I thank Jacques Cremer, Hans Haller, Fahad Khalil, and Bruno Parigi. I also thank Helmut Cremer, Richard Cothren, and Bill Smith for all their help and concern.

I am deeply grateful to my parents for their love and support. My appreciation and thanks also go to Tim, Sharon, Fahad, Nandini, Farhad, Nivedita, I. Kim, Jacek, Mark F., and Subashis.

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Chapter 1

Introduction

Economists have focused considerable attention in recent years on how problems of asymmetric information affect the incentives of regulated firms and the optimal policies of the regulator. A large and well-developed literature has emerged on incentive theory in regulation. Concurrently, many authors have sought applications for the theory, and government contracting provides one promising area in which to apply the theory and test its empirical implications.

The procurement projects undertaken by the government are often long-term in nature and require firms to make transaction specific investments. Exchange takes place under conditions of bilateral monopoly, and contracts are used to define the terms of trade. The contracting environment possesses a number of characteristics which may prevent first-best outcomes. First, the market for government contracts is often thin. The government often faces a small number of potential suppliers with heterogeneous, unknown costs. Second, when the projects involve untried technology, there may be significant cost uncertainty when contracting takes place. Third, after the contract has been awarded it may be difficult to observe the contractor's efforts to reduce cost. Thus, the contracting process may be complicated by problems of adverse selection, risk and moral hazard.

The following short survey outlines the analysis and results of several key papers from the regulation literature. Its purpose is to describe the progression of the literature, and some of the more fundamental results, and to indicate where the essays below fit in. Section II focuses on the problem of contracting with a monopolist and previews the first essay pertaining to the same topic. Section III describes models involving competition among bidders for a contract and provides an introduction to the second essay. Both monopoly and situations involving competition are encountered frequently in goverment contracting. For example, in U.S. defense procurement, 42% of the total spending for 1988 was awarded to firms on a non-competitive basis.[1]

I. *Contracting with a Monopolist*

The starting point for the study of contracting under asymmetric information is the 'principal-agent' problem explored by Holmstrom (1979), Shavell (1979), and others. The problem involves a buyer or principal who enlists a risk-averse agent to perform a task which yields a monetary payoff.[2] The principal may be risk-averse as well, but is assumed to have a greater tolerance for risk than the agent. The size of the payoff depends on the agent's effort as well as a random variable, the 'state of nature', which is realized after contracting. The principal and agent possess symmetric expectations concerning the state of nature when contracting takes place. The principal cannot observe the agent's effort or the realization of the state, but he does observe the monetary outcome. Effort involves a cost for the agent so the fundamental question concerns how to share the payoff in order to give the agent incentive to provide effort.

The principal, acting as a von Stackleberg leader, makes the contract offer. If the agent were risk neutral, then the simple solution makes him the residual claimant up to a constant so that he realizes the full benefit of his effort. This ensures that the agent will provide the full-information level of effort. However, because the agent bears all the risk, such a scheme is not optimal if the agent is more risk-averse than the principal. The primary finding is that the optimal sharing rule partially insures the agent with respect to the uncertainty in the payoff.

Consequently, under the optimal contract the agent chooses less effort than the principal would prefer, i.e. than the principal would choose if effort were observable.

These models generally do not yield an explicit solution for the sharing rule governing the division of the payoff. Weitzman (1980) applies principal-agent analysis in order to investigate the properties of the optimal 'linear incentive contract', the sharing rule employed most often in government contracting. Under the linear incentive contract, the principal pays the agent a lump-sum transfer plus a percentage of his realized production cost. Reimbursing realized cost reduces the agent's risk, but also mitigates his incentive to take unobservable actions to reduce cost. Weitzman finds that an increase in the risk aversion of the agent raises the proportion of cost reimbursed by the principal. Weitzman also demonstrates that the cost share borne by the principal increases with a mean-preserving increase in uncertainty, i.e. in the variance of the state of nature governing costs.

Principal-agent models involve parties who are both uninformed with respect to the state of nature when the terms of the contract are set. Subsequent work, beginning with the seminal paper of Baron and Myerson (1982) explores the problem of contracting with an 'informed' agent who privately observes the state of nature prior to contracting.

In the Baron and Myerson model, a principal contracts for the production of output with a monopolist who is privately informed of his production cost before contracting takes place. The principal is unable to observe the firm's cost prior to contracting, nor does he observe any information about the firm's cost ex post. As a result, the monopolist has an incentive to overstate his production cost (choose an inefficiently low level of output) in order to earn informational rents. The principal is assumed to be a regulator or social planner, whose objective is to maximize a weighted sum of expected consumer and producer surplus, with producer profit receiving a smaller weight than consumer surplus. The regulator offers the monopolist a contract which specifies a monetary transfer and quantity of output for each possible cost report of the monopolist. After accepting the contract, the agent reports to the principal concerning his cost, and produces the output level specified in the contract. The contract gives the agent an incentive to truthfully reveal his cost,[3] by rewarding a report of low cost with rents. In particular, the rents earned by the agent are inversely related to his reported cost.

The most important finding of the model concerns the level of production under the optimal contract. Baron and Myerson show that the monopolist produces a level of output which is strictly smaller than the 'full information' output level for all but the lowest possible cost report. That is, the output level is such that the marginal benefit of an additional unit exceeds the marginal cost. Decreasing the level of output for a report of high cost reduces the low cost monopolist's potential gain from misreporting cost as being high, thereby lowering the information rents necessary to induce a low cost type to trutfully reveal his cost.[4] At the full-information output level, the decrease in consumer surplus stemming from a small decrease in output represents a second-order loss, whereas the decrease in informational rents resulting from the quantity distortion represents a first-order gain for consumers. Therefore, the regulator optimally trades off the efficiency of output to reduce the cost of the adverse selection problem.

An important assumption underlying the analysis is that no other producer is available who can supply the good. In case another equally efficient supplier exists, the full-information outcome can be implemented by conducting an auction in which the firms compete for the 'monopoly franchise', i.e. for the ownership of the entire surplus. In this case, the competition drives the winning firm's expected profit to zero, and the monopolist makes efficient output decisions ex post. The implications of the availiability of a less efficient alternative supplier are examined in the section on competition.

The regulator is unable to observe any information ex post about the agent's cost in the

Baron and Myerson model. Noting that in practice the regulator will often monitor an agent's cost performance ex post, Baron and Besanko (1984) extend the Baron and Myerson analysis to incorporate the possibility that the principal observes the agent's realized cost ex post by incurring a monitoring cost. The model motivates the regulator's demand for ex post cost information and explores the optimal auditing strategy of the regulator.

In Baron and Besanko, the monopolist faces cost uncertainty when contracting takes place, but privately observes the state of nature governing the distribution of cost. Higher states of nature signal higher expected costs. The regulator is able to observe the agent's realized cost ex post by performing a costly audit.[5] The contract offered by the regulator consists of a quantity of output, monetary transfer, and probability of audit for each possible cost state, and a penalty schedule which depends on both the reported cost state and the cost observed by the regulator ex post. The principal is assumed to have the power to commit to an auditing policy ex ante.[6] This assumption is critical because the optimal contract elicits a truthful report concerning the state, and the principal therefore has no incentive ex post to devote resources to monitoring.

The authors find that the optimal policy involves auditing whenever the reported cost state exceeds some threshold level; low cost reports are not monitored. If the audit reveals total costs which are below a critical level consistent with the cost state reported ex ante, then the maximum penalty is imposed.[7] The auditing of high cost reports coupled with a penalty for low observed cost deters an agent with low expected costs from misrepresenting the cost state as being high. Thus, auditing reduces the information rents needed to elicit a truthful report of the state of nature. In addition, output levels under the optimal contract are smaller than the 'full information' level of output, but the distortions are generally smaller than those which accompany the Baron and Myerson contract.

The Baron and Besanko model shows that a regulator may engage in costly auditing activity ex post in order to reduce the cost of inducing truthful revelation ex ante. However, as noted above, the optimal policy is not self-enforcing: there is nothing to gain (in an expected sense) from performing the costly audit ex post. In an interesting recent extension, Khalil (1990) investigates the optimal contract to offer the monopolist when the principal cannot commit to the auditing policy. Considering a model in which the principal faces binary uncertainty with respect to the agent's cost, he finds that the optimal auditing policy involves monitoring the high cost report with positive probability and imposing the maximum penalty if the cost observed ex post is low. However, in contrast to Baron and Besanko, the probability of monitoring is too small to completely prevent cheating,and the low cost agent misrepresents his cost as being high with positive probability in equilibrium. As noted above, a monitoring policy which entirely eliminates cheating is not self-enforcing.

Khalil shows that the optimal contract in the absence of commitment involves a level of output in the high cost state which exceeds the full-information level, in marked contrast to previous contracting models with adverse selection. The upward quantity distortion for the high cost type raises the principal's gains to auditing and, by implication, reduces the agent's probability of cheating in the mixed strategy equilibrium. This decreases the expected informational rents of the agent. In effect, the artificially high level of output enables the principal to commit to a higher probability of auditing. This increases his welfare by reducing the cost of the adverse selection problem.

The three models discussed above are examples of pure 'adverse selection' problems. The models do not incorporate the possiblity of moral hazard: what if the monopolist were able to influence his cost by taking some action unobservable to the regulator? The Baron and Myerson results would be unchanged by including the possibility of moral hazard. Because the principal cannot observe any information about cost ex post, the agent bears the entire cost of production and thus will always take the efficient level of effort.[8]

In contrast, the results of the Baron and Besanko model would not be robust to the introduction of moral hazard. The precise manner in which moral hazard would alter the results seems to be an open question. Note however, that under the optimal scheme the agent is punished if observed costs are excessively low. Also, because the audit does not reveal the state of nature, the truthtelling agent may be punished if the realization of the random disturbance is low. With moral hazard, this type of scheme would encourage the agent to slack on effort in order to reduce the likelihood of punishment.[9]

The next major development in the literature involves models which combine the elements of moral hazard and adverse selection. Laffont and Tirole (1986) consider whether the principal should use ex post cost information in regulating the monopolist when the problems of adverse selection and moral hazard coexist. As in the previous models, the regulator contracts with a risk-neutral agent who knows the state of nature. The realized cost of producing output depends on the state of nature, a random cost disturbance, and the effort supplied by the firm during production. Effort is costly for the agent and unobservable by the principal. The principal costlessly observes the agent's realized cost, or a noisy signal of realized cost, ex post.[10] The contract offered by the principal designates a level of output for each possible cost state, and a transfer schedule which may depend on the reported cost state and realized cost.

Laffont and Tirole find that the optimal transfer scheme is a linear incentive contract, which reimburses a fraction of the agent's realized cost. The fraction of cost reimbursed increases with the agent's reported cost. By bearing a share of the costs of a high cost agent, the principal reduces a low cost agent's potential gains from overreporting the cost state ex ante. To demonstrate, suppose that there are only two states of nature and that in the high cost state the principal fully reimburses the agent's realized cost (a 'cost-plus' contract). The low cost agent clearly has no incentive to misreport the cost state in this case, since given a high cost report he will simply be reimbursed for his actual cost. The cost plus contract thus completely eliminates the need to pay the agent informational rents. However, the contract also gives the high cost agent no incentive to provide effort, since he bears none of the production cost. Under the optimal contract therefore, the principal bears only a fraction of realized cost. The cost sharing parameter is chosen to balance the expected cost of the adverse selection and moral hazard problems at the margin.

Laffont and Tirole also find that the agent's effort under the optimal contract is smaller than the level which is efficient, given output (the level which would be chosen by the regulator).[11] As in the principal-agent model, this last result stems from the positive level of cost sharing, which prevents the agent from realizing the entire benefit of his effort. As pointed out by the authors themselves, their findings are markedly different from those of Baron and Besanko (1984). One difference is of course that monitoring is costless in Laffont and Tirole, so that all cost reports are monitored instead of high cost reports alone. More significantly, note that in the presence of moral hazard the agent is not punished when a high state is reported and low costs are realized. Instead, the principal lowers the cost of the adverse selection problem by directly reimbursing a portion of the agent's cost.

Finally, Baron and Besanko (1988) consider the problem of contracting for defense procurement. The model is almost identical to that of Laffont and Tirole except that the firm is assumed to be risk-averse. This captures an important characteristic of the defense contracting environment: the considerable cost risk associated with high technology projects may be difficult for the firm to diversify. In addition, Baron and Besanko restrict attention at the outset to the linear contracts used in practice, rather than solving for the unconstrained optimal contract.[12]

Baron and Besanko find that the optimal linear contract involves a positive level of cost sharing. In addition to reducing the information rents associated with the contract, cost sharing insures the firm with respect to cost risk, reducing the risk premium. The authors also find that the agent may provide a level of effort either smaller or larger than the level which is preferred by the regulator. This contrasts markedly with previous results, which indicate that cost sharing induces 'too little' effort on the part of the agent.

The ambiguity concerning effort stems from the fact that the agent is risk-averse and the signal is noisy. Note that if effort were observable, the principal would use effort as an additional tool to reduce the cost of the adverse selection problem. Thus, if additional effort aggravates the adverse selection problem, the principal would choose an 'artificially low' level of effort, one where the marginal benefit in terms of cost reduction exceeds the marginal cost of effort. In this case, the possibility that the agent chooses a higher level of effort than that preferred by the principal cannot be ruled out. Despite the positive level of cost sharing, the agent may choose more effort than the principal prefers, because the agent does not take into account the effect of effort on the adverse selection problem. However, if either the agent were risk-neutral or the signal were perfect, the principal would never choose an artificially low level of effort, since if effort were observable in this case, the cost of the adverse selection problem could be eliminated using a cost-plus contract. Thus, in either of these two contingencies, the possibility that the agent overprovides effort may be ruled out.

Overview of the First Essay

The first essay considers the problem of contracting for defense procurement with a monopolist. The model incorporates elements of adverse selection, moral hazard, and risk aversion. In the adverse selection models described above, the agent is assumed to observe the state of nature before contracting takes place. For large-scale defense projects involving the production of new weapons using advanced technology, the agent may at the outset have little informational advantage over the government. It may therefore be more appropriate to assume that information is symmetric at contracting time.

I assume that the principal and agent are uninformed concerning the state of nature when contracting takes place, and that the agent privately discovers the state of nature after an initial period of work, during which the agent prepares for production. The agent also provides an unobservable effort to reduce costs during the initial period, and the principal costlessly observes a noisy signal of realized cost ex post. I solve for the optimal linear incentive contract.

The model resembles the principal-agent models discussed initially, in that the the agent is uninformed when contracting takes place and when effort is chosen. Thus, risk aversion and moral hazard play an important role in the analysis. In addition, the contract is allowed to be contingent on the state of nature, as in the standard adverse selection model. The contract offered by the principal designates a level of output and tranfers for each possible cost report. After the state is revealed to the agent at the end of the initial period, the agent submits a cost report. Thus, adverse selection plays a crucial role in the model as well.

Since the parties contract under symmetric information, the agent earns no informational rents (in an expected sense). Nevertheless, the adverse selection problem is costly, because it prevents the government from fully insuring the risk-averse agent. Lower cost reports must be rewarded with higher profits to induce the agent to truthfully reveal the state. This profit differential across states exposes the agent to risk ex ante. It is shown that cost sharing reduces the risk associated with an incentive compatible contract. Thus, the primary motivation for cost sharing is insurance, rather than rent reduction.

The primary result of the model concerns the value of effort to the principal. It is shown that additional effort helps to reduce the cost of the adverse selection problem. Since effort reduces unit production cost, its marginal benefit increases with output. Furthermore, because output varies inversely with reported cost, the return to effort diminishes as reported cost increases. Thus, the prospect of a decreased return on the prior investment in cost reduction dampens the firm's incentive to overstate cost, lowering the cost of the adverse selection problem for the principal. Clearly, this result stems from the fact that effort is sunk before the firm becomes informed.

II. *Competition for Contracts*

Several more recent studies have explored the effects of introducing competition into the contracting problem. Riordan and Sappington (1987) consider the interesting problem of auctioning a 'monopoly franchise', which guarantees the right to serve as the sole supplier in a market. Bidders in their model face uncertainty about the cost of producing output, but possess independent private signals indicating expected cost. Each bidder submits a report regarding his expected cost, and the franchise is awarded to the low bidder. The winning bidder pays a franchise fee and, prior to beginning production, privately observes his production cost.

The principal faces two sucessive problems of adverse selection. First, because the agents have independent private values, each bidder will tend to underestimate the value of the franchise (overstate his expected cost) in order to pay a franchise fee smaller than his true valuation of the franchise. Second, after the franchise is awarded, the monopolist will tend to choose an inefficient level of output, as in Baron and Myerson. Using the revelation principle, the optimal outcome can be implemented by a contract which elicits truthful reports of expected cost from the bidders and actual cost from the monopolist.

The principal offers a list or "menu" of contracts indexed by the bid. Corresponding to every possible bid is a franchise fee and a contract which designates output and transfers for each possible production cost reported by the monopolist. By bidding, each potential agent thus selects a quantity-transfer schedule. Riordan and Sappington show that the optimal menu of contracts generally involves production levels such that the marginal benefit of additional output exceeds the marginal cost. Moreover, the distortions in output depend on both the ex post cost report of the monopolist and the agent's bid. In particular, the higher the bid, the greater the distortions in the quantity schedule.

The reason for linking higher bids with quantity schedules involving greater distortions is similar to the reason for distorting the high cost monopolist's output: it reduces the cost of inducing the bidders to self-select ex ante. Since the bidders have independent private values, each bidder has an incentive to shade his bid to the expected cost of his closest rival, in order to pay a smaller franchise fee. Thus, in order to prevent a low cost bidder from pretending to have a higher cost, the auction must reward him with enough rents to induce him to truthfully reveal his expected cost. The regulator can reduce the necessary rents by linking higher bids with more severe distortions in the quantity schedule. By introducing such distortions, the regulator punishes the low cost agent for bidding high, since by bidding high the agent receives a franchise contract with greater distortions and, by implication, fewer expected rents next period. Thus, the regulator reduces the cost of sorting the bidders by basing the quantity schedule on the bid, rather than offering the bidders a single quantity-transfer schedule.

The authors find limiting cases in which the optimal contract corresponds to the full-information contract. For example, if the signal is not informative, then the agents have identical expected cost when bidding takes place, and in this case the full-information contract is optimal, as indicated in our discussion of Baron and Myerson. The full-information contract is also optimal in the limit as N becomes infinite, since in this case the probability of one agent having the lowest possible expected cost approaches one and the usual lack of distortion for the lowest cost agent applies.

Laffont and Tirole (1987) extend their analysis of regulation when cost observation is possible to incorporate competition for the contract. The model is identical to that discussed in section one, except that the project involves a fixed quantity of output, and instead of offering the contract to a single supplier with unknown cost, the principal offers a contract to several bidders with independent private values of expected cost. The auction induces the bidders to truthfully reveal their expected costs.

The optimal contract offered to the bidders is identical to the optimal monopoly contract, apart from one important feature. The principal optimally employs information about the second lowest cost, which is revealed in the auction, to reduce the information rents of the winning bidder. The logic behind this result is as follows. Without using the information provided by the second most efficient bidder, the principal pays the winning agent rents equal to the difference between the highest possible cost and his cost report to induce truthful revelation. Consider the alternative scheme, whereby the principal pays the agent rents equal to the difference between the second lowest reported cost and his reported cost. Truthtelling is still a dominant strategy under this scheme, and the winning agent's rents are reduced. Thus, competition improves on the result obtained under monopoly by reducing the transfers associated with the contract, but does not have any fundamental impact on the optimal incentive scheme.

For whatever reason, the contracts used in practice are considerably less complex than those considered above. In contrast to the optimal linear contract of Laffont and Tirole, the cost sharing parameter of an incentive contract typically does not vary with the firm's reported cost. Procurement auctions are generally conducted according to the following simple procedure. The government advertises a project, announcing a cost sharing parameter which indicates the fraction of 'cost overruns' that will be borne by the government.[13] Firms submit their bids and the low bidder is selected to perform the project. The selected firm's compensation is equal to the winning bid, plus an ex post adjustment proportional to the 'cost overrun', which is the difference between the realized cost of the project and the bid.

McAfee and McMillan (1986) consider a model in which risk-averse firms with independent private values compete in an auction for a linear incentive contract. The project is of fixed size, and the bidders possess independent private values of the expected cost of the project prior to the auction. The realized cost of the project, observed costlessly and without error by the principal ex post, depends on a random cost disturbance and unobservable effort provided by the agent. The contract offered by the principal consists of a fixed cost sharing parameter indicating the share of cost overruns to be borne by the principal. McAfee and McMillan show that the optimal contract reimburses a strictly positive fraction of overruns. In this case, the principal trades off the efficiency of effort both to limit the informational rents of the winning bidder and to insure the producer with respect to cost risk.

Overview of the Second Essay

A recurring theme in the models above is the tradeoff between adverse selection and moral hazard which arises when ex post cost observation is employed to regulate the agent. Without exception, the models involving moral hazard assume that the principal obtains ex post cost information without incurring any auditing cost. If monitoring is costly, the cost sharing provisions employed to reduce informational rents will induce the principal and agent to act strategically ex post. The principal will choose whether to incur the monitoring cost, or simply base cost reimbursement on cost data furnished by the firm ex post. The firm will choose between truthfully reporting cost performance ex post, or falsifying its cost data. The implications of cost sharing for the ex post incentives of the principal and agent should be taken into account when evaluating the potential benefits of cost sharing.

The second essay analyzes the optimal incentive contract to offer to risk-neutral bidders with independent private values when it is costly to observe the agent's cost performance ex post. Cost sharing reduces the informational rents of the winning bidder, but decreases the agent's cost reducing effort and gives the agent an incentive to pad his report of realized cost ex post. As in Khalil, it is assumed that the principal cannot commit to a monitoring policy ex ante. If the principal could commit, he would promise not to monitor ex ante, and the gains from ex post cost padding would be eliminated in the bidding competition. Without commitment, the principal and agent play a two-stage game ex post in which the agent reports his realized cost and the principal makes a monitoring decision based on the agent's report.

It is shown that a low cost agent will overstate his realized cost with positive probability ex post, and that both pooling (no monitoring) and mixed strategy equilibria are possible depending upon the cost sharing parameter. Low sharing parameters induce pooling while high sharing parameters yield a mixed strategy outcome, in which the principal randomizes between monitoring and not monitoring and the agent randomizes between cheating and truthtelling.

The optimal contract generally differs from the contract which is optimal if monitoring is costless. In the pooling case, the optimal sharing parameter is weakly smaller than the optimal cost sharing parameter given costless monitoring. In the mixed strategy case, the optimal cost sharing parameter under costly monitoring is strictly larger than the optimal parameter when monitoring is costless.

The principal chooses the cost sharing parameter so that the marginal gain from reducing the winning bidder's informational rents is matched by the marginal loss from reduced effort and from the ex post misreporting of the agent. Monitoring plays a somewhat different role in this model than it does in the models of Baron and Besanko or Khalil, who also consider costly monitoring. In our model, the principal monitors in order to reduce the cost of the <u>ex post</u> private information problem that arises when cost sharing is employed to reduce the ex ante informational rents of the winning bidder.

Footnotes

1. See Gansler (1989).

2. It should be noted that the principal-agent model does not assume that the agent is a monopolist. Instead, the agent receives an exogenous level of utility which is determined either through prior competition or negotiation.

3. According to the revelation principle, the optimal outcome can be implemented with a scheme which induces the agent to report truthfully.

4. The full-information level of output is produced in the lowest cost state, because output distortion in the low cost state cannot possibly affect the incentives of a lower cost agent.

5. The support of the cost distribution is assumed to be independent of the state. Otherwise the principal might implement the full information outcome using a forcing contract.

6. Baron and Besanko assume that this is accomplished either via legislative means, or that the repeated nature of the game for the principal makes it desirable to establish and maintain a reputation for carrying out the announced policy.

7. The critical level for observed cost corresponds to the maximum likelihood estimator of realized cost, given reported cost. Note that the agent may be penalized although he reports truthfully if he draws an exceptionally low cost.

8. The agent's effort will be efficient, given the level of output. However, since the level of output is smaller than the first-best level, the agent's effort will be as well.

9. In Khalil's model, the audit reveals the state of nature so that this type of problem would not arise.

10. The cost disturbance may represent either a forecast error by the firm, or a cost observation error by the regulator. Given the risk neutrality of the parties, either interpretation gives the same results.

11. As in previous models, the optimal contract involves underproduction as well.

12. In general, the optimal contract is not linear when the agent is risk-averse, although linearity of the optimal scheme has been demonstrated for some special cases. See Holmstrom and Milgrom for an example involving risk aversion and moral hazard.

13. There may also be a 'target profit', which is generally some specified fraction of the bid, but this does not affect the agent's incentives so it is ignored in subsequent analysis.

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Chapter 2

Contracting for Procurement: Risk Aversion, Pre-production Investment and Private Information

I. *Introduction*

The defense procurement process has recently become the subject of a fair amount of theoretical research. The problem faced by the Defense Department when it sets out to buy a new weapon system presents an interesting and complicated set of issues for economic investigation. Much of the work in this area has followed in the tradition set by the regulation literature, particularly that of Baron and Myerson (1982), and Laffont and Tirole (1986). Baron and Myerson examine the problem of a government regulator who faces a risk-neutral monopolist with private information about his production cost. They demonstrate that when a monopolist possesses such private information, the regulator is unable to implement the 'full-information' outcome. To prevent the monopolist from misrepresenting his cost, the regulator rewards the firm with rents if it admits that cost is low. If the firm claims that cost is high, the regulator chooses an artificially low level of output for the firm. This distortion of output below the full-information level serves to reduce the information rents paid to the firm if cost is low. Laffont and Tirole describe the further complications that arise when the firm can take some unobservable, costly action to reduce cost during the production process.

Many of the problems encountered in defense procurement are similar to those which arise in the context of regulation. Although the government has recently taken steps to introduce more competition into the procurement process (for example, by developing a second-source for some systems), the military still often finds itself with only one supplier foran item. This producer often obtains private information while working on the project, and can influence the cost outcome by taking an unobservable action. In addition to these problems, a third factor complicates this bilateral monopoly relationship. New weapon systems attempt to integrate the latest technology, so both the contractor and the government face a high degree of cost uncertainty. Because large sums of money are involved, the presence of this non-diversifiable technical risk causes risk aversion on the part of the firm to become an important issue affecting contract design.

In practice, risk does appear to be an important factor influencing the design of procurement contracts. The production contracts for weapon systems are often "linear incentive contracts". Under such a contract, the firm receives a fixed payment, and is reimbursed for a fraction of its realized costs. Though partial cost reimbursement interferes with the firm's incentive to engage in cost reducing activity, it helps to insure the firm with respect to the cost risk that is still present as the system is taken from the development stage into production. The greater the degree of perceived risk, the higher the portion of costs borne by the government. For example, the Navy has been using an incentive contract with 50% cost sharing to procure its DDG-51 Class destroyers. However, recently the ship's design has been upgraded to include new 'stealth' technology. Since this has increased the technical risk associated with the project, the Navy is currently considering raising cost reimbursement to 80%.

The purpose of this paper is to investigate the outcome of the contracting problem, when both contracting and the firm's action to reduce the cost outcome take place in an environment of cost uncertainty. Our model incorporates elements of adverse selection and moral hazard. We assume that the government offers a linear incentive contract to a single, risk-averse supplier. The government and the firm possess identical information about cost when contracting takes place.[1] The firm privately learns production cost following an initial period of work, during which it invests in cost reduction. After reporting to the government concerning its production cost, the firm undertakes full-scale production according to the terms of the contract. The government's output decision is based on the firm's cost announcement. The government's eventual payment to the firm is based on this cost announcement, and on a cost signal observed by the government after production. Figure 1(a) illustrates the timing of the actions and arrival of information in our model.

The assumption that contracting takes place before the firm learns the state of nature is meant to capture the fact that a great deal of cost uncertainty remains even after system production has begun. Numerous unforseeable problems with design are typically encountered during production of the initial units. These often have a significant impact on total cost, making ex ante cost estimation very difficult.[2] In this connection, note the importance of our assumption that the firm is risk-averse. As is well-known, if an agent is risk-neutral and information is symmetric when contracting takes place, the principal can implement the full-information outcome by offering a contract which makes the firm a 'residual claimant'. When the firm is risk averse, this nice solution is no longer feasible, since such a contract must be accompanied by a risk premium. The government can eliminate this premium by insuring the firm's profit, however, it then can no longer guarantee that the firm's production and effort decisions will be efficient.

Our assumption that effort is chosen before cost is learned and reported reflects the fact that in the real world, a contractor's production costs are largely determined by planning and design work which take place early in the procurement program. The several analyses of procurement related to ours (in that they also consider adverse selection and moral hazard together) assume that the firm is informed when contracting takes place and chooses effort after uncovering its private information. For example, in Baron and Besanko's (1988) model, the government offers a linear contract to a single, risk-averse supplier with private information about the expected cost of production.[3] After accepting the contract, the firm submits a cost announcement, chooses effort and produces output. The firm's compensation can depend both on its cost announcement and on a post-production cost signal. Figure 1 (b) illustrates the timing of events in Baron and Besanko's model.

Because the firm possesses private information about cost when offered the contract, the principal problem for the government in this model is to choose a contract that limits the firm's information rents while maintaining incentives for a socially desirable level of effort. The government does this by choosing a contract that partially reimburses the firm's cost, based on the realization of the signal. This cost sharing reduces the information rents which the firm receives.[4] Risk aversion plays a secondary role in this analysis, since the basic cost sharing result is driven by the presence of private information rather than risk.

Baron and Besanko also find that the agent may either over- or underprovide effort under the optimal contract. The inability to obtain a general prediction regarding effort stems from the fact that when effort is chosen after the firm learns cost, additional effort may either improve or worsen the adverse selection problem, depending upon the properties of the cost function.[5] If effort significantly worsens the private information problem, the firm may actually provide more effort than preferred by the government under the optimal contract.

By way of contrast, our model produces the intuitively appealing result that the firm unambiguously provides too little effort under the optimal contract. The intuition behind this result is as follows. By the time the firm in our model discovers its production cost, effort has taken on the characteristics of a sunk, match-specific investment. The presence of this up-front investment discourages the firm from overstating its production cost to the government. Thus, effort has a beneficial effect on the adverse selection problem; it reduces the government's cost of eliciting a truthful report from the firm. Since the firm does not take such 'informational benefits' into account when choosing effort, it provides less effort than the government would prefer under the optimal contract.

The remainder of the paper is organized as follows. Section II sets up the procurement problem and presents the firm's and government's objectives. Section III discusses two special cases: the case of perfect cost information and observable effort, and the case of asymmetric cost information with observable effort. Building on this analysis, section IV characterizes the optimal contract when cost information is asymmetric and effort is unobservable. Section V summarizes our results and places them within the context of the related literature.

II. *A Model of Procurement under Uncertainty*

When weapon system development is completed, or near completion, the government is confronted with the problem of contracting for production with a sole-source, risk averse supplier. In our model, the government makes a take-it-or-leave-it contract offer to the firm for the production of a quantity of output, denoted by q. The government's valuation of the output is represented by a continuous, twice-differentiable function $V(q)$, with $V'(q)>0$ and $V''(q)<0$.[6]

The firm's total cost of producing output is $C = c(e,i)q$, where fixed costs are deterministic and normalized to zero, and marginal cost $c(e,i)$ is independent of the quantity of output. The firm's marginal cost depends on the realization of a random variable, i, representing the firm's 'cost type'. We consider the case of binary uncertainty; cost may turn out to be either 'high' (i=H) or 'low' (i=L). Cost also depends on the firm's provision of effort, e, which is unobservable to the government. Marginal cost is assumed to be twice-differentiable with respect to e, with $c_e(e,i)<0$ and $c_{ee}(e,i)\geq 0$.

The government cannot directly observe the true cost of production, even ex-post. However, it performs a post-production audit and obtains a verifiable signal about total cost, $s_i = c(e,i)q + \eta$, where η is a normally distributed random variable with zero mean and variance σ^2. (The random variable η represents measurement error, and is assumed to be uncorrelated with the state of nature i). The firm's compensation, P, is a linear function of the signal, written as $P = a + bs_i$.[7]

The government and the firm are uninformed about the state of nature when contracting takes place. They are endowed with identical prior beliefs about cost, represented by the probabilities of high and low costs, p_H and p_L respectively. These beliefs are 'common knowledge'. The government offers the firm a contract $<a_{\hat{i}}, b_{\hat{i}}, q_{\hat{i}}>$, which consists of a lump-sum payment, cost-sharing parameter, and quantity of output for each possible cost report of the firm. (The index $\hat{i}$ denotes announced cost, so if the firm truthfully reports cost then $\hat{i} = i$).

If the firm accepts the offer, then the action proceeds as follows. First, the firm performs some preliminary work prior to starting full-scale production.[8] This involves tooling up for production, and producing and testing initial units of the system. The firm can take effort at this stage in order to achieve lower production costs. Also, during this preliminary phase the firm privately learns its true cost state, H or L. When this work is complete, the firm sends a cost report to the government ($\hat{i} = H$ or L), and full-scale production takes place according to the terms of the contract. Finally, output is exchanged, the government audits the firm, observing s_i, and payments are made.

The Firm's Problem

The firm has two choices to make after signing a contract. It must first decide how much effort to invest in cost reducing activities. Later, after learning i, the firm must choose to report either high or low costs. The firm's 'utility' depends on gross profit π, and effort, and is assumed to have the following functional form:

$$\mathrm{U}(\pi, e) = 1 - \exp\{-\rho\pi\} - \phi(e)$$

The constant $\rho > 0$ measures absolute risk aversion. The term $\phi(e)$ represents the disutility of effort, and has the properties $\phi(0) = 0$, $\phi'(e) > 0$, and $\phi''(e) \geq 0$.

First, we consider the choice of a cost report by the firm. The firm's profit in state i when cost $\hat{i}$ is reported is denoted by $\pi_{\hat{i}/i}$. Since compensation takes place according to the linear scheme described above, the mean and variance of profit are:

$$E(\pi_{\hat{i}/i}) = a_{\hat{i}} - (1 - b_{\hat{i}})c(e,i)q_{\hat{i}} \qquad \text{and} \qquad \mathrm{Var}(\pi_{\hat{i}/i}) = b_{\hat{i}}^2\sigma^2$$

Because the measurement error η is normally distributed, the firm's expected utility (after learning its cost type i), can be expressed as the following function of the mean and variance of profit:

$$E_\eta[U(\pi_{\hat{i}/i}\ , e)] = 1 - \exp\{-\rho\ [a_{\hat{i}} - (1 - b_{\hat{i}})\ c(e,i)q_{\hat{i}} - \tfrac{1}{2}\rho b_{\hat{i}}^2\sigma^2]\} - \phi(e) \tag{1}$$

Letting $\gamma(x) = 1 - \exp\{-\rho\ [x]\}$, we can rewrite (1) as:

$$E_\eta[U(\pi_{\hat{i}/i}\ , e)] = \gamma(a_{\hat{i}} - (1 - b_{\hat{i}})\ c(e,i)q_{\hat{i}} - \tfrac{1}{2}\rho b_{\hat{i}}^2\sigma^2) - \phi(e) \tag{2}$$

The firm chooses the cost report $\hat{i}$ in order to maximize expected utility. Since $\gamma'(x) > 0$ this is equivalent to maximizing:

$$[a_{\hat{i}} - (1 - b_{\hat{i}})\ c(e,i)\ q_{\hat{i}} - \tfrac{1}{2}\rho b_{\hat{i}}^2\sigma^2] \equiv Y_{\hat{i}/i}$$

$Y_{\hat{i}/i}$ is the certainty equivalent of expected profit for the type i firm which reports type $\hat{i}$, and the term $\frac{1}{2}\rho b_{\hat{i}}^2\sigma^2$ is the risk premium. For instance, $Y_{H/L}$ represents the certainty equivalent for the low-cost firm if it reports high cost, while $Y_{L/H}$ is the certainty equivalent for the high cost firm if it misreports. Let Y_L and Y_H denote the certainty equivalent if the firm truthfully reports cost in the low cost and high cost state, respectively. The firm chooses effort before learning the state of nature. Therefore e is chosen to maximize *ex ante* expected utility, which is given by:

$$\sum_{i=H,L} p_i E_\eta[U(\pi_{\hat{i}/i}, e)] = \sum_{i=H,L} p_i\ [\gamma(a_{\hat{i}} - (1 - b_{\hat{i}})\ c(e,i)q_{\hat{i}} - \tfrac{1}{2}\rho b_{\hat{i}}^2\sigma^2)] - \phi(e) \tag{3}$$

The Government's Problem

Using the revelation principle (Myerson, 1979), the optimal contract is contained in the set of contracts which elicit a truthful cost announcement from the firm.[9] We therefore can restrict our attention to contracts which base the output and compensation parameters on the firm's true cost. The government's problem then is to find the contract $<a_i, b_i, q_i>$ which maximizes its expected surplus,

$$\sum_{i=H,L} p_i \left[V(q_i) - (a_i + b_i\, c(e,i)\, q_i)\right] \tag{4}$$

subject to the following constraints:

$$a_L - (1 - b_L)\; c(e,L)q_L - \tfrac{1}{2}\rho b_L^2\sigma^2 \;\geq\; a_H - (1 - b_H)\; c(e,L)q_H - \tfrac{1}{2}\rho b_H^2\sigma^2 \tag{5a}$$

$$a_H - (1 - b_H)\; c(e,H)q_H - \tfrac{1}{2}\rho b_H^2\sigma^2 \;\geq\; a_L - (1 - b_L)\; c(e,H)q_L - \tfrac{1}{2}\rho b_L^2\sigma^2 \tag{5b}$$

$$p_H\; \gamma(Y_H) + p_L\; \gamma(Y_L) - \phi(e) \geq\; \pi_A \tag{6}$$

$$-p_H\gamma'(Y_H)c_e(e,H)(1 - b_H)q_H - p_L\gamma'(Y_L)c_e(e,L)(1 - b_L)q_L - \phi'(e) = 0 \tag{7}$$

The inequalities (5a) and (5b) are the truthtelling or incentive compatibility constraints for the two possible cost realizations. Constraint (6) guarantees that the expected utility associated with the contract is at least equal to what the firm can earn if it does not accept the offer (π_A).[10] Constraint (7) is required because the government cannot observe the firm's effort directly and therefore cannot specify effort in the terms of the contract. Therefore in choosing the contract, the government must take into account that the firm will choose its effort to maximize expected utility. Equation (7) is the first-order condition from the firm's maximization problem.

The severity of the moral hazard problem depends on the values of b_H and b_L. For example, if $b_H = b_L = 1$ (a 'cost plus fixed fee' contract), then the government receives the benefits of any cost reduction, and so the firm will not provide any effort. On the other hand, under a "fixed-price" contract ($b_H = b_L = 0$) all the cost savings from effort accrue directly to the firm, and so the moral hazard problem disappears. In fact, it follows from condition (7) that if b_H and b_L are increased, while expected utility is held constant (by reducing a_H and a_L appropriately), then the firm's effort will fall.

Before proceeding to the solution of (4) - (7), we first look at the optimal contracts in two related settings. After describing the properties of the perfect information (first-best) contract, we derive the optimal contract in case the government can observe effort, but not the state of nature. These two special cases provide some insight concerning the solution to our problem.

III. *Special Cases*

Case 1: *Firm and Government Jointly Observe i*

Suppose that effort is observable, and that the government learns the state of nature along with the firm (after the contract has been signed, and effort has been taken). Formally, the government chooses $<a_i, b_i, q_i>$ and e to maximize (4) subject to (6). This 'first-best' contract has the following properties:

1) $b_H{}^* = b_L{}^* = 0$

2) $\gamma(Y_H) = \gamma(Y_L) = \phi(e^*) + \pi_A$

3) $V'(q_H{}^*) = c(e^*,H)$ and $V'(q_L{}^*) = c(e^*,L)$

4) $-p_H\ c_e(e^*,H)\ q_H{}^* - p_L\ c_e(e^*,L)\ q_L{}^* = \dfrac{\phi'(e^*)}{\gamma'(Y_L)}$

When information is symmetric, the only relevant concern in choosing the contract is optimal sharing of risk. Because the government is risk neutral with respect to the payment it makes to the firm, the optimal contract will fully insure the firm's compensation. For this reason, the contract guarantees the firm the same level of utility in each state of nature (property 2). Risk sharing concerns also imply that $b_H{}^* = b_L{}^* = 0$. When the government observes the state of nature, it clearly prefers to base the firm's payment on this information rather than on the signal s_i (as long as $\sigma^2 > 0$).[11] At the chosen output levels $q_H{}^*$ and $q_L{}^*$, the benefit and cost of an additional unit of output are equal. Effort is chosen by the government so that the expected cost saving from an increase in effort is equal to the marginal disutility of effort (expressed in monetary terms).

Clearly, the 'first-best' results carry over if the government observes the state of nature but cannot observe the firm's effort. The government will choose the contract $<a_i^*,\ b_i^*,\ q_i^*>$. The fixed-price contract which shares risk optimally also ensures that the firm fully internalizes the benefits from effort, therefore the firm will choose $e = e^*$.

Case 2: Firm Privately Observes i; Effort Observable Solution

Suppose now that after signing the contract and taking effort, the firm privately learns the state of nature. In order to focus on the interaction between adverse selection and risk aversion, we assume for the time being that effort is observable. The government's problem in this case is to choose $<a_i,\ b_i,\ q_i>$ and e to maximize (4) subject to constraints (5) and (6). We will use $<\tilde{a}_i,\ \tilde{b}_i,\ \tilde{q}_i>$ and $\tilde{e}$ to represent the optimal values of the choice variables. The Lagrangian for this problem is:

$$\mathcal{L} = p_H\ [\mathrm{V}(q_H) - a_H - b_H c(e,H) q_H] + p_L\ [\mathrm{V}(q_L) - a_L - b_L c(e,L)\ q_L] + \tag{8}$$
$$\theta\ \{a_L - (1 - b_L)\ c(e,L)\ q_L - \tfrac{1}{2}\rho b_L{}^2\sigma^2 - [a_H - (1 - b_H)\ c(e,L)\ q_H - \tfrac{1}{2}\rho b_H{}^2\sigma^2]\ \} +$$
$$\mu\ \{p_H\ \gamma(\mathrm{Y}_H) + p_L\ \gamma(\mathrm{Y}_L) - \phi(e)\ \}$$

The incentive compatibility constraint which prevents the high cost firm from understating costs has been omitted, since we can show that it never binds at the optimum. The multiplier θ is associated with constraint (5a) and represents the marginal value to the government of a decrease in the low cost firm's potential gains from misrepresenting cost. The multiplier μ measures the value to the government (in dollar terms) of a small increase in firm utility.

As a first step in characterizing the solution to this problem, we demonstrate that the incentive compatibility constraint must be binding at the optimum ($\theta > 0$). To show this, we assume the contrary, that the constraint is non-binding, and then obtain a contradiction. So suppose that:

$$\tilde{a}_L - (1 - \tilde{b}_L)\ c(\tilde{e},L)\ \tilde{q}_L - \tfrac{1}{2}\rho\tilde{b}_L^2\sigma^2\ > \tilde{a}_H - (1 - \tilde{b}_H)\ c(\tilde{e},L)\ \tilde{q}_H - \tfrac{1}{2}\rho\tilde{b}_H^2\sigma^2 \tag{9}$$

Consider the following change to the contract. The government raises a_H and lowers a_L slightly, so that (9) still holds, and so that:

$$da_L = \frac{-p_H}{p_L}\ da_H - \epsilon \qquad (\epsilon > 0) \tag{10}$$

Changing payments in this manner makes the government better off, since total expected lump-sum payments to the firm ($p_H a_H + p_L a_L$) fall by $p_L\epsilon$. Next, consider the effect of this new policy on the firm's utility. Expected utility changes by:

$$p_H\ \gamma'(\mathrm{Y}_H)\ da_H + p_L\ \gamma'(\mathrm{Y}_L)\ da_L$$

which, given (10), simplifies to:

$$p_H\ [\gamma'(\mathrm{Y}_H) - \gamma'(\mathrm{Y}_L)]\ da_H - \epsilon p_L\gamma'(\mathrm{Y}_L) \tag{11}$$

To sign this expression, note that (9) together with the fact that $c(e,H) > c(e,L)$ implies that:

$$\tilde{a}_L\text{-}(1\text{-}\tilde{b}_L)c(\tilde{e},L)\tilde{q}_L\text{-}\tfrac{1}{2}\rho\tilde{b}_L^2\sigma^2 > \tilde{a}_H\text{-}(1\text{-}\tilde{b}_H)c(\tilde{e},H)q_H\text{-}\tfrac{1}{2}\rho\tilde{b}_H^2\sigma^2$$

Since $\mathrm{Y}_L > \mathrm{Y}_H$, $\gamma'(\mathrm{Y}_H) > \gamma'(\mathrm{Y}_L)$ and (11) is positive provided ϵ is not too big. Although the firm's expected profits have fallen by $p_L\epsilon$, by raising a_H and decreasing a_L the government more fully insures the firm, and so its expected utility increases. Since the new policy makes both the government and the firm better off, the original contract could not have been optimal, and we have a contradiction. Therefore the incentive compatibility constraint must bind at the optimum.

The above proof demonstrates that the incentive compatibility constraint binds as a direct consequence of the firm's risk aversion. To encourage the contractor to submit a truthful cost report, there must be a profit differential between the high and low cost states. If the firm is risk averse, the government wants to make this difference in profits across states as small as possible. By doing so, the government minimizes the risk-premium required to induce the firm to accept the contract.

The optimal contract in this case has the following properties:

$$\tilde{b}_L = 0, \;\; 0 < \tilde{b}_H \leq 1 \tag{12a}$$

$$V'(\tilde{q}_L) = c(\tilde{e},L) \tag{12b}$$

$$p_H[V'(\tilde{q}_H) - c(\tilde{e},H)] = \theta\,[c(\tilde{e},H) - c(\tilde{e},L)](1 - \tilde{b}_H) \tag{12c}$$

$$- p_H c_e(\tilde{e},H)\tilde{q}_H - p_L c_e(\tilde{e},L)\,\tilde{q}_L - \theta[c_e(\tilde{e},H) - c_e(\tilde{e},L)](1-\tilde{b}_H)\tilde{q}_H = \mu\phi'(\tilde{e}) \tag{12d}$$

Property (12a) indicates that the firm's compensation in the high cost state is at least partially based on observed cost ($b_H>0$). The intuition behind this result follows from the discussion above. We argued that the government would like to insure the firm fully against the uncertainty associated with the state of nature (hereafter referred to as 'cost risk'). Put differently, the government would like to set $Y_L = Y_H$. However, given the incentive compatibility constraint the best that the government can do is to choose the contract so that:

$$Y_L = Y_{H/L} = a_H - (1 - b_H)\; c(e,L)\; q_H - \tfrac{1}{2}\rho b_H^2\sigma^2 > Y_H$$

The difference between Y_L and Y_H is then:

$$Y_L - Y_H = [c(e,H) - c(e,L)]\;(1 - b_H)\; q_H \tag{13}$$

The difference between the certainty equivalents, Y_L- Y_H, measures the degree of exposure to cost risk that is necessary to induce revelation. All other things equal, the larger this difference, the greater the risk premium that must accompany the contract. (In particular, notice that by comparing the certainty equivalents, we are ignoring for now the second type of risk, that which is introduced by basing payment on the signal). Expression (13) shows that the amount of cost risk associated with the contract depends on the parameters b_H, q_H, and e. By increasing b_H or decreasing q_H the government can reduce the amount of cost risk which accompanies an incentive compatible contract. The relationship between effort and cost risk is ambiguous and will be discussed further below.

Expression (13) indicates that incentive compatibility and full insurance against cost risk can be accomplished simultaneously by setting $b_H = 1$. However, such a policy will not generally be optimal, because the government's cost observation is noisy. While increasing b_H more fully insures the firm with respect to cost risk, it also increases the firms exposure to the risk associated with the signal, s_i. This tradeoff between the two types of risk is reflected in the first-order condition for b_H, which after some manipulation can be written as:

$$\frac{\partial \mathcal{L}}{\partial b_H} + \frac{\partial \mathcal{L}}{\partial a_H} \cdot \frac{\partial a_H}{\partial b_H} |_{\mathrm{Y_H}} = \theta[c(e,H) - c(e,L)]\, q_H - p_H \rho b_H \sigma^2 = 0 \tag{14}$$

Condition (14) represents the gains to increasing b_H, while adjusting lump sum transfers to keep the firm's expected utility constant in state H. The first term reflects the fact that increasing b_H makes the incentive compatibility constraint less binding by reducing the cost risk which must be borne by the firm. The second term measures the increase in the risk premium required to compensate the firm for the variance in income associated with the signal. It follows from (14) that $\tilde{b}_H > 0$. It can also be shown that as long as $\sigma^2 > 0$, then $\tilde{b}_H < 1$. On the other hand if the signal is perfect, the optimal contract fully insures the firm against cost risk, that is, $\tilde{b}_H = 1$ and the 'first-best' outcome is obtained.

Expression (13) indicates that the firm's exposure to cost risk is independent of the contract parameters for the low cost state, which explains why $\tilde{b}_L = 0$. Making $b_L > 0$ needlessly exposes the firm to risk stemming from the randomness in the cost signal. Also, since changing q_L cannot mitigate risk, $\tilde{q}_L$ is chosen to equate the marginal benefit and marginal cost of production. On the other hand, the amount of cost uncertainty borne by the firm varies directly with q_H. Therefore as (12c) indicates, at $\tilde{q}_H$ the benefit of an additional unit of output exceeds the cost. 'Underproduction' in the high cost state is used as another means to more fully insure the firm.

Additional effort may serve to either increase or reduce the cost risk associated with incentive compatibility. Expression (13) reveals that effort's effect on cost risk depends upon the sign of $[c_e(e,H) - c_e(e,L)]$. Suppose that effort is equally effective in the two states of nature, that is $|c_e(e,H)| = |c_e(e,L)|$. In this case, greater effort neither increases nor reduces the firm's exposure to cost uncertainty. Thus, property (12d) indicates that at $\tilde{e}$, the expected cost saving from additional effort will be equal to the marginal disutility of effort (measured in dollars). On the other hand if effort is more effective in the high cost state, i.e. $|c_e(e,H)| > |c_e(e,L)|$, then it may be used as a tool to reduce the firm's exposure to cost uncertainty. In this case, the effort chosen by the government will strictly exceed the level at which expected cost savings and the marginal disutility of effort are equal. Conversely, if $|c_e(e,H)| < |c_e(e,L)|$ then the effort chosen by the government will fall short of this level.

Comparing $\tilde{e}$, $\tilde{q}_H$, and $\tilde{q}_L$ with the first-best effort and output levels, we see that when $|c_e(e,H)| \leq |c_e(e,L)|$, the adverse selection problem causes the government to distort both q_H and e downward. Therefore, we can conclude that $\tilde{e} < e^*$, and consequently $\tilde{q}_H$ and $\tilde{q}_L$ are both strictly below their first best levels.[12] When $|c_e(e,H)| > |c_e(e,L)|$, the government distorts q_H downward and effort upward to lessen the adverse selection problem. In this case we cannot infer anything about the relationship between $\tilde{e}$ and e^*.

Finally, we prove one last result concerning $\tilde{e}$ that provides some valuable intuition for the case in which the government cannot observe the firm's effort. Let e^F denote the level of effort that maximizes the firm's utility given the contract $<\tilde{a}_i, \tilde{b}_i, \tilde{q}_i>$. We can show that e^F

$< \tilde{e}$, that is the effort level chosen by the government is strictly greater than that which the firm would choose itself.

To see this, consider the first-order condition for $\tilde{e}$:

$$\frac{\partial \mathcal{L}}{\partial e}=0=-\{p_H \tilde{b}_H c_e(\tilde{e},H)\tilde{q}_H+p_L \tilde{b}_L c_e(\tilde{e},L)\tilde{q}_L\} +\theta[(1-\tilde{b}_H)\tilde{q}_H-(1-\tilde{b}_L)\tilde{q}_L]c_e(\tilde{e},L) +$$
$$\mu \{-p_H \gamma'(Y_H)c_e(\tilde{e},H)(1-\tilde{b}_H)\tilde{q}_H -p_L\gamma'(Y_L)c_e(\tilde{e},L)(1-\tilde{b}_L)\tilde{q}_L - \phi'(\tilde{e})\} \tag{15}$$

The first term in brackets represents the effect of additional effort on the government's payments to the firm. Given that $\tilde{b}_H > 0$ and $\tilde{b}_L = 0$, this term is positive. The term involving θ describes the effect of effort on the private information problem. Since $\tilde{q}_L > (1 - \tilde{b}_H)\tilde{q}_H$, this term is also positive. The last term in brackets reflects the effect of additional effort on the participation constraint. Because the first two terms are positive, it must be the case that at $\tilde{e}$:

$$-p_H\gamma'(Y_H)c_e(\tilde{e},H)(1-\tilde{b}_H)\tilde{q}_H -p_L\gamma'(Y_L)c_e(\tilde{e},L)(1-\tilde{b}_L)\tilde{q}_L- \phi'(\tilde{e})< 0$$

This expression is the first order condition for the firm's effort choice. Thus, the level of effort that the firm would choose must be strictly less than $\tilde{e}$.

Intuitively, there are two reasons why $e^F < \tilde{e}$. First, since $\tilde{b}_H > 0$, the firm receives only a fraction of the cost savings from effort. Second, for reasons described below, effort has a beneficial effect on the private information problem. The firm will fail to take such benefits into account when choosing its optimal e.

The result that effort always helps to ameliorate the private information problem is in itself somewhat interesting, because this is something which is not found in the related literature. The explanation for our result is straightforward. Effort can be thought of as an investment on the part of the firm. Recall that this investment is made before the state of nature becomes known. Until production takes place the actual return on this investment is uncertain as the firm's return to effort depends upon both the state of nature and the quantity of output produced. It also depends upon (1- b_i), the fraction of cost which is not reimbursed by the government. In particular note that given the state of nature, the firm's return to effort increases with output and with (1-b_i).

Now consider the decision faced by the firm which, having taken effort, discovers that the low-cost state of nature prevails. The firm must decide whether to report its true cost state L or to misrepresent its cost state as being H. Since $\tilde{q}_L > (1 - \tilde{b}_H)\, \tilde{q}_H$, the return on the firm's effort investment is higher if it reports cost truthfully than if it misreports.[13] Effort lessens the firm's incentive to overstate cost, because it is a sunk investment whose rate of return increases as announced cost decreases. Thus, as is shown in (15), additional effort unambiguously lessens the severity of the private information problem.

The adverse selection effect just described reinforces the usual "moral hazard" effect, whereby cost sharing causes the agent to underprovide effort. This allows us to conclude with certainty that $e^F < \tilde{e}$. This in turn implies that when effort is unobservable, the contract $<\tilde{a}_i, \tilde{b}_i, \tilde{q}_i>$ and $\tilde{e}$ is not enforceable. It also suggests that when effort is not observable, the firm will provide less effort than the government would like.

IV. *The Optimal Contract with Private Information and Unobservable Effort*

Typically, the government is unable to observe the firm's cost controlling effort, and therefore cannot contract upon e. In this case the government chooses the remaining parameters $<a_i, b_i, q_i>$ bearing in mind that these uniquely determine the level of effort that the firm provides.

Formally, we model the government's decision problem as if the government chooses $<a_i, b_i, q_i>$ and e directly, but we add the constraint that e be incentive compatible for the firm in order to ensure that the contract chosen is a feasible one. That is, e must maximize the firm's expected utility given the other parameters of the contract (constraint 7). We use $<\hat{a}_i, \hat{b}_i,$

$\hat{q}_i>$ and $\hat{e}$ to represent the solution to this problem.

The Lagrangian is:

$$\mathcal{L} = p_H\,[\mathrm{V}(q_H) - a_H - b_H c(e,H) q_H] + p_L\,[\mathrm{V}(q_L) - a_L - b_L c(e,L)\,q_L] +$$

$$\theta\,\{a_L - (1 - b_L)c(e,L)q_L - \tfrac{1}{2}\rho b_L^2\sigma^2 - [a_H - (1 - b_H)c(e,L)q_H - \tfrac{1}{2}\rho b_H^2\sigma^2]\,\} +$$

$$\mu\{p_H\gamma(\mathrm{Y}_H) + p_L\gamma(\mathrm{Y}_L) - \phi(e)\} + \delta\{-p_H\gamma'(\mathrm{Y}_H)c_e(e,H)(1 - b_H)q_H$$

$$- p_L\gamma'(\mathrm{Y}_L)c_e(e,L)(1 - b_L)q_L - \phi'(e)\}$$

where the shadow price of the moral hazard constraint is represented by the multiplier δ. Note that a positive δ implies that given the contract the government would like the firm to take more effort. Conversely, $\delta < 0$ implies that the government would benefit from a lower level of effort, other things the same. From our earlier analysis, it follows immediately that $\delta \neq 0$.[14] Knowing that the government chooses b_H, b_L, q_H, q_L and e to influence the firm's incentives, while the lump-sum payments a_H and a_L are chosen to divide up the gains from production in a way which guarantees that the firm will participate, we can rewrite the first-order conditions in a way that is more easily interpretable:

$$\frac{\partial\mathcal{L}}{\partial b_H}+\frac{\partial\mathcal{L}}{\partial a_H}\cdot\frac{\partial a_H}{\partial b_H}|_{\mathrm{Y_H}}=-p_H\rho\hat{b}_H\sigma^2+ q_H\{\theta[c(\hat{e},H) - c(\hat{e},L)] + \delta p_H\gamma'(\mathrm{Y}_H)c_e(\hat{e},H)\}=0 \tag{16}$$

$$\frac{\partial\mathcal{L}}{\partial q_H} + \frac{\partial\mathcal{L}}{\partial a_H}\cdot\frac{\partial a_H}{\partial q_H}|_{\mathrm{Y_H}}=p_H[\mathrm{V}'(\hat{q}_H)-c(\hat{e},H)] - (1-\hat{b}_H)\{\theta[c(\hat{e},\mathrm{H}) - c(\hat{e},\mathrm{L})] + \delta p_H\gamma'(\mathrm{Y}_H)c_e(\hat{e},H)\}=0 \tag{17}$$

$$\frac{\partial\mathcal{L}}{\partial b_L} + \frac{\partial\mathcal{L}}{\partial a_L}\cdot\frac{\partial a_L}{\partial b_L}|_{\mathrm{Y_L}} = -p_L\rho\hat{b}_L\sigma^2 + \hat{q}_L\delta p_L\gamma'(\mathrm{Y}_L)c_e(\hat{e},L)=0 \tag{18}$$

$$\frac{\partial\mathcal{L}}{\partial q_L} + \frac{\partial\mathcal{L}}{\partial a_L}\cdot\frac{\partial a_L}{\partial q_L}|_{\mathrm{Y_L}}= p_L[\mathrm{V}'(\hat{q}_L) - c(\hat{e},L)] - (1 - \hat{b}_L)\delta p_L\gamma'(\mathrm{Y}_L)c_e(\hat{e},L)=0 \tag{19}$$

$$\frac{\partial \mathcal{L}}{\partial e} + \frac{\partial \mathcal{L}}{\partial a_L} \cdot \frac{\partial a_L}{\partial e} \Big|_{Y_L} + \frac{\partial \mathcal{L}}{\partial a_H} \cdot \frac{\partial a_H}{\partial e} \Big|_{Y_H} = \tag{20}$$

$$- p_H c_e(\hat{e},H)\hat{q}_H - p_L c_e(\hat{e},L)\hat{q}_L - \theta[c_e(\hat{e},H) - c_e(\hat{e},L)](1-\hat{b}_H)\hat{q}_H - \mu\phi'(\hat{e}) -$$

$$\delta\ \{\ p_H\gamma'(Y_H)c_{ee}(\hat{e},H)(1 - \hat{b}_H)\hat{q}_H + p_L\gamma'(Y_L)c_{ee}(\hat{e},L)(1 - \hat{b}_L)\hat{q}_L + \phi''(\hat{e})\ \}=0$$

Conditions (16) - (20) show the gains to increasing b_H (respectively q_H, b_L, and q_L and e) while adjusting lump sum transfers to keep expected utility in each state constant. These gains must be zero at the optimum, since otherwise the government can alter the contract so as to make itself better off without making the firm any worse off.

According to (16) and (17), the values of b_H and q_H depend upon the sign of the common expression:

$$Z \equiv \{\theta[c(e,H) - c(e,L)] + \delta p_H\gamma'(Y_H)c_e(e,H)\}$$

Z measures the net cost of the moral hazard and adverse selection problems. In the previous section, we demonstrated that the government can reduce the firm's exposure to cost risk by increasing b_H or reducing q_H. The gain from a marginal change in either of these variables is measured by the first term in brackets. However, raising b_H or lowering q_H now effects the firm's preferred effort level, causing it to fall. The second term of Z measures this moral hazard effect. (Note that if $\delta > 0$ the decrease in effort is costly for the government, whereas if $\delta < 0$ it is beneficial). Thus, $Z > 0$ if the gain from alleviating the private information problem exceeds the loss from aggravating the moral hazard problem (or if $\delta < 0$ so that both problems are lessened by raising b_H and/or lowering q_H). A negative Z implies that the gain from lessening the private information problem is smaller than the loss from making the moral hazard problem more severe. Conditions (18) and (19) indicate that the values of the low-cost state parameters b_L and q_L depend only upon moral hazard considerations. This is consistent with our earlier finding that these variables do not affect the private information problem.

Clearly, the properties of the optimal contract depend critically on which way the moral hazard constraint binds, as well as on which of the constraints (private information or moral hazard) is more severe. The following proposition is of some help in this regard:

Proposition: Under the optimal contract $<\hat{a}_i, \hat{b}_i, \hat{q}_i>$ and $\hat{e}$, the firm takes less effort than the government would like, i.e. $\delta > 0$.

Proof: First, note that the firm's chosen effort level solves:

$$\frac{\partial \mathcal{L}}{\partial \delta} = -p_H \gamma'(Y_H) c_e(e,H)(1-\hat{b}_H)\hat{q}_H - p_L \gamma'(Y_L) c_e(e,L)(1-\hat{b}_L)\hat{q}_L - \phi'(e) = 0$$

Substituting this into the first order condition for optimal effort we obtain:

$$\begin{aligned}\frac{\partial \mathcal{L}}{\partial e} = 0 = &-\{p_H \hat{b}_H c_e(e,H)\hat{q}_H + p_L \hat{b}_L c_e(e,L)\hat{q}_L\} + \theta\,[\,(1 - \hat{b}_H)\hat{q}_H - (1 - \hat{b}_L)\hat{q}_L] c_e(e,L) + \\ &\delta\,\{-p_H \gamma'(Y_H) c_{ee}(e,H)(1 - \hat{b}_H)\hat{q}_H - p_L \gamma'(Y_L) c_{ee}(e,L)(1 - \hat{b}_L)\hat{q}_L - \phi''(\hat{e}) \\ &p_H \gamma''(Y_H)[c_e(e,H)(1 - \hat{b}_H)\hat{q}_H]^2 + p_L \gamma''(Y_L)[c_e(e,L)(1 - \hat{b}_L)\hat{q}_L]^2\} \qquad (21)\end{aligned}$$

The first two terms are familiar from the previous section. They represent effort's effect on the government's payments, and on the private information problem, respectively. The third term is just the second order condition for the firm's effort choice.

We will prove that $\delta > 0$ by contradiction. Suppose that $<\hat{a}_i, \hat{b}_i, \hat{q}_i>$ and $\hat{e}$ is an optimal contract with $\delta < 0$. Conditions (16) and (18) indicate that if $\delta < 0$, then both $\hat{b}_H$ and $\hat{b}_L$ are strictly positive. Therefore, the first term of (21) is also strictly positive. The third term of $\frac{\partial \mathcal{L}}{\partial e}$ is positive as well since the second order condition and δ are both negative. Now, if we can show that the second term of (21) is non-negative, then $\frac{\partial \mathcal{L}}{\partial e} > 0$ and we will have obtained a contradiction. This term is non-negative provided that $(1 - \hat{b}_H)\hat{q}_H \leq (1 - \hat{b}_L)\hat{q}_L$.[15]

Recall that any solution to our problem must satisfy the two incentive compatibility constraints:

$$a_L - (1 - b_L)\ c(e,L)q_L - \tfrac{1}{2}\rho b_L^2\sigma^2 \ \geq\ a_H - (1 - b_H)\ c(e,L)q_H - \tfrac{1}{2}\rho b_H^2\sigma^2$$

$$a_H - (1 - b_H)\ c(e,H)q_H - \tfrac{1}{2}\rho b_H^2\sigma^2 \ \geq\ a_L - (1 - b_L)\ c(e,H)q_L - \tfrac{1}{2}\rho b_L^2\sigma^2$$

By adding these constraints together, it is easy to see that a necessary condition for both of them to be satisfied is that $(1 - \hat{b}_H)\hat{q}_H \leq (1 - \hat{b}_L)\hat{q}_L$. It follows immediately that:

$$\frac{\partial \mathcal{L}}{\partial e} > 0$$

Because this contradicts our assumption that the contract is optimal, we can conclude that $\delta > 0$ at the optimum.

Using (16) - (20) together with the fact that $\delta > 0$, we can draw the following inferences concerning the optimal contract:

1) $\hat{b}_L < 0$ and $V'(\hat{q}_L) < c(\hat{e}, L)$

2) If $Z > 0$, then $\hat{b}_H > 0$ and $V'(\hat{q}_H) > c(\hat{e},H)$

If $Z = 0$, then $\hat{b}_H = 0$ and $V'(\hat{q}_H) = c(\hat{e},H)$

If $Z < 0$, then $\hat{b}_H < 0$ and $V'(\hat{q}_H) < c(\hat{e},H)$

3) $- p_H c_e(\hat{e},H)\hat{q}_H - p_L c_e(\hat{e},L)\hat{q}_L - \theta[c_e(\hat{e},H) - c_e(\hat{e},L)](1-\hat{b}_H)\hat{q}_H > \mu\phi'(\hat{e})$

Recall that under the first-best contract $b_H{}^* = b_L{}^* = 0$ and $V'(q_i^*) = c(e^*,i)$. When effort is unobservable the government will distort the cost-sharing parameters and output levels in order to elicit more effort from the firm. For the low-cost state, $\hat{b}_L < 0$ and $V'(\hat{q}_L) < c(\hat{e}, L)$ because 'overproduction' and a low cost sharing parameter encourage firm effort. Similarly, the moral hazard problem alone will tend to make $b_H < 0$ and $V'(q_H) < c(e,H)$, but the private information problem works in the opposite direction (recommending 'underproduction' and $b_H > 0$). The results for $\hat{b}_H$ and $\hat{q}_H$ thus depend on whether the adverse selection problem is more or less serious than the moral hazard problem, i.e. whether Z is positive or negative.

If the adverse selection problem is more costly than the moral hazard problem, then Z > 0 and the contract involves cost sharing in the high cost state ($\hat{b}_H > 0$). The expression for Z shows that cost sharing is most likely when the degree of cost uncertainty is high, or when effort is not very effective at reducing cost.[16] If the moral hazard problem is more costly than the adverse selection problem, then Z < 0 and $\hat{b}_H < 0$. A negative b_i has the following interpretation. Not only is the firm fully responsible for covering its cost, as with a fixed price contract, but in addition a proportional tax is levied on the firm's cost. The tax motivates the firm to provide additional effort.

Property three says that at effort level $\hat{e}$, the marginal social benefit of effort (the expected decrease in production costs plus the change in the cost risk borne by the firm), exceeds its marginal cost (the dollar value of effort's disutility). In other words, the government would be willing to pay the firm for the disutility it incurs, if by doing so it could get the firm to increase its effort. This is the precise interpretation of the result that $\delta > 0$.

V. *Conclusion*

Our model of the defense procurement process is a cross between the standard principal-agent model and the standard adverse selection model. Specifically, in our model, the government and a supplier have the same cost information when the production contract is signed, but the supplier subsequently acquires private information about production costs. Our results show that the supplier's attitude toward risk has a significant impact on the optimal contract. If the supplier is risk-averse, the optimal output, effort, and cost-sharing parameters will differ from their full-information levels. In the typical adverse selection model, the government or regulator contracts with an informed firm. In this model, the regulator uses quantity reductions in high cost states and partial cost sharing to limit the firm's information rents. Similar distortions are used in our model to reduce the risk premium that accompanies an incentive compatible contract.

Our results suggest an additional instrument which may reduce the severity of problems connected with private information. An investment made by the firm prior to learning the state of nature will help to prevent the firm from misreporting costs, provided that the investment's return varies inversely with announced cost. In our model, effort functions as such an investment. As a result, we find that the moral hazard constraint is binding at the optimum, and that the firm chooses less effort than the government would like.

When effort is chosen after the firm learns the state of nature (as in Baron & Besanko), its effect on the private information problem is fundamentally different. If effort is more effective at reducing cost in higher cost states than in lower cost states (that is, when $|c_e(e,H)| > |c_e(e,L)|$), then additional effort reduces the size of the information rent that the principal must pay the agent. In this case, the agent chooses too little effort, since he does not internalize these benefits. On the other hand, if $|c_e(e,H)| < |c_e(e,L)|$, then additional effort increases the information rents that the government must pay. The agent may value effort more highly than the principal does in this case, and therefore choose too much effort at the optimum.[17]

In conclusion, we should stress the rather strong underlying assumption we have made with respect to the commitment abilities of the government and firm in our model. To focus attention on the roles played by risk aversion and investment, we have assumed that the government and the firm irrevocably commit to a contract. Since the military's requirements are often subject to change depending on the political environment and other factors, the assumption that the government can make such a commitment may seem questionable. Also, a high cost firm may prefer to breach the contract rather than produce and suffer losses in the high cost state (if the penalties for doing so are not too high). In practice, the parties will frequently renegotiate a contract in either of these contingencies.[18]

Footnotes

1. The government can obtain an estimate about the cost of the current project using cost information it has obtained from past projects completed by the firm. A more general assumption would allow the firm to have better (but not perfect) information than the government about the state of nature when contracting takes place, but this would complicate the analysis immeasurably.

2. Under what conditions the government would prefer to contract with an uninformed versus an informed firm is an interesting question which is beyond the scope of this paper. Cremer and Khalil investigate this issue by endogenizing the amount of information which a (risk-neutral) agent gathers prior to signing a contract. They find that the principal offers a contract such that the agent's equilibrium response is to remain uninformed about the state of nature.

3. See also Laffont & Tirole (1986) and McAfee and McMillan (1986)

4. This partial cost reimbursement has two opposing effects on risk sharing. It insures the firm with respect to the cost uncertainty attributable to the firm's error in forecasting cost, but exposes the firm to additional risk if the cost signal is noisy.

5. McAfee and McMillan simplify the problem by choosing a specific cost function with the property that effort has no effect on the private information problem. Consequently, the cost sharing properties of the contract cause the firm to underprovide effort at the optimum.

6. We impose the restrictions $V'(0) = \infty$ and $\lim_{q \to \infty} V'(q) = 0$ in order to ensure that the government chooses a positive, finite q.

7. Although we impose linearity to keep the analysis simpler, we may note that linear contracts are used extensively in practice.

8. See Gansler (1989) for a detailed description of the weapons procurement process. He notes that production takes place at very low rates initially, so that the 'producibility' of the system can be established.

9. It is straightforward to show that the revelation principle holds even when, as in our model, the agent takes an action before sending his message to the principal. It is also easy to show that imposing linearity does not affect this result. That is, starting with a general linear mechanism we can find a direct truthtelling mechanism (also linear) that implements the same outcome.

10. Note that we are assuming the government can credibly commit to letting the firm suffer losses in the bad state of nature, so that the issue of interim incentive compatibility does not arise.

11. If the signal is perfect ($\sigma^2 = 0$) and effort is observable, the optimal contract is no longer unique. In this case, any combination of a_i and b_i such that $\gamma(a_i - (1 - b_i)\ c(e^*,i)q_i^*) = \phi(e^*)$ will work.

12. Note that when $|c_e(e,H)| = |c_e(e,L)|$, the government tends to distort q_H only, but the same conclusions apply.

13. Note that in each case the per unit return to additional effort is $c_e(e,L)$.

14. To see why, suppose that $\delta = 0$, i.e. the firm chooses the same level of effort that the government wants. In this case, the optimal contract must be $<\tilde{a}_i, \tilde{b}_i, \tilde{q}_i>$ and $\tilde{e}$ since adding a non-binding constraint to the problem does not change the solution. However, we showed in the previous section that $\tilde{e}$ would not be chosen by the firm. Therefore $\delta \neq 0$.

15. In the previous section, we could easily check that this inequality held by appealing to the first order conditions. Now that moral hazard presents a (potential) problem, it is impossible to do this.

16. A 'high degree of cost uncertainty' here refers to a large difference between costs in the two states, $c(e,H)$ and $c(e,L)$, rather than implying anything about the probabilities of the two states of nature. In fact, the likelihood of cost sharing does not depend on these probabilities.

17. Because of the private information problem, b_i will be positive, as in our model. This tends to make the agent's effort lower than the principle would like. Therefore $|c_e(e,H)| < |c_e(e,L)|$ is a necessary but not a sufficient condition for the agent to choose too much effort.

18. Tirole (1986) examines the consequences of the absence of commitment for the firm's pre-production investment level. Modelling the procurement problem as a bargaining game with bilateral asymmetric information and moral hazard, he finds that the inability to commit prior to investment leads the firm to supply a level of pre-production effort which is less than first-best (although it may be greater or less than the socially efficient level, given the asymmetry of information).

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(a) Our Model

Gov't offers a contract	Firm performs preliminary work; chooses effort	Firm observes the state of nature and submits cost report	Full-scale production takes place	Gov't observes signal; payments made

(b) Baron and Besanko

Firm observes the state of nature	Gov't offers a contract	Firm submits a cost announcement	Firm chooses effort and produces output	Gov't observes signal, makes payments

Figure 1. Summary of Timing

Chapter 3

Costly Verification of Cost Performance and the Competition for Incentive Contracts[1]

I. *Introduction*

Production and service contracts often tie the agent's compensation at least in part to the cost incurred in fulfilling the terms of the contract. For example, a law or consulting firm may bill a client according to the manhours actually required to complete a project. The 'linear incentive contract' used in government procurement provides another example. Under this contract, the principal is required to make a fixed payment, and pay a fraction of the agent's realized cost. If it is costly for the principal to observe realized cost, he may to some extent rely on information provided him by the agent. Thus, cost-based compensation schemes may create an opportunity for the agent to profit by submitting false claims ex post. For instance, consider the law firm which charges its client by the hour. Since the client cannot costlessly observe the firm's activity, the firm may attempt to overreport its costs by billing the client at attorney's rates for work actually performed by a lower paid law clerk.

Overreporting of costs is often alleged to occur in government contracting, where contracts frequently contain cost sharing provisions. For example, Rockwell's Collins division, which performs production and repair for the Space Shuttle program, was recently barred from competing for government contracts following charges that it padded costs by falsifying employee timecards.[2] Monitoring costs is made especially difficult by the fact that contractors often have several related ongoing projects. This may afford a contractor the opportunity to falsely charge costs from commercial projects or fixed-price government contracts to contracts containing provisions for cost reimbursement.[3]

In the recent literature analyzing the use of cost-based compensation, ex post monitoring is assumed to be costless for the principal. Several studies concentrate on the potential risk sharing benefits of cost sharing. For example, Holt (1979) examines how cost sharing affects the behavior of risk averse bidders in competition for a contract. He shows that increased cost sharing reduces the risk premium built into the equilibrium bid, thereby lowering the principal's expected costs. Other studies focus primarily on the tradeoff between inducing effort and eliciting private information acquired by the agent ex ante. Laffont and Tirole (1986) analyze the problem of a regulator contracting with a single, risk-neutral agent who possesses private information about his expected cost. Cost sharing is preferred to a simple fixed price arrangement, because it limits an agent's ability to exploit his ex ante informational advantage.[4] In both contexts, the authors demonstrate that some cost sharing is optimal, even though it weakens the agent's incentive to control cost. However, by assuming that the principal costlessly observes the agent's realized cost, the models do not allow for the possibility that cost sharing itself creates another asymmetric information problem ex post.

This paper incorporates the possibility of misconduct by the agent ex post. We analyze how predictions concerning the optimal level of cost sharing are altered if monitoring is costly for the principal. The starting point for our model is a paper by McAfee and McMillan (1986), that investigates the optimal linear incentive contract to offer a group of bidders. McAfee and McMillan consider a model in which several would-be agents compete for a contract in a first-price auction. The principal promises to pay a fixed fee equal to the winning bid, and he agrees to reimburse the agent for a fraction of the amount by which cost exceeds the bid. Bidders possess independent private values concerning the expected cost of completing the project. Actual cost depends upon the realization of a random cost disturbance and on the level of cost reducing effort chosen by the agent. As in the standard first-price auction with independent private values, each bidder optimally shades his bid above his expected cost in order to earn positive profits if selected. Cost sharing by the principal reduces the rents the agent earns by inflating his bid, but at the expense of inducing the agent to put forth less effort.

There is no scope in McAfee and McMillan's model for the agent to act strategically ex post because the principal can monitor without cost. Since the principal always monitors, the agent need not be called upon to report his realized cost. In any case, if required to do so, the agent would always report truthfully. When monitoring is costly, it becomes important to analyze the ex post cost reporting strategy of the agent. To accomplish this in the simplest possible manner, we assume that the random cost disturbance may take two values, representing 'high' and 'low' costs. The agent privately observes his 'type', the realization of this random component, during production. The principal can observe total cost ex post, provided that he incurs a fixed monitoring cost.

We begin our analysis by considering the two stage game that arises between the agent and the principal. In the first stage, the agent submits a cost report to the principal. The principal subsequently decides whether to monitor the agent's cost or not. We show that when monitoring costs are positive, there cannot be a separating equilibrium in which each type of agent reports cost truthfully. In particular, the low cost agent must with some probability misrepresent his cost as being high.

Having ruled out a separating equilibrium, we obtain a simple condition which determines whether a 'pooling' or a 'mixed-strategy' equilibrium solves the game. The cost sharing parameter plays a crucial role in determining whether or not the solution to the monitoring game involves pooling. Intuitively, if the fraction of cost reimbursed by the principal is sufficiently small, then the principal's expected gains from monitoring will be smaller than the cost. The game will thus have a pooling equilibrium in which the principal does not monitor and the low cost agent claims to be high cost. On the other hand, if the level of cost sharing is relatively high, then the expected gains from monitoring are likely to exceed the cost. In this case, the game has a mixed strategy equilibrium. The principal randomizes between monitoring and not monitoring, and the low cost agent randomizes between high and low cost reports.

After determining the solution to the monitoring game, we proceed to examine how the agent's anticipated cost reporting strategy effects the equilibrium bid and the principal's expected cost. An interesting question arises as to whether the agent's overreporting of cost ex post really harms the principal or not. In this regard, McAfee and McMillan (1988) have argued informally that cost padding is of no real consequence for the principal's cost if the contract is awarded competitively because the expected profit from cheating will be eliminated in the bidding competition, provided that bidders have symmetric expectations concerning the gains from cheating. Because the lower bidding ex ante exactly compensates the principal for the overreporting ex post, the principal's cost will not be affected by the agent's cheating. Thus, there is really no loss of generality in assuming that monitoring is costless: the optimal contract with costly monitoring corresponds to the optimal contract with costless monitoring.

The bidders in our model possess identical expectations of the gains from cheating, allowing us to investigate more closely the claim that cheating is irrelevant. We find that the conclusion regarding the irrelevance of cheating rests on a strong underlying assumption, namely, that prior to bidding, the principal be able to commit not to monitor the agent ex post. This assumption is not always appropriate.

As noted by Khalil (1991), if the principal-agent relationship is not repeated, or alternatively if the principal's short-term gains from monitoring outweigh any possible long-term benefits from investing in reputation, then it is reasonable to assume that the principal cannot make any promise ex ante which is not in his best interest to honor ex post. In the case of government contracting, political considerations may well make it impossible for the principal to commit to a monitoring policy. For example, public outrage over perceived cost overruns by a contractor may lead the Congress to demand an audit. Our analysis demonstrates that in cases where the principal cannot commit not to monitor the agent ex post, the ex post cheating of the agent will impact the principal's expected cost.

We conclude the analysis by determining the principal's optimal contract. Although the principal cannot explicitly commit not to monitor in our model, he may do so indirectly by offering a sharing parameter such that the subsequent gains from monitoring are small enough that he prefers not to monitor ex post. Alternatively, the principal may offer a mixed strategy contract, in which case he must incur monitoring and other costs related to the agent's cheating, costs he would avoid with the pooling contract. The type of contract chosen depends on several factors, including the number of bidders participating in the competition, the variance of the bidders' expected costs, the cost of monitoring, and the prior probability of low costs. Furthermore, the optimal 'costly monitoring' contract will generally differ from the contract which is optimal when monitoring is costless. While the optimal sharing parameter in the mixed strategy case is strictly larger than the optimal cost sharing parameter when monitoring is costless, the optimal sharing parameter in the pooling case is weakly smaller than the optimal costless monitoring sharing parameter. Thus, when monitoring is costly, the optimal sharing parameter will be either very high or very low, but will not take on in between values.

The remainder of the paper is organized as follows. Section II describes the model's basic setup and timing in more detail. Section III presents an analysis of the ex post cost reporting/monitoring game and describes the pooling and mixed strategy solutions. Section IV determines the optimal bidding strategy corresponding to each of these outcomes and examines the implications for the principal's expected cost. Section V considers the optimal contract.

Concluding observations are presented in section VI.

II. *Outline of the Model*

We consider a two-period model. An initial period of competition for the contract is followed by a second period in which the principal and the selected agent fulfill the terms of the contract. In period one, several prospective agents compete for a contract which is awarded to the lowest bidder. Prior to bidding, each bidder privately observes a cost parameter indicating his own expected cost of completing the project. Let c_i denote bidder i's idiosyncratic cost. The c_i are independently drawn from a distribution F(c) whose corresponding density f(c) has support $[c_L, c_H]$. We assume that the inverse hazard function $\frac{F(c)}{f(c)}$ is increasing in c.

In period two, the winning agent 'produces', or performs the work specified by the contract. The actual cost to agent i of completing the project is:

$$C_i = c_i - e + \theta_t. \tag{1}$$

As equation (1) indicates, the agent can reduce the cost of the project by supplying effort, e, during production. The cost of effort to the agent is given by $\nu(e)$, where $\nu'(e) > 0$ and $\nu''(e) > 0$.[5] As effort is not directly observable by the principal, this cost must be borne by the agent. In addition, project cost depends upon the realization of a random variable, θ_t, which represents unforeseen costs (or savings) realized during production. We consider the case of binary uncertainty, with t=H or L and $\theta_H > \theta_L$. The probability of the high cost state θ_H is represented by p, and:

$$E(\theta_t) = p\,\theta_H + (1 - p)\,\theta_L = 0$$

The principal and the agent have identical priors regarding the cost disturbance θ, and their priors are common knowledge. However, the realized value of θ is observed privately by the firm.

After production is complete, the agent reports his realized cost to the principal. The principal may verify the agent's cost report by monitoring. If the principal chooses to monitor, he incurs a monitoring cost K_m and observes the agent's actual cost, C_i, without error.[6] The contract specifies the agent's compensation as a linear combination of the bid, b, and either reported cost or, if the principal monitors, realized cost. As the principal cannot observe the individual components of C_i, the contract cannot be contingent on e, θ_t or c_i.

Let $\tilde{C}_i$ represent the agent's reported cost. A contract is distinguished by its cost sharing parameter $s \in [0, 1]$. The parameter s represents the fraction of realized cost reimbursed by the principal. If the principal does not monitor, the agent's payment P_i is given by $P_i = b + s(\tilde{C}_i - b)$. If the principal monitors, then $P_i = b + s(C_i - b)$.

Due to the ex post asymmetry of information, reported cost may or may not reflect actual cost in equilibrium. Should the agent's reported cost exceed that observed by the principal, the agent suffers a finite loss or punishment, L. We take L to be exogenous, and to represent a reputational loss suffered by the agent.[7] That is L represents a loss of future profits (in present value terms), because an agent caught cheating will be excluded or disadvantaged in future competition for contracts.[8]

The sequence of events in our model is summarized in figure 2. In period one, the principal announces a contract, s. This is followed by bidding and selection of the agent. In period two, the agent produces, choosing e and learning θ_t in the process.[9] The agent makes a post-production cost report $\tilde{C}_i$. After observing the agent's cost report, the principal chooses whether or not to monitor. Finally, output is exchanged and the agent is compensated according to the terms of the contract.

III. *Equilibrium Cost Reporting and Monitoring Strategies*

We begin the analysis by investigating the outcome of the cost reporting game that the principal and agent i play in period two after production is completed. Figure 3 illustrates the game in extensive form. The payoffs in the tree denote the agent's profit and the principal's total cost. As noted above, the agent reports his total cost after privately observing θ_t. Upon receiving the agent's cost report, the principal updates his beliefs concerning the realization of θ and decides whether to monitor. Note that the principal can infer c_i by inverting the agent's equilibrium bid and can infer e knowing that the agent will choose effort to balance the marginal gain from effort against the marginal cost.[10] The cost report $\tilde{C}_i$ therefore only conveys additional information concerning θ.

We demonstrate below that the reporting game possesses a unique perfect bayesian equilibrium. Depending on the underlying parameters, this equilibrium entails either complete pooling or mixed strategies by both players. Two of the players' equilibrium actions are immediately apparent: it clearly never pays the principal to monitor a report of low cost, and it never pays an agent with high cost to report that his cost is low. In describing the game's equilibrium, we thus focus on the low cost agent's cost report and the principal's response to a report of high cost, bearing in mind that the high cost agent always reports a high cost and that the principal who sees a report of low cost does not monitor. Let ℓ represent the probability that the low cost agent lies, i.e. reports θ_H, and let m represent the probability of monitoring, given a report of high cost. In addition, let μ_H represent the principal's assessment of the probability that the agent is high cost given that he reports high cost, and let μ_L denote his assessment of the probability that the agent is high cost when he reports low cost. Since the high cost agent reports high cost with probability one, Bayes' rule requires that

$$\mu_H = \frac{p}{p+(1-p)\ell} \tag{2}$$

The following proposition serves as a useful starting point for our analysis of the cost reporting game.

PROPOSITION 1: There can be no separating equilibrium.

PROOF: Given that the high cost agent reports truthfully, the only possible separating equilibrium is one in which the low cost agent reports truthfully ($\ell = 0$). Suppose $\ell = 0$. Then from (2), Bayes' rule requires that $\mu_H = 1$: the principal infers that a high cost report must come from a high cost agent. Given this belief, the principal is strictly better off choosing not to monitor, so that $m = 0$ is his best response. However, if the principal does not monitor, the low cost agent benefits by deviating from $\ell = 0$ since he can increase his profit by cheating. Therefore, a separating equilibrium does not exist. □

Proposition 1 tells us that a low cost agent must misrepresent his cost with strictly positive probability in equilibrium. There are two possibilities: a low cost agent may always misrepresent his cost or may misrepresent his cost only part of the time.

The Pooling Equilibrium

If the principal's gain from monitoring is sufficiently small or the cost of monitoring is sufficiently large, then the principal will never monitor ($m = 0$) and the low cost agent will always claim to have high cost($\ell = 1$). To see when this occurs, note that if the principal does not monitor a high cost report, then his cost is

$\mathcal{C} \mid \text{not monitor} = b+s(c_i - e + \theta_H - b).$

If the principal monitors a report of high cost, his expected total cost is

$$\begin{aligned}\mathcal{C} \mid \text{monitor} &= \mu_H\{b+s(c_i - e + \theta_H - b)\} + [1 - \mu_H]\{b+s(c_i - e + \theta_L - b)\} + K_m \\ &= b + s(c_i - e + \theta_H - b) + K_m - (1 - \mu_H)s(\theta_H - \theta_L). \qquad (3)\end{aligned}$$

The principal prefers (weakly) not to monitor a report of high cost if

$$b + s(c_i - e + \theta_H - b) + K_m - (1 - \mu_H)s(\theta_H - \theta_L) \;\geq\; b+s(c_i - e + \theta_H - b). \qquad (4)$$

If a low cost agent always overstates his cost, then $\ell = 1$ and we see from (2) that the the principal's belief following a report of high cost must be $\mu_H = p$. Substituting p for μ_H in equation (4) and simplifying, we obtain

$$(1 - p)\, s\, [\theta_H - \theta_L] \;\leq K_m. \qquad (5)$$

The term on the left hand side of (5) is the principal's expected gain from monitoring when a low cost agent overstates his cost with probability one. If this gain does not exceed the cost of monitoring, then $m = 0$ is the principal's best reply to a high cost report. Of course, if the principal does not monitor, a low cost agent always finds it advantageous to overstate his cost. This gives us

PROPOSITION 2: If $(1 - p)s[\theta_H - \theta_L] \leq K_m$, the cost reporting game has a pooling equilibrium characterized by the following strategies and beliefs.[11]

Strategies:

AGENT: Low cost type reports high cost ($\ell = 1$) and high cost type reports truthfully

PRINCIPAL: Does not monitor if agent reports high cost (m=0) and does not monitor if agent

reports low cost

Beliefs: $\mu_H = p$; $\mu_L = 0$

PROOF: The proof follows immediately from the preceding discussion. Note that the out-of-equilibrium belief μ_L cannot be computed using Baye's rule, and we have assigned $\mu_L = 0$ arbitrarily. However, as mentioned above the principal prefers not to monitor a report of low cost, no matter what his beliefs. Therefore, the equilibrium strategies are robust to any change in the beliefs off the equilibrium path. □

The Mixed Strategy Equilibrium

If condition (5) is violated, then the principal prefers to monitor when $\ell = 1$, so that there does not exist a pure strategy equilibrium. However, there is a unique equilibrium in mixed strategies. The values of m and ℓ are both strictly between 0 and 1, as the principal randomizes between monitoring and not monitoring and the low cost agent randomizes between truthtelling and lying. More precisely, we have

PROPOSITION 3: If $(1 - p)s[\theta_H - \theta_L] > K_m$, the cost reporting game has a unique equilibrium. This mixed strategy equilibrium is characterized by the following strategies and beliefs.

Strategies:

AGENT: the low cost type misreports his cost with probability $\ell = \dfrac{p\,K_m}{(1 - p)\,[s(\theta_H - \theta_L) - K_m]}$

and the high cost type reports truthfully

PRINCIPAL: Monitors a high cost report with probability $m = \dfrac{s(\theta_H - \theta_L)}{s(\theta_H - \theta_L) + L}$

and does not monitor a low cost report

Beliefs: $\mu_H = \dfrac{s(\theta_H - \theta_L) - K_m}{s(\theta_H - \theta_L)}$; $\mu_L = 0$

PROOF: Because an agent with high cost reports low cost with probability zero, the belief $\mu_L = 0$ is clearly consistent with the agent's equilibrium strategy. To verify that μ_H is also consistent with the agent's equilibrium strategy, substitute $\ell = p\,K_m/(1 - p)\,[s(\theta_H - \theta_L) - K_m]$ into (2) to obtain $\mu_H = [s(\theta_H - \theta_L) - K_m]/s(\theta_H - \theta_L)$.

When the low cost agent reports high cost, his expected profit is given by

$$\pi_L \mid \text{report high} = (1 - s)[b - c_i + e - \theta_L] - m\,L + (1 - m)s(\theta_H - \theta_L). \tag{6}$$

Substituting $s(\theta_H - \theta_L)/[s(\theta_H - \theta_L) + L]$ for m into (6) yields

$$\begin{aligned}\pi_L \mid \text{report high} &= (1 - s)[b - c_i + e - \theta_L] - \left\{ \frac{s(\theta_H - \theta_L)}{s(\theta_H - \theta_L) + L} \right\} L + \left\{ \frac{L}{s(\theta_H - \theta_L) + L} \right\} s(\theta_H - \theta_L) \\ &= (1 - s)[b - c_i + e - \theta_L] \\ &= \pi_L \mid \text{report low.}\end{aligned}$$

Thus, given the principal's monitoring strategy, the low cost agent is indifferent between reporting high and low cost. Any $\ell \in [0, 1]$ is a best response, including $\ell = p K_m/(1 - p)[s(\theta_H - \theta_L) - K_m]$.

Finally, note that $(1-\mu_H) = (1-p)\ell/[p + (1-p)\ell] = K_m/s(\theta_H - \theta_L)$. Substituting this result into (3)

gives us

$$\mathcal{C} \mid \text{monitor} = b + s(c_i - e + \theta_H - b)$$
$$= \mathcal{C} \mid \text{not monitor}.$$

Thus, given his beliefs, the principal is indifferent between monitoring and not monitoring. Any $m \in [0, 1]$ is a best response, including $m = s(\theta_H - \theta_L)/s[(\theta_H - \theta_L) + L]$.

It is straightforward to verify that the equilibrium is unique. □

In the mixed strategy equilibrium, the principal monitors with sufficient probability to curtail, but not completely eliminate, the likelihood of cheating. Differentiating we find that $\frac{\partial \ell}{\partial K_m} > 0$: the equilibrium probability of cheating is smaller the lower is the cost of monitoring. Differentiation also reveals that $\frac{\partial \ell}{\partial s} < 0$: the probability of cheating is smaller the larger the cost sharing parameter. This is due to the fact that an increase in s raises the gain to monitoring. Therefore, the probability of cheating must fall to maintain the principal's indifference between monitoring and not monitoring. It can also be shown that $\frac{\partial m}{\partial s} > 0$: the principal's probability of monitoring is larger the greater is the degree of cost sharing. Because an increase in s raises the potential gain to cheating, m must increase to preserve the agent's indifference between cheating and truthtelling. The probability of monitoring is also larger, the smaller is L, the penalty for cheating.

Our analysis indicates that the equilibrium outcome to the cost reporting game depends critically on the cost sharing parameter chosen by the principal ex ante.[12] Other things equal, if s is small the contract will induce a pooling equilibrium in period two, while a mixed strategy equilibrium will result if the share of cost reimbursed by the principal is large. More precisely, the cost reporting game in period two has a pooling equilibrium if $s \leq s^c$ and a mixed strategy equilibrium if $s > s^c$, where $s^c = \min[\, K_m/(1\text{-}p)(\theta_H - \theta_L)\, ,\, 1\,]$.

The Principal's Expected Cost

Let $\mathcal{C}(s \mid c_i,\, s \leq s^c)$ denote the principal's expected cost when the contract has cost sharing parameter $s \leq s^c$ and the agent has idiosyncratic cost c_i. Because the principal never monitors and the agents always reports a high cost when $s \leq s^c$, we have

$$\mathcal{C}(s \mid c_i,\, s \leq s^c) = b_i + s(c_i - e + \theta_H - b_i).$$

Noting that $p\theta_h + (1\text{-}p)\theta_L = 0$, we may rewrite this as

$$\mathcal{C}(s \mid c_i,\, s \leq s^c) = b_i + s(c_i - e - b_i) + s(1\text{-}p)(\theta_H - \theta_L), \tag{7}$$

where $s(1\text{-}p)(\theta_H - \theta_L)$ is the expected value of the principal's overpayment to the agent.

Similarly, let $\mathcal{C}(s \mid c_i,\, s > s^c)$ denote the principal's expected cost when the contract has cost sharing parameter $s > s^c$. Because the agent reports high cost with probability $p + (1\text{-}p)\ell$ and the principal monitors a high cost report with probability m, the principal's expected monitoring cost is $\{p + (1\text{-}p)\ell\}mK_m$. Since the principals pays the agent $b_i + s(c_i - e + \theta_H - b_i)$ with probability $p + (1\text{-}p)\ell(1\text{-}m)$ and $b_i + s(c_i - e + \theta_L - b_i)$ with probability $(1\text{-}p)(1\text{-}\ell(1\text{-}m))$, we have

$$\mathcal{C}(s \mid c_i, s > s^c) = b_i + s(c_i - e - b_i) + \{p + (1\text{-}p)\ell\}mK_m + s\{p + (1\text{-}p)\ell(1\text{-}m)\}\theta_H + s(1\text{-}p)(1\text{-}\ell(1\text{-}m))\theta_L$$

$$\mathcal{C}(s \mid c_i, s > s^c) = b_i + s(c_i - e - b_i) + \{p + (1\text{-}p)\ell\}mK_m + (1\text{-}p)\ell(1\text{-}m)s(\theta_H - \theta_L) \qquad (8)$$

where

$$\ell = \frac{p\ K_m}{(1 - p)\ [s(\theta_H - \theta_L) - K_m]} \quad \text{and} \quad m = \frac{s(\theta_H - \theta_L)}{s(\theta_H - \theta_L) + L}$$

and $(1\text{-}p)\ell(1\text{-}m)s(\theta_H - \theta_L)$ is the expected value of the principal's overpayment to the agent.

There is an alternative way of expressing $\mathcal{C}(s \mid c_i, s > s^c)$ that will be helpful in our subsequent analysis. Recall that in the mixed strategy equilibrium the principal is indifferent between monitoring and not monitoring. Noting that if the principal always monitored a high cost report, he would incur the monitoring cost K_m with probability $p + (1\text{-}p)\ell$ and he would pay the agent $b_i + s(c_i - e + \theta_H - b_i)$ with probability p and $b + s(c_i + \theta_L - e - b)$ with probability 1-p, it follows immediately that

$$\mathcal{C}(s \mid c_i, s > s^c) = b_i + s(c_i - e - b_i) + \{p + (1\text{-}p)\ell\}K_m \qquad (9)$$

IV. *The Optimal Bidding Strategies*

Bidders for the contract possess heterogeneous costs, as reflected by the cost component c_i, but they face the same distribution of the unforeseeable component θ.[13] Among other things, a bidder's profit expectations depend upon whether he anticipates a pooling or mixed strategy outcome in period two. If the contract induces a pooling equilibrium, each bidder expects to earn positive informational rents from overreporting costs. But if the contract induces a mixed strategy equilibrium, bidders expect no rents from overstating cost in period two. Their equilibrium bidding strategies thus depend crucially on whether s is less than or greater than s^c. The symmetric Nash equilibrium bidding strategies for both cases are derived below.[14]

The Bidding Equilibrium When $s \leq s^c$

When a contract with $s \leq s^c$ is offered, bidder i knows that if cost turns out to be low, he can overstate cost without fear of punishment next period. His expected profit conditional on winning the contract with a bid of b_i is therefore:

$$E(\pi_i|\text{win}) = p(1 - s)[\, b_i - c_i - \theta_H + e] + (1 - p)\{(1 - s)[b_i - c_i - \theta_L + e] + s(\theta_H - \theta_L)\} - \nu(e)$$
$$= (1 - s)[\, b_i - c_i + e] + (1 - p)s(\theta_H - \theta_L) - \nu(e)$$

where $(1 - p)s(\theta_H - \theta_L)$ represents the ex ante expected rent from overstating cost. Letting $B(\cdot)$ denote the bidding strategy employed by each of the N - 1 other bidders, bidder i wins the bidding competition with probability $[1\text{-}F(B^{-1}(b_i\,))\,]^{N-1}$, so that his expected profit is given by[15]

$$E(\pi_i) = [\, 1 - F(B^{-1}(b_i\,))\,]^{N-1}\Big\{(1 - s)\,[\, b_i - c_i + e] + (1 - p)s(\theta_H - \theta_L) - \nu(e)\,\Big\}. \tag{10}$$

Bidder i chooses his bid b_i to maximize $E(\pi_i)$.

As b_i maximizes $E(\pi_i)$, we can differentiate (10) with respect to c_i and apply the envelope theorem to obtain

$$\frac{dE(\pi_i)}{dc_i} = \; - \;[\, 1 - F(B^{-1}(b_i\,))\,]^{N-1}\,(1 - s). \tag{11}$$

In a symmetric Nash equilibrium, we must have $b_i = B(c_i)$. Making this substitution in equation (11) gives us

$$\frac{dE\pi_i}{dc_i} = - [1 - F(c_i)]^{N-1} (1 - s) \tag{12}$$

Integrating (12) and observing that the expected profit of a bidder with the highest possible cost c_H must be zero then yields:

$$E(\pi_i(c_i)) = (1 - s) \int_{c_i}^{c_H} [1 - F(c)]^{N-1} \, dc \quad . \tag{13}$$

Substituting (13) into (10), again invoking the Nash condition that $b_i = B(c_i)$, and solving for $B(c_i)$ finally gives us the equilibrium bidding strategy:

$$B(c_i) = c_i + \frac{\int_{c_i}^{c_H} [1 - F(c)]^{N-1} dc}{[1 - F(c_i)]^{N-1}} - e + \frac{1}{1 - s} \nu(e) - \frac{1 - p}{1 - s} s(\theta_H - \theta_L) \tag{14}$$

In interpreting (14), recall that since the principal does not monitor, bidder i's compensation is

$$\begin{aligned} P_i &= B(c_i) + s\,(\tilde{C}_i - B(c_i)) \\ &= (1 - s)\, B(c_i) + s\, \tilde{C}_i \end{aligned} \tag{15}$$

where $\tilde{C}_i = c_i - e + \theta_H$ is the agent's reported cost. Note that a one dollar increase in the winning bid raises the agent's payment from the principal by only (1 - s) dollars. To increase his payment by a dollar, a bidder must therefore bid an extra 1/(1 - s) dollars. Thus, the agent adjusts his bid upward by $\nu(e)/(1\text{-}s)$, so that he may receive full compensation for the cost of effort. Similarly, the last term of (14) reflects the fact that competition for the project induces the agent to lower his bid by $(1\text{-}p)s(\theta_H\text{-}\theta_L)/(1\text{-}s)$ in anticipation of the gain from overreporting cost ex post.

In the appendix, we show that $c_i + \int_{c_i}^{c_H} [1 - F(c)]^{N-1}dc/[1 - F(c_i)]^{N-1}$ is simply the expected value of the second order statistic from the sample $[c_1. . . c_N]$, conditional on the first order statistic being c_i. This is a standard result for a first price auction with independent private values: in formulating his bid, bidder i assumes that he has the lowest idiosyncratic cost and submits a bid equal to the expected value of the second lowest idiosyncratic cost, conditioned on his cost being the lowest.

Substituting (14) into (15), agent i's total payment is given by

$$P_i = c_i + (1 - s) \frac{\int_{c_i}^{c_H} [1 - F(c)]^{N-1}dc}{[1 - F(c_i)]^{N-1}} - e + \nu(e) - (1 - p)s(\theta_H - \theta_L) + s\theta_H$$

$$= c_i + (1 - s) \frac{\int_{c_i}^{c_H} [1 - F(c)]^{N-1}dc}{[1 - F(c_i)]^{N-1}} - e + \nu(e) \qquad (16)$$

Because the principal is not able to observe agent i's idiosyncratic cost ex ante, agent i obtains rents equal to $(1\text{-}s)\int_{c_i}^{c_H} [1 - F(c)]^{N-1}dc/[1 - F(c_i)]^{N-1}$ if he wins the bidding competition. We shall refer to these rents as 'ex ante' informational rents to distinguish them from the gains from inflating realized cost. Note that an increase in the cost sharing parameter reduces these rents.

Each bidder knows that if he wins the bidding competition, he will be able to falsify his cost report in period two. The expected rents from overstating cost in period two equal $(1\text{-}p)s(\theta_H - \theta_L)$ and are the same for all bidders. Competition for the contract causes each of them to reduce his bid by the full value of the expected rents from misreporting cost. Expression (16) confirms that the principal fully recoups his expected overpayment in period two in the form of a lower bid in period one. Given that the principal does not incur monitoring costs in the pooling equilibrium, the payment to the agent in (16) represents the principal's total expected cost

$$\mathcal{C}(s \mid c_i, s \leq s^c) = c_i + (1 - s) \frac{\int_{c_i}^{c_H} [1 - F(c)]^{N-1} dc}{[1 - F(c_i)]^{N-1}} - e + \nu(e) \tag{17}$$

To find the principal's ex ante expected cost, note from (14) that $B'(c_i) > 0$, so that the winning bidder will be that producer with the lowest expected cost. Let c_{min} denote this expected cost. Because c_{min} is simply the first-order statistic from the sample $[c_1, c_2, \ldots c_N]$, c_{min} has the distribution function

$$F_{min}(c) = \text{Prob}(\min[c_1, c_2, \ldots c_N] \leq c) = 1 - \text{Prob}(\min[c_1, c_2, \ldots c_N] > c)$$
$$= 1 - [1 - F(c)]^N.$$

The corresponding density function is $f_{min}(c) = N[1 - F(c)]^{N-1} f(c)$. If $s \leq s^c$, the principal's expected cost prior to the bidding competition is thus given by

$$\mathcal{C}(s \mid s \leq s^c) = N \int_{c_L}^{c_H} \left\{ c + (1 - s) \frac{\int_{c}^{c_H} [1 - F(u)]^{N-1} du}{[1 - F(c)]^{N-1}} - e + \nu(e) \right\} [1 - F(c)]^{N-1} f(c)\, dc.$$

Integrating by parts, one obtains

$$\mathcal{C}(s \mid s \leq s^c)) = G(s), \tag{18}$$

where

$$G(s) \equiv N\int_{c_L}^{c_H}\left\{c + (1 - s)\,\frac{F(c)}{f(c)}\right\}[1 - F(c)]^{N-1}f(c)\,dc + \nu(e) - e\,. \tag{19}$$

According to (18) and (19), the overreporting of cost ex post has no actual impact on the expected cost of the project.[16] The principal's expected cost is simply the expected cost of the lowest cost producer, $N \int c\,[1 - F(c)]^{N-1}f(c)\,dc - e + \nu(e)$, plus the expected information rent obtained by the winning bidder, $(1\text{-}s)\,N \int \{F(c)/f(c)\}\,[1 - F(c)]^{N-1}f(c)\,dc$.

The Bidding Equilibrium When $s > s^c$

If $s > s^c$, bidder i anticipates the mixed strategy outcome in period two. Because a low cost agent is indifferent between lying and truthtelling in the mixed strategy equilibrium, bidder i's expected profit conditional on winning the contract with a bid of b_i is

$$E(\pi_i|\text{win}) = p(1 - s)[b_i - c_i - \theta_H + e] + (1 - p)(1 - s)[b_i - c_i - \theta_L + e] - \nu(e)$$

$$= (1 - s)\,[b_i - c_i + e] - \nu(e)$$

Solving for the equilibrium bid in the manner outlined above, we obtain:

$$B(c_i) = c_i + \frac{\int_{c_i}^{c_H}[1 - F(c)]^{N-1}dc}{[1 - F(c_i)]^{N-1}} - e + \frac{1}{1 - s}\,\nu(e) \tag{20}$$

Comparing (20) and (14), we see that the equilibrium bid under a mixed strategy contract when $s > s^c$ is identical in every respect to the equilibrium bid under a pooling contract except for the absence of the term reflecting rents from mistating cost ex post. Given the principal's equilibrium monitoring policy, bidders expect no such rents when $s > s^c$.

Substituting the equilibrium bid $B(c_i)$ for b_i in equation (8) gives us

$$\mathcal{C}(s \mid c_i, s > s^c) = c_i + (1\text{-}s)\,\frac{\int_{c_i}^{c_H}[1 - F(c)]^{N-1}dc}{[1 - F(c_i)]^{N-1}} - e + \nu(e) + \{p + (1\text{-}p)\ell\}mK_m + (1\text{-}p)\ell(1\text{-}m)s(\theta_H\text{-}\theta_L).$$

Thus, prior to bidding, the principal's expected cost is given by

$$\mathcal{C}(s \mid s > s^c) = N\int_{c_L}^{c_H}\left\{c + (1 - s)\,\frac{\int_{c}^{c_H}[1 - F(u)]^{N-1}du}{[1 - F(c)]^{N-1}}\right\}[1 - F(c)]^{N-1}f(c)\,dc - e + \nu(e)$$

$$+ \{p + (1\text{-}p)\ell\}mK_m + (1\text{-}p)\ell(1\text{-}m)s(\theta_H\text{-}\theta_L)$$

$$= G(s) + \{p + (1\text{-}p)\ell\}mK_m + (1\text{-}p)\ell(1\text{-}m)s(\theta_H\text{-}\theta_L) \qquad (21)$$

From (21), we see that the agent's inflating realized cost impacts the expected cost of the principal's project in two ways when $s > s^c$. First, there is a deadweight loss because the principal must devote resources to monitoring. Second, the principal expects to overpay the agent because he will not always detect cheating. Because an agent faces an offsetting loss if he is caught cheating, this premium does not result in a net profit for bidders and therefore cannot be recovered at the bidding stage.

Our analysis indicates, somewhat paradoxically, that monitoring ultimately serves to increase the expected cost of the project. Clearly, if the principal could credibly do so, he would guarantee bidders that he would not monitor. The only means to make a convincing promise to this effect is to choose a pooling contract ($s \leq s^c$), so that monitoring is not in the principal's best interest in period two. However, such a promise may be costly because the cost sharing parameter has several other effects on behavior. The next section addresses the question of the optimal contract.

V. *The Optimal Contract*

Prior to the bidding competition, the principal can select s to minimize the expected cost of his project. The sharing parameter has three important effects on cost. First, s determines the level of effort supplied by the firm. An agent's profit maximizing level of effort satisfies

$$\nu'(e) = 1 - s. \tag{22}$$

Note that the agent's effort level is first best only if $s = 0$. If the cost sharing parameter is positive, the agent provides too little effort because he himself realizes only part of the gain. The greater is s, the less is the effort that the agent provides.

The cost sharing parameter also affects the producer's bidding behavior. As (19) indicates, an increase in s reduces the winning bidder's expected rent from his private cost information. By making compensation more cost based and less dependent on the agent's bid, a higher s induces each bidder to ask for a smaller premium over his expected cost.[17]

These moral hazard and ex ante adverse selection effects of cost sharing are considered by McAfee and McMillan in their analysis of the costless monitoring case.[18] In their model, the optimal level of cost sharing balances the principal's loss from moral hazard against his loss from ex ante adverse selection. An additional factor comes into play in our model because there is a second informational asymmetry. The principal must now worry about the cost reporting game that arises because it is costly for him to observe the agent's realized cost.

The optimal sharing rule minimizes $\mathcal{C}(s)$, the principal's expected cost prior to bidding. Let s^* denote the optimal sharing rule. For the sake of comparison, let $\hat{s}$ denote the optimal sharing rule when monitoring is costless. When $K_m = 0$, the cost reporting game has a unique equilibrium with $m = 1$ and $\ell = 0$, so that the principal's expected cost is simply $\mathcal{C}(s) = G(s)$. Thus, $\hat{s}$ satisfies

$$G'(\hat{s}) = 0 = - N \int_{c_L}^{c_H} F(c) [1 - F(c)]^{N-1} dc + [\nu'(e) - 1] \frac{\partial e}{\partial s},$$

where e is implicitly a function of $\hat{s}$.[19] Since $\nu'(e) = 1 - \hat{s}$, we may rewrite this condition as

$$G'(\hat{s}) = - N \int_{c_L}^{c_H} F(c) [1 - F(c)]^{N-1} dc \ - \ \hat{s} \frac{\partial e}{\partial s} = 0 \tag{23}$$

The optimal sharing parameter when monitoring is costly depends crucially on whether $\hat{s} \leq s^c$ or $\hat{s} > s^c$. First consider the case where $\hat{s} \leq s^c$.

The Optimal Sharing Parameter When $\hat{s} \leq s^c$

Note that if $\hat{s} \leq s^c$, then the principal can commit to not monitoring when he offers the sharing parameter $\hat{s}$. This immediately gives us

Propositiion 4: If $\hat{s} \leq s^c$, then $s^* = \hat{s}$.

Proof: If $s \leq s^c$, then by the definition of $\hat{s}$, $\mathcal{C}(\hat{s}) = G(\hat{s}) \leq G(s) = \mathcal{C}(s)$. If $s > s^c$, then $\mathcal{C}(s) = G(s) + \{p + (1-p)\ell\} m K_m + (1-p)\ell(1-m)s(\theta_H - \theta_L) > G(\hat{s}) = \mathcal{C}(\hat{s})$. □

Figure 4A illustrates the situation described by Proposition 4. For $s \leq s^c$, the ex post asymmetry of information regarding θ has no impact on cost, since the principal does not monitor and the gains from overreporting θ are eliminated through competition. Therefore, the principal chooses s^* by weighing the cost of the moral hazard and ex ante adverse selection problems alone. The first term of (23) represents the gain from increasing s stemming from a reduction in the bidder's ex ante informational rents. The second term represents the loss resulting from the decrease in effort. Note that if $s = 0$ we have $G'(s) < 0$, therefore the optimal s must be strictly positive. Thus, some degree of cost sharing is optimal even when monitoring is costly.

The situation described by proposition 4 is more likely to occur under the following circumstances. First, if the number of bidders is large, then $\hat{s}$ will tend to be small. It can be shown that as N increases, the first term of (23) decreases (in absolute value) and thus $\hat{s}$ decreases. Increasing the number of bidders has two effects on the expected ex ante informational rents paid by the principal. First, an increase in N causes the bidder's to bid more competively.[20] The equilibrium bid decreases as N increases. Second, an increase in N lowers the expected minimum cost and, provided that a lower cost bidder earns higher rents, this leads to an increase in expected ex ante informational rents.[21] We demonstrate in the appendix that if the inverse hazard rate is increasing, an increase in the number of bidders unambiguously decreases the expected ex ante informational rents paid by the principal.

For particular distributions such as the normal and the uniform, we are able to demonstrate that the expected ex ante informational rent decreases as the variance of the distribution of idiosyncratic cost decreases. Thus, for these common distributions, $\hat{s}$ is lower the smaller the variance of idiosyncratic costs. Finally, if $\frac{\partial e}{\partial s}$ is large (in absolute value), then effort is very responsive to changes in s, and $\hat{s}$ will be small.[22]

Given $s^c = \min[\, K_m/(1 - p)[\theta_H - \theta_L]\, ,\, 1\,]$, the critical value s^c will tend to be relatively high if either monitoring costs are high, the prior probability of low cost is small, or the absolute difference between high and low costs is small.[23] Thus, these three circumstances tend to favor $\hat{s} \leq s^c$ as well.

The Optimal Sharing Parameter When $\hat{s} > s^c$

If $\hat{s} > s^c$, then the contract $\hat{s}$ induces a mixed strategy equilibrium in period two and the principal's expected cost will be higher than in the benchmark case where monitoring is costless. When $\hat{s} > s^c$, the agent's misreporting of θ imposes a real cost on the principal because the principal cannot commit not to monitor the agent's cost report when the contract has the sharing parameter $\hat{s}$. In order to solve for the optimal contract, we determine whether or not the cost of the optimal mixed strategy contract exceeds $G(s^c)$. If it does, then the loss from overreporting associated with a mixed strategy contract outweighs the potential benefit of increasing s beyond the critical point s^c and the principal will opt for a contract which induces pooling in period two. Otherwise, the principal will offer a contract with $s > s^c$, yielding a mixed strategy outcome in period two.

Let $\bar{s}$ represent the sharing parameter which minimizes (21). To find $\bar{s}$, use (9) to rewrite $\mathcal{C}(s \mid s > s^c)$ as:

$$\mathcal{C}(s \mid s > s^c)=G(s) + \{p +(1-p)\ell\}K_m \tag{24}$$

Differentiating (24) with respect to s, we obtain:[24]

$$\mathcal{C}'(\bar{s} \mid s > s^c) = G'(\bar{s}) + (1-p)\frac{\partial \ell}{\partial s} K_m = 0 \tag{25}$$

Proposition 5 characterizes the optimal contract, given $s > s^c$.

PROPOSITION 5: If $\hat{s} > s^c$, and $\mathcal{C}(\bar{s}) < G(s^c)$ then the principal offers the "mixed strategy" contract $s^* = \bar{s}$. Otherwise the principal offers the contract $s^* = s^c$.[25]

PROOF: Given $\hat{s} > s^c$, we have $G'(s^c) < 0$. Thus, s^c yields the lowest cost of any pooling contract, and $\bar{s}$ is a global minimum if $\mathcal{C}(\bar{s}) < G(s^c)$.[26]

Figures 4B and 4C illustrate each of the contingencies in proposition 5. The proposition confirms that the principal may optimally offer a contract which induces monitoring in period two. The 'mixed strategy' contract will be offered if:

$$G(s^c) - G(\bar{s}) \geq \{p + (1 - p)\ell\} K_m$$

The expression on the left hand side measures the net effect of raising s from the critical level s^c to $\bar{s}$ on the moral hazard and ex ante adverse selection problems. If these savings are large enough to offset the costs of the ex post private information problem which arise for $s > s^c$, then a mixed strategy contract is optimal. Proposition 5 also implies that for some $\hat{s} > s^c$, the optimal contract will involve pooling. In particular, for $\hat{s}$ sufficiently close to s^c, the gains from increasing s beyond s^c will not be large enough to outweigh the added costs stemming from the agent's overstating of θ.

We established in proposition 4 that if $\hat{s} < s^c$, the optimal contract with costly monitoring corresponds to the optimal contract when monitoring is costless. With $\hat{s} > s^c$, the two contracts will differ because of the cost of the ex post private information problem. There are two contingencies. First, if the pooling contract is optimal, we have $s^* = s^c < \hat{s}$ and the costly monitoring contract involves less cost sharing then the costless monitoring contract. The following proposition compares the level of cost sharing under the mixed strategy contract, $s^* = \bar{s}$, with the optimal costless monitoring contract.

PROPOSITION 6: Given $s^* = \bar{s}$, the optimal level of cost sharing exceeds $\hat{s}$, the optimal cost sharing parameter if monitoring is costless.

Proof: Noting that $G'(\hat{s}) = 0$ and $\frac{\partial \ell}{\partial s} < 0$, it follows immediately from (25) that $\bar{s} > \hat{s}$.

Under the mixed strategy contract, the principal reimburses a higher fraction of cost than he would if monitoring were costless. In fact, an increase in the cost sharing parameter helps to reduce the costs related to the ex post private information problem. This can be demonstrated as follows. Differentiating $\mathfrak{C}(s \mid s > s^c)$ in (21) with respect to s we obtain:

$$\mathfrak{C}'(s \mid s > s^c)=G'(s)+\Big\{[\, p+(1\text{-}p)\ell]K_m\text{-}(1\text{-}p)\ell s(\theta_H\text{-}\theta_L)\Big\}\,\frac{\partial m}{\partial s} +$$
$$\Big\{(1\text{-}p)mK_m+(1\text{-}p)(1\text{-}m)s(\theta_H\text{-}\theta_L)\Big\}\,\frac{\partial \ell}{\partial s} +(1\text{-}\ p)\ell(1 - m)(\theta_H\text{-}\theta_L) \tag{26}$$

We argued in section III that an increase in cost sharing raises the equilibrium monitoring probability and reduces the probability of cheating, thus $\frac{\partial m}{\partial s} > 0$ and $\frac{\partial \ell}{\partial s} < 0$. The decrease in the cheating probability ℓ clearly has a negative effect on the principal's cost. At the same time, expected cost is unaffected by the increased probability of monitoring. Intuitively, the principal's indifference between monitoring and not monitoring implies that a change in the montoring probability m does not affect cost. Therefore, the change in equilibrium strategies induced by an increase in s has a negative effect on cost. The increase in s also has a direct effect on cost, reflected in the last term of (26). Raising s increases the value of the premium paid to the cheating agent. However, this effect is insufficient to outweigh the beneficial effect cited above. Therefore, the increased cost sharing reduces the cost associated with the ex post privated information problem.

VI. *Conclusion*

This paper has examined how the principal's inability to costlessly verify an agent's cost report affects the optimal cost sharing contract. If the principal could make an ex ante commitment never to monitor an agent's cost report, then cost padding would be of no real consequence because agents' expected profit from cheating would be eliminated in the bidding competition for the principal's contract. But if one imposes the subgame perfect restriction that the principal monitors whenever it is in his interest ex post to do so, then cost padding considerations will generally both raise the principal's cost and affect the optimal cost sharing parameter.

The equilibrium in the cost reporting - monitoring game that arises after (or perhaps during) the completion of the principal's project depends crucially on the cost sharing parameter s. The principal does not monitor when when the cost sharing parameter is small. Thus, although the agent will almost certainly be padding his costs, in practice we should not observe a principal detecting overcharging when contracts involve only a small amount of cost sharing.

If the sharing parameter exceeds the critical level s^c, the principal will sometimes monitor a high cost report. Our analysis indicates that the equilibrium probability of monitoring increases with the cost sharing parameter s while the equilibrium probability of overreporting falls. At first glance it thus seems that a higher s can be associated with either a higher or lower frequency of detected cheating, depending upon which effect dominates. In fact, it can be shown that as s increases beyond s^c, the probability that the agent is caught cheating, $(1-p)\ell m$, actually falls. Thus, our model predicts that the probability an agent is detected cheating should fall as the cost sharing parameter approaches one.

In selecting the optimal sharing contract, the principal raises s until the marginal loss stemming from the agent's ex post cheating and reduced effort just equals the marginal benefit from reducing the winning bidder's ex ante informational rents. The winning bidder's ex ante informational rents are greater the smaller number of producers competing for the principal's project and the more diffuse are competitors' expected costs. Thus, the smaller the number of producers and the more diffuse their expected costs, the higher the level of cost sharing that we should observe.

Interestingly, the optimal sharing parameter does not necessarily move smoothly in response to a change in the underlying parameters. For example, let us examine what happens when we raise N, the number of competing producers, holding the other parameters constant. If N is large, the optimal sharing parameter with costly monitoring will be $s^* = \hat{s}(N) < s^c$. Because the principal can credibly commit not to monitor when the contract offers the cost sharing parameter, $\hat{s}(N)$, that is optimal when monitoring is costless, the optimal sharing parameter with costly monitoring is also $\hat{s}(N)$. As discussed above, a fall in N raises $\hat{s}$ and thus the optimal cost sharing parameter. If N falls sufficiently, $\hat{s}(N)$ will rise above s^c, but as long as N is not too small, it will not pay the principal to offer a cost sharing parameter above s^c, as the loss from offering the sharing rule s^c, below $\hat{s}(N)$, will be smaller than the loss from monitoring that would arise were the principal to offer a sharing parameter above s^c.

For a sufficiently small N, say N', the loss from keeping the sharing parameter fixed at s^c will be sufficiently high that it pays for the principal to offer a sharing parameter that induces monitoring in the cost reporting game. Thus, when the number of competing producers falls from N' + 1 to N', the optimal sharing parameter jumps to $s' > \hat{s}(N') > s^c$. Because an increase in s raises the gains from monitoring and, thus, lowers the frequency with which the agent overstates cost in equilibrium, the optimal sharing parameter s' exceeds the costless monitoring sharing rule $\hat{s}$. Note that as a further reduction in N below N' will cause the optimal sharing paramter to rise above s', a sharing parameter between s^c and s' can never be optimal. Thus, our model suggests that in practice a principal may choose either a small or a high cost sharing parameter parameter, but will have an incentive to avoid intermediate values of s.

Finally, we should note that our model provides a possible explanation for the phenomenon of 'cost overruns'. A cost overrun occurs when the realized cost of a project exceeds the winning bid. Cost overruns have received a great deal of attention in connection with government contracting, where they are often interpreted as a sign of fraud or mismanagement. With costless monitoring, one can show that the difference between an agent's bid $B(c_i)$ and expected cost, $c_i - e$, is given by

$$B(c_i) - c_i - e = \frac{\int_{c_i}^{c_H} [1 - F(c)]^{N-1} dc}{[1 - F(c_i)]^{N-1}} + \frac{1}{1 - s} \nu(e) . \tag{27}$$

According to (27), a producer's bid exceeds his expected cost because the producer attempts to obtain compensation for the disutility of effort and to benefit from his private cost information. Since bidders bid more than their expected cost, on average there is a tendency not for cost overruns, but cost underruns.

Systematic overruns become possible only when one introduces costly monitoring.[27] For instance, recall that when the principal offers a pooling contract, producer i's bid is given by

$$B(c_i) = c_i + \frac{\int_{c_i}^{c_H} [1 - F(c)]^{N-1} dc}{[1 - F(c_i)]^{N-1}} - e + \frac{1}{1 - s} \nu(e) - \frac{1- p}{1 - s} s(\theta_H - \theta_L) .$$

Because an agent who bids $B(c_i)$ will always report his cost to be $c_i - e + \theta_H$, his expected cost overrun is given by

$$c_i - e + \theta_H - B(c_i) = \theta_H + \frac{1- p}{1 - s} s(\theta_H - \theta_L) - \frac{\int_{c_i}^{c_H} [1 - F(c)]^{N-1} dc}{[1 - F(c_i)]^{N-1}} - \frac{1}{1 - s} \nu(e), \tag{28}$$

which is positive if $\theta_H + \frac{1-p}{1-s} s(\theta_H - \theta_L) > \frac{\int_{c_i}^{c_H} [1 - F(c)]^{N-1} dc}{[1 - F(c_i)]^{N-1}} + \frac{1}{1-s} \nu(e).$

As an agent both inflates his cost ex post and lowers his ex ante bid in anticipation of the gains from cheating, systematic cost overruns may now occur.[28]

An increase in the number of bidders and a decrease in the variance of idiosyncratic cost both dampen the agent's tendency to shade his bid above expected cost, which shows up formally as a reduction in the term $\int_{c_i}^{c_H} [1 - F(c)]^{N-1} dc/[1 - F(c_i)]^{N-1}$. Thus, although we cannot establish with certainty that there will be systematic cost overruns, we see that cost overruns are more likely the larger the number of bidders and the smaller the variance of idiosyncratic cost. We do not have a clear prediction concerning the relationship between the level of cost sharing and the likelihood of cost overruns.

Although cost overruns have provoked much public criticism, the more meaningful question from an economist's point of view concerns whether the overreporting of realized costs has any impact on the surplus accruing to the agent and the principal. Our results indicate that as long as $N \geq 2$ the ex post private information problem has no real effect on an agent's expected surplus because producers bidding for the principal's project will compete away any ex post gain from overreporting cost. Whether the agent's overreporting of costs reduces the principal's surplus depends on whether or not the principal can credibly commit not to monitor when the contract offers the optimal "costless monitoring" cost sharing parameter. If so, then $s^*=\hat{s}$, and the overreporting of realized cost ex post does not affect the principal's welfare. If not, then the principal chooses a cost sharing parameter either strictly smaller or greater than the costless monitoring sharing rule, and suffers losses as a consequence of his inablility to commit.

Footnotes

1. This paper was coauthored with my advisor Mark. A. Loewenstein.

2. "Rockwell Division gets Suspension on U.S. Contracts", Wall Street Journal, November 11, 1991, p. A5.

3. See Kovacic (1991), pp. 231-2, or McAfee and McMillan (1988), p. 85.

4. Baron and Besanko (1987) also reach this conclusion in a similar model with a risk-averse agent.

5. It is also assumed that $\nu(0) = 0$ and $\nu'(0) = 0$.

6. It might seem more reasonable to assume that the principal can observe less accurate signals at smaller cost, but little is lost by our assumption that he either observes cost perfectly or not at all. Presumably, the principal can punish the agent for overstating cost only if the principal's cost signal achieves some minimal level of accuracy. Since both the principal and the agent are risk-neutral, the principal gains nothing by obtaining a signal whose accuracy exceeds the minimum required level .

7. Our results would not be altered substantially if part or all of the penalty consists of a payment to the principal. In government contracting, both fines and exclusion from competition are common as penalties.

8. This interpretation of L is consistent with the model only if the contract guarantees positive expected profits in equilibrium. As shown below, this is true provided the number of bidders is not too large.

9. Because the marginal cost and benefit of effort do not depend on θ, it makes no difference whether effort is chosen before or after the realization of θ.

10. In the case where effort is chosen after θ is realized, it is straightforward to show that it does not pay the low cost agent to mimic the high cost agent's realized cost by choosing a smaller level of effort.

11. If $(1 - p)s[\theta_H - \theta_L] < K_m$, then the equilibrium is obviously unique. If $(1 - p)s[\theta_H - \theta_L] = K_m$, there are many pooling equilibria. The absence of a unique solution stems from the principal's indifference between monitoring and not monitoring. In this case, the agent's strategy and the principal's beliefs are as described above, but the probability of monitoring may take any value between 0 and and the "mixed strategy" equilibrium monitoring probability, defined below. Below we demonstrate that the principal can minimize his ex ante expected cost by committing not to monitor when $(1 - p)s[\theta_H - \theta_L] = K_m$. This commitment is credible since the principal can gain nothing by reneging on his promise ex post. In the analysis below, we therefore assume that m=0 when $(1 - p)s[\theta_H - \theta_L] = K_m$.

12. For given s, the pooling equilibrium is more likely the smaller the probability of the low cost outcome and the higher the cost of monitoring, K_m.

13. Expected cost c_i includes opportunity cost, so the ex ante cost heterogeneity may in part reflect differing alternative production opportunities for the agents.

14. Our methodology for finding the optimal bidding strategy follows McAfee and McMillan (1987).

15. Note that we are assuming that bidder i knows that other bidders follow the bidding strategy $B(\cdot)$. We are also implicitly assuming that $s < 1$. If $s = 1$, then the principal's payment to the agent will be independent of the bid. Because all agents will pretend to have the lowest possible expected cost c_L, their bids will fail to reveal the lowest cost producer. Note that $s=1$ could never be optimal for the principal, since an s arbitrarily close to 1 induces the same cost reporting outcome and essentially the same effort, while ensuring selection of the lowest cost bidder.

16. Although the cost padding has no real effects on project cost, it may cause the equilibrium bid to be significantly lower than ex post reported cost, so that there are "cost overruns". Of course, the principal should anticipate these cost overruns. This issue is addressed further below.

17. Note that although the agent's acutal bid $B(c_i)$ does not change, the bid now corresponds to a smaller expected payment.

18. McAfee and McMillan consider the more complicated case where bidders are risk averse.

19. We assume that $\lim_{s \to 1} G'(s) > 0$, so that $\hat{s} < 1$ exists. We also assume $\nu'''(e) \leq 0$, which is sufficient to guarantee that the second order condition is satisfied.

20. Holt (1982) has demonstrated that the equilibrium bid decreases as N increases. The result follows from the properties of order statistics.

21. We are unable to say in general whether the rent $B(c_i) - c_i$ is increasing or decreasing in c_i.

22. Given $\partial e/\partial s = -1/\nu''(e)$, effort is very sensitive to changes in s if the disutility of effort increases at a slowly increasing rate.

23. Given that $E(\theta_t) = p\ \theta_H + (1 - p)\ \theta_L = 0$, a mean preserving change in the distribution of θ requires that the value of θ_H and/or θ_L change as well. However, no particular relationship between the probabilities and the absolute difference between high and low costs $(\theta_H - \theta_L)$ is implied.

24. We assume that $\lim_{s \to 1} \mathcal{C}'(s) > 0$, so that $\bar{s} < 1$.

25. We have chosen to break the tie when $\mathcal{C}(\bar{s}) = G(s^c)$ by assuming that the principal chooses the pooling contract.

26. Our earlier assumption that the principal can commit to not monitoring when he is indifferent ($s=s^c$) plays a critical role here. If instead he chooses a positive probability of monitoring when $s=s^c$, then s^c is not the lowest cost pooling contract, because a cost sharing

parameter arbitrarily close to s^c offers a smaller total cost. In this case, if $\mathcal{C}(\bar{s}) > G(s^c)$ then, strictly speaking, the optimal contract does not exist. This should not pose a problem in practice however, as the principal would simply choose a cost sharing parameter as close to s^c as possible.

27. Other factors, such as midstream changes in the project's specification, may also lead to cost overruns. Tirole (1986), Lewis (1986), and Arvan and Leite (1990) examine other possible sources of cost overruns.

28. Other things the same, a pooling contract leads to greater average cost overruns than a mixed strategy contract. Nevertheless, it is straightforward to show that the expected cost overrun may be positive when the principal offers a mixed strategy of contract.

APPENDIX

We first verify that the expression:

$$c_i + \frac{\int_{c_i}^{c_H} [1 - F(c)]^{N-1} dc}{[1 - F(c_i)]^{N-1}}$$

which constitutes the component of the bid related to the agent's idiosyncratic cost, is equivalent to the expectation of the second lowest idiosyncratic cost, conditional on the lowest cost being c_i.

More generally, let $c_{(2)}$ represent the second-order statistic and $c_{(1)}$ the first order statistic from the sample $[c_1 \ldots, c_N]$. We will demonstrate that:

$$c_i + \frac{\int_{c_i}^{c_H} [1 - F(c)]^{N-1} dc}{[1 - F(c_i)]^{N-1}} = E(c_{(2)} \mid c_{(1)} = c_i)$$

Let $F_{(2)}(c \mid c_{(1)} = c_i)$ represent the distribution of the second-order statistic, conditional on the value of the first order statistic being c_i. We have:

$$F_{(2)}(c \mid c_{(1)} = c_i) = \text{Prob}\left\{ \min [c_2 \ldots, c_N] \leq c \mid \min [c_2 \ldots, c_N] > c_i \right\}$$

$$= 1 - \text{Prob}\left\{ \min [c_2 \ldots, c_N] > c \mid \min [c_2 \ldots, c_N] > c_i \right\}$$

This yields the distribution function and probability density function:

$$F_{(2)}(c \mid c_{(1)} = c_i) = 1 - \frac{[1 - F(c)]^{N-1}}{[1 - F(c_i)]^{N-1}}$$

and $f_{(2)}(c \mid c_{(1)} = c_i) = \dfrac{(N-1)\, [1 - F(c)]^{N-2} f(c)}{[1 - F(c_i)]^{N-1}}$

The expectation of the second order statistic, conditional on the first order statistic being c_i is therefore given by:

$$E(c_{(2)}|\ c_{(1)} = c_i) = \int_{c_i}^{c_H} c\ \ f_{(2)}(c \mid c_{(1)} = c_i)\ dc = \frac{(N\text{-}1)\int_{c_i}^{c_H} c\ \ [1 - F(c)]^{N-2} f(c)\ dc}{[1 - F(c_i)]^{N-1}}$$

$$E(c_{(2)}|\ c_{(1)} = c_i) = \frac{1}{[1 - F(c_i)]^{N-1}} \cdot \left\{ \int_{c_i}^{c_H} c\ [1 - F(c)]^{N-2}\ f(c)\ (N - 1)\ dc \right\}$$

Denote the term in brackets by A. Integrating A by parts yields:

$$A = c_i\ [1 - F(c_i)]^{N-1}\ + \int_{c_i}^{c_H} [1 - F(c)]^{N-1}\ dc$$

Therefore:

$$E(c_{(2)}|\ c_{(1)} = c_i) = \frac{A}{[1 - F(c_i)]^{N-1}} = c_i + \frac{\int_{c_i}^{c_H} [1 - F(c)]^{N-1} dc}{[1 - F(c_i)]^{N-1}}$$

The component of the bidding strategy involving the agent's idiosyncratic cost is therefore identical to the expected second order statistic, conditional on the first order statistic being c_i.

□

We next prove that as N increases, the bidder's ex ante information rent declines, as asserted in the text. Given:

$$G(s) \equiv N\int_{c_L}^{c_H} \left\{c + (1 - s)\,\frac{F(c)}{f(c)} - e + \nu(e)\right\} [\,1 - F(c)]^{N-1} f(c)\ dc$$

the expected ex ante informational rent paide by the principal, denoted by R(s; N), is:

$$R(s;\ N) = N\int_{c_L}^{c_H} (1 - s)\,\frac{F(c)}{f(c)}\,[1 - F(c)]^{N-1} f(c)\,dc$$

Note that $R(s;\ N) = (1 - s)\ E\left\{ E(c_{(2)} | c_{(1)}) - c_{(1)} \right\} = (1 - s) \left\{E(c_{(2)}) - E(c_{(1)})\right\}$. Thus, R(s;N) is just a fraction of the expected difference between the first-order and second-order statistics.

R(s; N) decreases as N increases if:

$$N\int_{c_L}^{c_H} (1 - s)\,\frac{F(c)}{f(c)}\,[1 - F(c)]^{N-1} f(c)\,dc > (N+1)\int_{c_L}^{c_H} (1 - s)\,\frac{F(c)}{f(c)}\,[1 - F(c)]^{N} f(c)\,dc$$

Note that $N[1 - F(c)]^{N-1}f(c) = f_{min}(c;\ N)$. Consider first how an increase in N affects the density function. Given $f_{min}(c;\ N+1) = (N+1)[1 - F(c)]^N f(c)$, we will have $f_{min}(c;\ N) > f_{min}(c;\ N+1)$ if:

$$\frac{N}{N+1} > [1 - F(c)]$$

Let c^* denote the critical c such that:

$$\frac{N}{N+1} = [1 - F(c^*)]$$

Then for $c_L \leq c < c^*$ we have $f_{min}(c;\ N) < f_{min}(c;\ N+1)$ and for $c^* < c \leq c_H$, we have $f_{min}(c;\ N) > f_{min}(c;\ N+1)$. Intuitively, increasing the number of draws from the distribution raises the likelihood of a low minimum cost.

Based on these observations concerning the distribution f_{min}, it follows that if the inverse hazard function $\frac{F(c)}{f(c)}$ is non-decreasing we have:

$$N \int_{c_L}^{c_H} (1 - s) \frac{F(c)}{f(c)} [1 - F(c)]^{N-1} f(c)\, dc > (N+1) \int_{c_L}^{c_H} (1 - s) \frac{F(c)}{f(c)} [1 - F(c)]^{N} f(c)\, dc$$

and the expected ex ante informational rents paid by the principal decrease as the number of bidders increases.□

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Bidders observe c_i	Principal offers a contract	Bidding and selection of agent	Agent observes θ and chooses effort	Agent reports $\tilde{C}_i$	Principal chooses whether to monitor	Output and payments exchanged

Figure 2. Sequence of Events

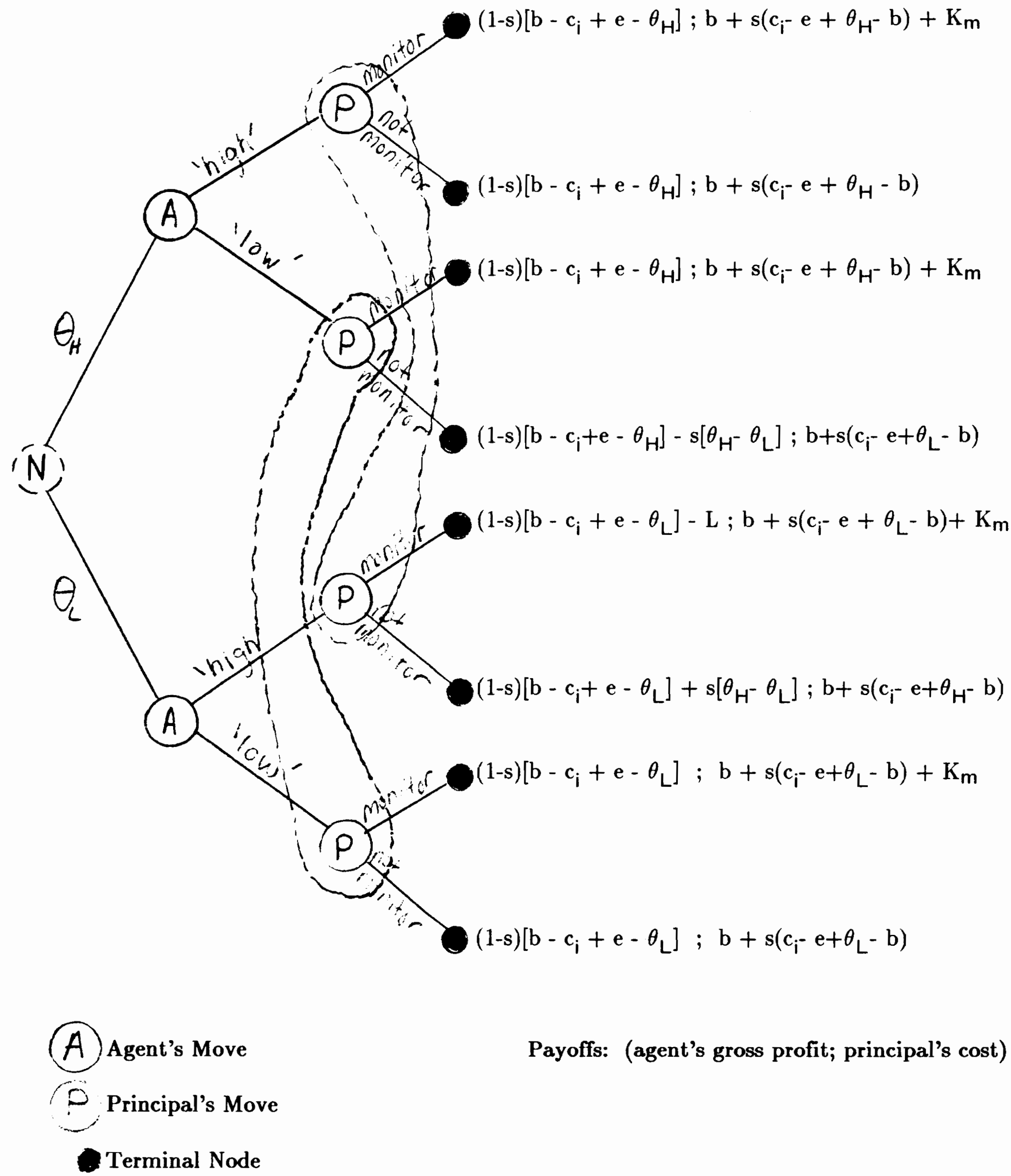
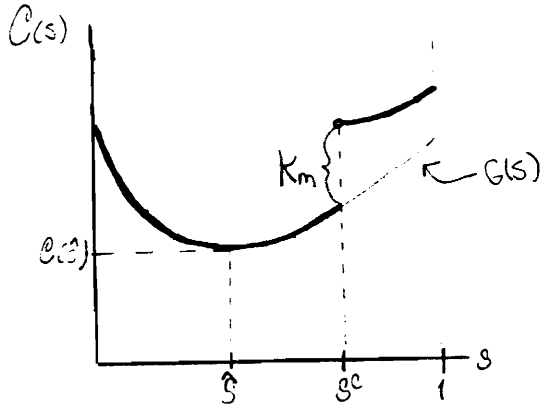
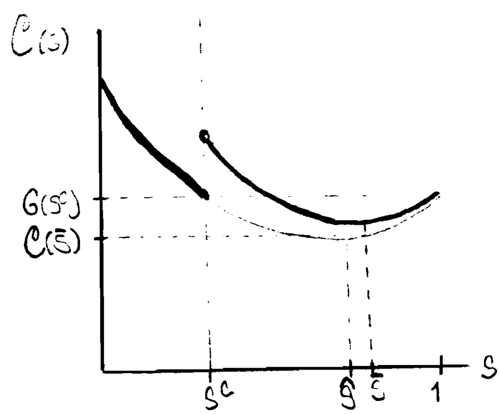


Figure 3. The Cost Reporting Game

Case A: $s^* = \hat{s}$



Case B: $s^* = \bar{s}$



Case C: $s^* = s^c$

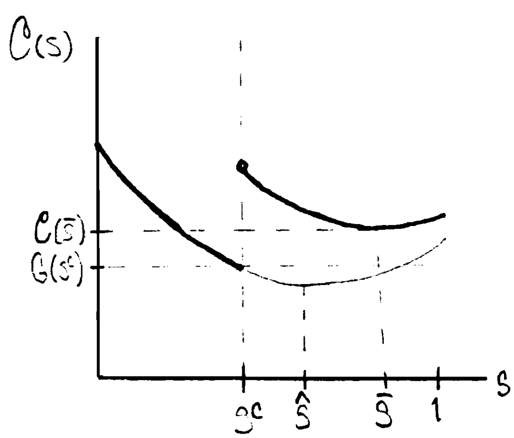


Figure 4. The Optimal Contract

Conclusion

The essays above have examined problems involving contracting in the presence of adverse selection and moral hazard. The first essay investigates the interactions between risk aversion, adverse selection, and moral hazard which result when contracting and the agent's effort take place before the firm becomes informed. The second essay examines how costly monitoring affects the optimal linear incentive contract.

In the first essay, the government contracts with a risk-averse, uninformed firm who privately discovers the state of nature prior to production. Before discovering the cost of the project, the producer may take costly and unobservable actions which affect cost. The model resembles the standard principal-agent model with an added element of adverse selection: the contract may be contingent on the state of nature observed privately by the agent after contracting. The motivation behind this formulation is that both risk-aversion and private information seem to play an important role in government contracting.

The analysis demonstrates that there is a fundamental conflict between insuring the agent ex ante and eliciting his private information ex post. An incentive compatible contract must reward lower costs with higher profits. Cost sharing and distortion of output below the full-information level in the high cost state will be employed to reduce the uncertainty in profit necessary to induce revelation, provided that the adverse selection problem is more costly than the moral hazard problem.

The primary result of the model concerns how the effort investment made by the uninformed agent affects the cost of eliciting the agent's private information after he becomes informed. Since the return to effort is increasing in output, an up-front investment in effort lessens the agent's incentive to overstate cost, i.e. produce an inefficiently low level of output. Because of this beneficial incentive effect, the principal would prefer a level of effort such that the marginal value of effort from cost reduction is smaller than the marginal cost of effort. The principal would like to subsidize effort in order to reduce the cost of the adverse selection problem.

Competition for the contract is not considered explicitly in my model, however note that the firm need not be the only available producer. As in the principal-agent model, the optimal contract guarantees the agent an exogenous level of expected utility, which may have been determined either through prior competition or through negotiation between the firm and the government. Therefore, the model may represent a situation in which the market for contracts is initially competitive, and the agent awarded the contract acquires an informational monopoly after an initial period of investment.

The second essay examines the optimal linear incentive contract to offer to potential agents who possess independent private estimates of the project's expected cost and may affect the cost outcome ex post through costly, unobservable effort. The several previous analyses of optimal incentive contracting under adverse selection and moral hazard assume that the principal costlessly observes either realized cost or an unbiased signal of realized cost ex post. In these models, the principal chooses the cost sharing parameter to balance the cost of the moral hazard and adverse selection problems at the margin.

We introduce the possibility that monitoring is costly. In this case, cost sharing gives the agent an incentive to overstate his realized cost ex post. Allegations of this type of overcharging are common in practice. Restricting attention to monitoring policies which are subgame perfect, we find that agent will pad his ex post cost report with positive probability. Moreover, despite the presence of competition for the contract, the agent's overreporting generally affects the principal's expected cost and thus, the optimal contract.

We find that the agent's cost padding does not affect the principal's cost if and only if the sharing rule which is optimal when monitoring is costless induces pooling when monitoring is costly. If the optimal sharing parameter when monitoring is costless would induce a mixed strategy outcome when monitoring is costly, and if the cost associated with the agent's ex post cheating is high enough to outweigh the beneficial net effect of raising s on the ex ante adverse selection/moral hazard problems, the principal will choose the highest level of cost sharing which induces pooling, s^c. Thus, the principal may distort the cost sharing parameter below the level which is optimal when monitoring is costless to enable him to commit not to monitor ex post. If, however, the cost stemming from the agent's cost padding is small, relative to the net gain from increasing s beyond the pooling level, then the principal chooses a mixed strategy contract. In this case, the optimal level of cost sharing is strictly greater than the level of cost sharing which is optimal when monitoring is costless. By increasing cost sharing beyond the costless monitoring level, the principal increases the gains to monitoring which lowers the probability of cheating in equilibrium. The expected information premium paid to the agent is thereby reduced.

There is a parallel between this result and that of Khalil. Recall that he found, in the context of a pure adverse selection model, that the inability to commit to a monitoring policy led to 'overproduction' in comparison with the full-information benchmark. The increased output enabled the principal to commit to an increased probability of monitoring. Likewise, we find that when the optimal 'costless monitoring' sharing parameter induces a mixed strategy outcome in period two, the principal distorts the cost sharing parameter from its optimal level when monitoring is costless to enable him to commit to either a higher or lower probability of monitoring.

Our model yields several predictions concerning the optimal sharing rule. We have shown that the bidder's ex ante information rents increase as the number of bidder's decline and the variance of their expected costs increases. This gives two potentially testable predictions. First, our model predicts that the cost sharing parameter should be higher, the smaller N and the more diffuse the bidder's expected costs. Second, other things equal, an increase in ex ante informational rents reduces the likelihood that a cost overrun will be observed. Our model thus predicts a positive correlation between cost overruns and the number of bidders and a negative correlation between overruns and the variance of the bidder's expected costs. Put differently, cost overruns should increase as the market for the contract becomes more competitive. The testing of these hypotheses is a topic for future research.

Vita

Stephanie West was born in Alexandria, Virginia, in October 1959. She received her B.A. in Economics from the College of William and Mary in 1981, entered the Virginia Polytechnic Institute and State University in September, 1987, and received her Ph. D. in July 1992.

Stephanie West