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FINAL TECHNICAL REPORT

Paul R. Kleindorfer

decision sciences

The Wharton School
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FINAL TECHNICAL REPORT

Paul R. Kleindorfer

September, 1980

Prepared for the
Office of Naval Research
Information Systems
Arlington, VA 22217

under

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This Technical Report is the Final Report on the Research Project, "Internal Financial Incentives in Systems Acquisition", which was conducted at the University of Pennsylvania between February, 1977 and July, 1980.

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This Report is the Final Report for the Research Project N0014-77-C-0171 on "Internal Financial Incentives in Systems Acquisition". It includes as an Appendix a final version of the major theoretical output of this research: a theory of multistage contractual incentives in the systems acquisition cycle. The theory proposed links up incentives in the development and production stages of systems acquisition in a unified framework. The impact of such incentives under various government contracting policies, environmental conditions, and market structures is analyzed. The results are illustrated with an extended numerical example.

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FINAL REPORT OF RESEARCH ON

"Internal Financial Incentives in Systems Acquisition"

PAUL R. KLEINDORFER, PRINCIPAL INVESTIGATOR

(CONTRACT N0014-77-C-0171) - O.N.R.

When we started this research in 1977, we were motivated primarily by an interest in how DoD could get more for its dollars through better design of internal financial incentives, e.g., Design-to-cost and various forms of incentives contracts. In the first year we explored institutional arrangements within DoD and between DoD and contractors in order to determine the major constraints on incentives contracts in system acquisition and the behavioral consequences of varying key design parameters on the contractual side of the system acquisition process. The second stage of our research, carried out over the last two and a half years, was concerned with a theoretical analysis of these same matters, with primary attention to the multi-stage nature of major system acquisition and the resulting dynamic analysis of interdependent development, production, deployment and operation contracts.

In providing a perspective on this research, the figure below is useful. In brief, DoD attempts to interpret and carry out the wishes of the public as represented by Congress. In the area of system acquisition, this entails engaging the services of agents (contractors), who have their own preferences and constraints. These latter must be respected in designing contractual incentives and monitoring and enforcement procedures associated with the system acquisition process.

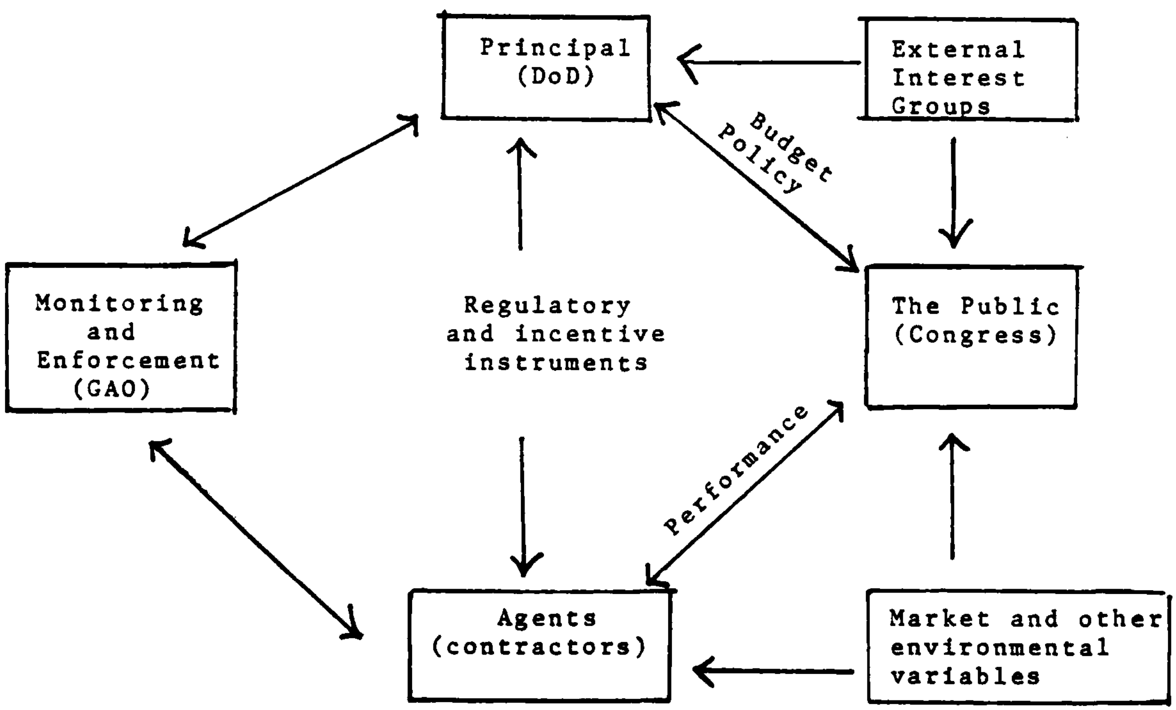

Figure: The Institutional Setting for System Acquisition

A number of interesting research questions are apparent from the above Figure. We have primarily been concerned with general principal-agent (i.e., DoD-contractor) incentive problems and with the more specific form these take under Design-to-cost contractual arrangements. In the general case, a series of papers by Kleindorfer and Sertel have worked out the theoretical relationship between various classes of incentives and contractor performance. This work is cast in the context of a profit-maximizing entrepeneur who, through incentives and related information systems, motivates a set of other agents to cooperate in an endeavor at some cost to themselves. The framework in these papers suggests that optimal design of incentives must draw a delicate balance between the performance effects of incentives and the monitoring and transactions costs of implementing them. Also apparent from this work is the importance of what other market opportunities are available to agents, as this restricts the range-of-acceptance of incentive contract terms and potentially affects their behavior in other ways which we explore further below.

A second strand of theoretical research undertaken was in the decision processes area. In joint work by Kleindorfer and Kunreuther, the question was studied as to what the implications for incentives and regulation would be of changing the standard economic assumptions of perfect rationality and information to more plausible assumptions regarding a firm's planning process. Such changes imply enormously different conclusions for the design of regulatory and incentival mechanisms directed at such firms. The concrete empirical exploration of these matters in the systems acquistion area remains a key open research issue for the future.

Having delineated a reasonable theoretical structure in general terms, we turned our attention to the more specific problem of Design-to-Cost (DTC) contracts. Although DTC has been viewed as a life cycle costing system and a production cost control system, we have viewed it in this research as an incentive system in which lower levels of DoD are rewarded for effecting cost savings and penalized for incurring cost overruns.

Our work emphasizes two characteristics of the DTC system. The first is its dynamic properties. The weapons acquisition process is viewed as a multistage process whose characteristics change substantially over time. The process includes the following three steps: (1) a development stage in which one or more contractors receive funds to design and test a prototype system, at the end a single contractor is awarded a production contract; (2) a production stage in which the winning contractor produces one or more copies of the system; and (3) an implementation and maintenance stage in which the system is maintained and modified in the field, often with some contractor support. Since the principal interactions occur between the first two stages (i.e., contractors behave differently than they otherwise would during the development stage in the hope of being awarded the production contract), we have confined our analysis to these two stages. We assume that the development contract is a fixed-price contract and the production contract includes (1) full cost recovery, (2) a reward or penalty depending on the cost of production relative to a preselected cost target, and (3) a reward or penalty depending on system performance relative to a preselected preformance target.

The second characteristic of the DTC system emphasized in our research is the hierarchical nature of the system. Important informational and decisional processes occur at four levels of the government/contractor hierarchy. At the highest level, representing the Congress and the administration, DTC goals and allowable probabilities of exceeding these goals were established. At a second level, representing DoD and the appropriate military service, the DTC goal is partitioned into two subgoals, one for the development stage and one for the production stage, and the contractors participating in the development stage are selected. At a third level, representing the military service and its project managers, most of the parameters in the incentive system are established and the production contract is awarded. At the fourth level, representing the contractors, contract parameters are established as are the levels of contractor effort (hiring personnel, purchasing raw material, etc.) for the two stages.

Within the above context we studied how DoD should design DTC incentives to achieve tradeoffs between overall project cost, including incentive payments, and the quality of the end product. This involves considerable effort in understanding and modeling the effects of the parallel development efforts on cost and performance. In this regard, the amount of effort a given contractor will be willing to expend, when he is engaged in competitive development activities, can be expected to depend on the likelihood of his carrying its design through into production, as well as the relative benefits of so doing. We conclude that the two critical elements in predicting the outcome of DTC incentives with parallel development activities are:

(1) how contractors conceive their chances of success in relation to the competition, and (2) what other market opportunities they have for deploying their resources outside of the project in question. We have pursued these matters in some detail and their relative cost-effort-performance efficiencies in relation to cost-overrun and performance incentives in development and production contracts. The results of this theoretical work, discussed in detail in the Technical Report by Blanning, Kleindorfer, and Sankar,* are highly interesting and rich in policy implications.

* (See Appendix of this Report for the final revised version of this Technical Report.)

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BIOGRAPHY OF THE PRINCIPAL INVESTIGATOR

PAUL ROBERT KLEINDORFER is a 1961 graduate of the U.S. Naval Academy. After completing his service obligation, he studied mathematics at Eberhard-Karl University in Tübingen and then entered the Doctoral Program (GSIA) at Carnegie-Mellon University from which he graduated in 1970. Professor Kleindorfer has held teaching and research appointments at Carnegie, M.I.T., and the International Institute of Management (Berlin) before coming to his present post at the University of Pennsylvania, where he is Professor of Decision Sciences. Professor Kleindorfer's current research is concerned with incentives and regulation, with special emphasis on public utilities and federal procurement policy.

APPENDIX

Revised Technical Report 80-06-08

"A Theory of Multistage Contractual Incentives
with Application to Design-to-Cost"

by

Robert W. Blanning

Paul R. Kleindorfer

C.S. Sankar

University of Pennsylvania
The Wharton School
Department of Decision Sciences

TECHNICAL REPORT
80-06-08

A THEORY OF MULTISTAGE CONTRACTUAL INCENTIVES WITH APPLICATION TO DESIGN-TO-COST

Robert W. Blanning
Paul R. Kleindorfer
C. S. Sankar

July, 1980

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I. Introduction

A topic of increasing importance in public-sector management is the design and implementation of financial incentive systems that will encourage lower-level government units and profit-making organizations under contract to these units to use government funds efficiently and satisfy nonfinancial government objectives. One such incentive system is the Design-to-Cost (DTC) system, implemented for many major weapons acquisition projects in the Department of Defense [5, 14] in which a DTC goal is established for each project. Any deviations from the goal are corrected by changing the performance of the weapons system or by changing the number of weapons produced, or both. This paper constructs a simple model of the information, incentive and decision aspects of such an incentive system and offers insights into the tradeoffs and policy issues involved.

There is substantial literature on the theory of contracts [15, 8] and the design of incentives [2, 6, 7, 10, 9]. However, an examination of this literature discloses the need for research in two areas that are essential to an understanding of the weapons acquisition process. The first need arises whenever a development effort precedes a production effort. The dynamic incentive process--that is, a multistage process in which contractor behavior during any one stage is affected, by the incentives operative during that stage, and by an expectation of rewards or punishments in the subsequent stages--is not addressed by the literature. The second need arises due to lack of consideration of any but the most simple of hierarchies. Yet in any large government/contractor effort, the government is represented by at least three distinct organizations (the Congress, the Administration, and the

Bureaucracy), and the contracting agent may be represented by several organizations as well (e.g., contractors and subcontractors). This paper addresses both the dynamic and hierarchical aspects of contracting in the DTC context (see [12], [1]).

The weapons acquisition process is viewed here as a multistage process whose characteristics change substantially over time. The acquisition process consists of (at least) three steps: (1) a development stage in which two or more contractors receive funds to design and test a prototype weapon, at the end of which a single contractor is awarded a production contract; (2) a production stage in which the winning contractor produces one or more copies of the weapon; and (3) an implementation and maintenance stage in which the weapon is maintained and modified in the field, often, with some contractor support. The principal interactions occur between the first two stages (i.e., contractors behave differently during the development stage as the award of the production contract is uncertain). Hence, we will confine our analysis to the first two stages. We assume that the contract during development stage is a fixed-price contract and the contract during production stage is an incentive contract including (1) full cost recovery, (2) a reward or penalty depending on the cost of production relative to a negotiated cost target, and (3) a reward or penalty depending on weapon performance relative to a prespecified performance target.

The hierarchical nature of the DTC system is also emphasized in our research. We examine four levels of government and contractor hierarchy. At the highest level, representing the Congress and the Administration, DTC goals and allowable probabilities of exceeding these goals are established. (Weapon cost and performance are assumed to be random variables whose mean values are controllable.) At the second level, representing DoD and the appropriate military service, the DTC goal is partitioned into two subgoals, one for the development stage and one for the production stage, and the contractors participating in the development stage are selected. At the third level, representing the military service and its project managers, most of the parameters in the incentive system are established and the production contract is awarded. (In our analysis, we assume that the decisions at this level are established by decision rules known in advance to both the government and the contractors.) At the fourth level, representing the contractors, contract parameters are negotiated and the levels of contractor effort (number of personnel, cost of raw material, etc.) are chosen for the two stages.

In the following section a model of the DTC incentive system is developed. We show that under specified conditions, the contractors will compete during the development stage, but the winner of the production contract will put forth minimal effort during the production stage. The characteristics of a DTC incentive system that give rise to this behavior are identified. The model is solved to determine the impact of government decisions (contractual incentive parameters, the allocation of the DTC goal between development and production stages, and the level of risk acceptable to the government) and the technological and market environment of the project on outcomes such as the quality of the weapon produced, the cost to the government, the profit of the firms in the industry, the risks assumed by the government and the risks assumed by the firms. Some of the policy implications of the model are then illustrated by a series of examples.

II. The Basic Model

We consider a given project and assume that Congress has established a Design-to-Cost (DTC) goal, G, for the project. G is understood to be a constraint on total project cost and it is assumed that G may be exceeded only with ex ante probability γ. One might anticipate that DoD would set γ strategically to trade off the transactions costs of exceeding budgets and exposing itself to (re)appropriations hearings against the internal transactions costs which occur if γ is small.

We assume that n firms have been preselected[1] as candidates for carrying out the project, in two stages. In the development stage, the n firms compete against one another in producing the best design. In the second stage, the firm with the best first-stage design is awarded (the opportunity to bid on) a production contract. To state the problem precisely we need the following notation.

e_{si} = Effort expended by firm i in stage s. In the development stage, s = d, and in the production stage, s = p;

$Q_{si}(e_{si})$ = Quality (or performance level) achieved by firm i in stage s;

$C_{si}(e_{si})$ = Costs incurred by firm i in stage s as a function of effort expended.

DoD is assumed to consider the following types of contract. All development contracts are firm fixed price contracts with each of the n firms involved receiving G_d/n dollars. $G_d \le G$ is therefore the total development cost to the government. The production contract, if awarded to firm i, is assumed to be a general incentive contract with payments above costs to firm i specified as:

$$(1) \qquad \tilde{\Pi}_{pi}(T_{pi}, e_{pi}, \tilde{Q}_d) = a\,T_{pi} + b\,[T_{pi} - \tilde{C}_{pi}(e_{pi})] + R_i\big(\tilde{Q}_d + \tilde{Q}_{pi}(e_{pi})\big),$$

where random quantities have a ˜ over them, and where

T_{pi} = Target cost rate, negotiated by firm i at the beginning of the production stage; T_{pi} is assumed constrained to be nonnegative (negative bids are not allowed);

Q_d = Cumulative progress in quality of the project during the development stage, which is the starting point for the production stage;

a,b = Contract incentive parameters, where $a \geq 0$, $0 \leq b \leq 1$;

R(q) = Performance incentive payment, for firm i, expressed as a function of total quality achieved over both stages.

At the end of the development stage, DoD would have spent exactly G_d dollars, leaving $G_p = G - G_d$ dollars in the overall project budget. Suppose firm i achieves the best performance in the development stage, i.e., suppose

$$(2) \qquad \tilde{Q}_{di}(e_{di}) = \tilde{Q}_d = \max_{1 \leq j \leq n} \tilde{Q}_{dj}(e_{dj}) \quad .$$

We assume that if (2) obtains, then firm i is given the exclusive right to bid on a production contract. In a realistic setting, one might assume that more than one of the leading firms at the end of the development stage is given the opportunity to bid on a production contract. This possibility is excluded here. Thus, it is assumed that the leading development firm, say i, is interested at the beginning of the production stage in setting T_{pi}, e_{pi}, a and b so as to maximize its profits in development stage $\bar{U}_{pi}(T_{pi}, e_{pi}, Q_d)$ where

(3) $\bar{U}_{pi}(T_{pi},e_{pi},Q_d) =$

$$E\,\{\tilde{\Pi}_{pi}(T_{pi},e_{pi},Q_d) + F_i\big(\tilde{Q}_{di}(e_{di}),\tilde{Q}_{pi}(e_{pi})\big)\,|\,\tilde{Q}_{di}(e_{di}) = Q_d\ ,$$

where $F_i(q_d,q_p)$ represents expected follow-on benefits to firm i (e.g., in terms of maintenance contracts, future benefits from the technology developed, etc.), $\tilde{\Pi}_{pi}$ is given in (1), and $\tilde{\Pi}_{pi} + \tilde{C}_{pi}$ represents total (incentive plus cost) payments made by the government in the production stage.

Of course, firm i will be subject to some constraints in indulging with its preferences as represented by (3). Indeed we assume that "a" is fixed in advance by the government and the following holds for variables (T_{pi},e_{pi},b):

(4) $$\Pr\,\{\tilde{\Pi}_{pi}(T_{pi},e_{pi},Q_d) + \tilde{C}_{pi}(e_{pi}) \geq G_p\} \leq \gamma,$$

where γ is specified by the Congress and the Administration. The fact that firms accept (4) as a constraint, of course, presumed that in the case of cost overruns, acceptable auditing practices, can expose and penalize firms which cannot make a credible ex post case that (4) was observed in their planning. This dependence of contractual incentives on (legitimate) enforcement and monitoring procedures cannot be overemphasized.

Beyond fixing "a" and imposing (4), we will assume that production contracts are negotiated through one of two methods[2] (firm i is the leading development firm):

Method 1, <u>M1</u>: "b" is fixed ex ante and any T_{pi},e_{pi} satisfying (4) will be accepted by DoD.

Method 2, <u>M2</u>: Firm i and DoD negotiation (T_{pi},e_{pi},b) at the beginning of the production stage such that (4) is satisfied and such that a Pareto efficient point is reached between firm i and DoD. The preferences of firm i are represented by (3). DoD is assumed to have preferences represented by a utility function $U_D(C,CO,Q)$, where $\tilde{Q} = \tilde{Q}_d + \tilde{Q}_{pi}(e_{pi})$ is final project quality, $\tilde{C} = G_d + \tilde{\Pi}_{pi} + \tilde{C}_{pi}$ is total project cost, and $\tilde{CO} = \tilde{C} - G$ is the cost overrun.

Formally, we may represent the two production stage decision processes just described as follows:

(5) <u>M1</u>: Maximize (3) with respect to (T_{pi},e_{pi}), subject to (4).

(5') <u>M2</u>: $$\underset{(T_{pi},e_{pi},b)}{\text{Maximize}} \Big[\alpha\bar{U}_{pi}(T_{pi},e_{pi},Q_d) +$$

$$(1-\alpha)\ E\{U_D\big(G_d+\tilde{\Pi}_{pi}+\tilde{C}_{pi},G_d+\tilde{\Pi}_{pi}+\tilde{C}_{pi}-G,Q_d+\tilde{Q}_{pi}(e_{pi})\big)\Big]$$

$$\text{s.t. } (4),\ T_{pi} \geq 0,\ e_{pi} \geq 0 \text{ and } 0 \leq b \leq 1,$$

where α is between 0 and 1 and reflects the relative bargaining power of the contractor against DoD, $\bar{U}_{pi}$ is defined in (3), $\tilde{\Pi}_{pi}$ is given in (1), $\tilde{C}_{pi} = \tilde{C}_{pi}(e_{pi})$ is the cost for the production stage, and Q_d is the observed realization of (2). We will define the optimal solution value to (5) or (5') as $V_{pi}(Q_d)$; this is the optimal expected return for firm i if the ending quality level in (2) is Q_d and firm i is awarded the production contract.

Now consider the development stage. Each of the n firms involved may be assumed to maximize the sum[3] of present benefits and expected follow-on benefits ($V_p(Q_d)$ if firm i is allowed to bid on the production contract). Expected follow-on benefits may then be written:

(6) $$\text{Expected follow-on Benefits} = \begin{cases} 0 & \text{if } \tilde{Q}_{di}(e_{di}) < \tilde{Q}_d \\ V_{pi}(\tilde{Q}_d) & \text{if } \tilde{Q}_{di}(e_{di}) = \tilde{Q}_d \end{cases}$$

From (6) we see that an expected profit-maximizing contractor would solve the following problem in determining his level of effort e_{di} in the development stage:

$$(7) \qquad \underset{e_{di}}{\text{Max}}\ E\ \{(G_d/n) - \tilde{C}_{di}(e_{di}) + V_{pi}\big(\tilde{Q}_{di}(e_{di})\big)\tilde{A}_i(e_{d1}, \ldots, e_{dn})\},$$

where $\tilde{C}_{di}(e_{1i})$ is the cost incurred in stage d for firm i and where $\tilde{A}_i(e_{d1}, \ldots, e_{dn})$ equal to 1 if $\tilde{Q}_{di}(e_{di}) = \tilde{Q}_d = \underset{j}{\text{Max}}\ \{\tilde{Q}_{dj}(e_{dj})\}$ and 0 otherwise. Note that the probability that firm i is allowed to bid on the production contract (i.e., $\Pr\{\tilde{A}_i = 1\}$) depends on the level of effort of all the n firms involved. Denote the optimal solution value in (7) by $V_{di}(\underline{e}_d, G_d, n)$, where $\underline{e}_d = (e_{d1}, \ldots, e_{dn})$.

The final step is the determination of $\underline{e}_d$. This problem may be formulated as a noncooperative game, with utility functions $V_{di}(\underline{e}_d, G_d, n)$. We are interested in a Nash solution $\underline{\hat{e}}_d = \underline{\hat{e}}_d(G_d, n)$ to this game, i.e., a joint strategy $\underline{\hat{e}}_d$ satisfying

$$(8) \quad V_{di}(\underline{\hat{e}}_d, G_d, n) = \text{Max}\ \{V_{di}(\hat{e}_{d1}, \ldots, \hat{e}_{di-1}, e_{di}, \hat{e}_{di+1}, \ldots, \hat{e}_{dn}) \mid e_{di} \geq 0\},$$

for every $i \in \{1, \ldots, n\}$.

Assuming $\underline{\hat{e}}_d(G_d, n)$ is unique (see below) for each G_d and n, the random variables $\tilde{C}$, $\tilde{CO}$, and $\tilde{Q}$ are determined by G_d and n through $\underline{\hat{e}}_d$. DoD is then interested in determining G_d (and possibly also n) so that its expected utility $E\{U_D(\tilde{C}, \tilde{CO}, \tilde{Q})\}$ is maximized. If firm i is awarded the production contract, then

$$(9) \qquad \tilde{C} = \text{COST} = G_d + (\tilde{\Pi}_{pi} + \tilde{C}_{pi})$$

(10) $$CO = \text{COST OVERRUN} = \tilde{C} - G,$$

(11) $$\tilde{Q} = \text{QUALITY} = \tilde{Q}_{di} + \tilde{Q}_{pi} \quad .$$

Thus, DoD wishes to set G_d (and possibly n) so as to

(12) $$\underset{0 \le G_d \le G}{\text{Max}} \sum_{i=1}^{n} E \{U_D(G_d + \tilde{\Pi}_{pi} + \tilde{C}_{pi}, (G_d + \tilde{\Pi}_{pi} + \tilde{C}_{pi} - G), \tilde{Q}_{di} + \tilde{Q}_{pi})\} \cdot \Pr \{\tilde{A}_i = 1\},$$

where all quantities are evaluated at $\hat{\underline{e}}_d(G_d,n)$, e.g.,

$$\tilde{\Pi}_{pi} = \tilde{\Pi}_{pi}\left\{T_{pi}(\tilde{Q}_{di}(\hat{e}_{di})),\ \hat{e}_{pi}(\tilde{Q}_{di}(\hat{e}_{di})),\ \tilde{Q}_{di}(e_{di})\right\},$$

where $\hat{T}_{pi}(Q_d), \hat{e}_{pi}(Q_d)$ are the optimal solution to (5)-(5') for given Q_d. Major problems occur in solving (5)-(5') and in obtaining $\hat{e}_d(G_d,n)$, to which we now turn.

III. Solution--Method 1

In order to obtain analytical results, it is necessary to make assumptions about the forms of the probability distributions and reward functions. Specifically we assume for each $i = 1, \ldots, n$ that:

1. $\hat{C}_{di}(e_{di})$ is random quantity with expected value e_{di}^2.

2. $\tilde{Q}_{di}(e_{di})$ is exponentially distributed, independently of $\{\tilde{Q}_{dj}(e_{dj}) | j \neq i\}$ with expected value $q_{di}e_{di}$, where $q_{di} > 0$.

3. $\tilde{C}_{pi}(e_{pi})$ and $\tilde{Q}_{pi}(e_{pi})$ are jointly normal with respective means e_{pi}^2 and $q_{pi}e_{pi}(q_{pi}>0)$, respective variances σ_{pi}^2 and η_{pi}^2, and with positive correlation coefficient δ_{pi}.

4. $R_i(Q) \equiv 0$, i.e., performance incentive payments are nil.

5. $F_i(Q_d,Q_p) = H_i + h_{di}Q_d + h_{pi}Q_p$, where $H_i, h_{di} \geq 0, h_{pi} \geq 0$ are constants.

For this data we may write (5) as

$$\max_{T_{pi},e_{pi}} [(a+b)T_{pi} - b\, e_{pi}^2 + H_i + h_{di}Q_d + h_{pi}q_{pi}e_{pi}] \tag{13}$$

subject to:

$$\Pr\{(a+b)T_{pi} - b\, \tilde{C}_{pi}(e_{pi}) + \tilde{C}_{pi}(e_{pi}) \geq G_p\} \leq \gamma \quad . \tag{14}$$

Collecting terms, (14) may be rewritten as:

$$\Pr\{[(1-b)\, \tilde{C}_{pi}(e_{pi})] \geq [G_p - (a+b)\, T_{pi}]\} \leq \gamma \quad . \tag{15}$$

Since $\tilde{C}_{pi}$, is normal, $(1-b)\, \tilde{C}_{pi}$ is also normal with mean $(1-b)\, e_{pi}^2$ and variance $(1-b)^2\, \sigma_{pi}^2$ so (15) may be expressed as

(16) $$[(1-b)\, e_{pi}^2 + (a+b)T_{pi} - G_p] + (1-b)\sigma_{pi}K(\gamma) \le 0$$

where $K(\gamma)$ is the $(1-\gamma)^{th}$ fractile of the unit normal, i.e., $\Pr\{\tilde{N}(0,1) \ge K(\gamma)\} = \gamma$.

Define $k_{pi}(\gamma,b)$ through

(17) $$k_{pi}(\gamma,b) = K(\gamma)(1-b)\,\sigma_{pi} \quad .$$

Then (16) becomes

(18) $$[(1-b)e_{pi}^2 + (a+b)\,T_{pi} - G_p] \le -\,k_{pi}(\gamma,b) \quad .$$

Thus, the constraint (14) may be written as (18). Since $b \le 1$, we see that (18) defines a convex region for every value of Q_d. Note also that $\partial k_{pi}/\partial\gamma < 0$ and $\partial k_{pi}/\partial b < 0$. Thus, as γ or b decreases the constraint region becomes larger. Similarly, as Q_d decreases the constraint region becomes larger.

To find the optimal T_{pi}, e_{pi} in (13), note that whatever e_{pi} is, the optimal T_{pi} will be set so that (18) holds an as an equality since otherwise firm i could simply increase T_{pi} with consequent higher profits. Solving for $(a+b)T_{pi}$ in (18), we see therefore that, at the optimum,

(19) $$(a+b)T_{pi} = G_p - k_{pi}(\gamma,b) - (1-b)e_{pi}^2 \quad .$$

Thus, substituting in (13) for $(a+b)T_{pi}$, the following problem characterizes the optimal e_{pi}.

(20) $$\text{Max } [-e_{pi}^2 - k_{pi}(\gamma,b) + G_p + H_i + h_{di}Q_d + h_{pi}q_{pi}e_{pi}],$$

subject to $e_{pi} \ge 0$ and $T_{pi} \ge 0$. Using (19), the nonnegativity constraint on

T_{pi} may be expressed in terms of e_{pi} as

(21) $$(1-b)e_{pi}^2 \le G_p - k_{pi}(\gamma,b) \quad .$$

Thus, the problem of interest is to maximize (20) subject to $e_{pi} \ge 0$ and (21). This simple quadratic programming problem has the solution

(22) $$\hat{e}_{pi} = \text{Min}\left\{\left(\frac{h_{pi}q_{pi}}{2}\right), \left(\frac{G_p - k_{pi}(\gamma,b)}{1-b}\right)^{\frac{1}{2}}\right\}$$

and the optimal target cost T_{pi} is therefore determined by (19) as

(23) $$\hat{T}_{pi} = \frac{G_p - (1-b)\hat{e}_{pi}^2 - k_{pi}(\gamma,b)}{(a+b)} \quad .$$

Finally, the optimal value of the objective function in (20) (respectively in (13)) is obtained by substituting $\hat{e}_{pi}$ for e_{pi} in (20). This yields

(24) $$V_{pi}(Q_d) = K_{pi} + h_{di}Q_d,$$

where K_{pi} is independent of Q_d and is given explicitly by

(25) $$K_{pi} = G_p - k_{pi}(\gamma,b) + H_i - \hat{e}_{pi}^2 + h_{pi}q_{pi}\hat{e}_{pi} \quad .$$

Notice from (22) that firm i will expend only the minimum effort (here $\hat{e}_{pi} = 0$) in stage P under Method 1 contracting unless there is some promise of follow-on rewards from such effort (i.e., unless $h_{pi} > 0$).

From (7) and (24) we see that firm i solves the following problem in determining its level of development effort e_{di}:

(26) $$\max_{e_{di}\ge 0} E\{(G_d/n) - e_{di}^2 + [K_{pi}+h_{di}\tilde{Q}_{di}(e_{di})]\tilde{A}_i(e_{di},e_d^i,n)\},$$

where $\underline{e}_d^i = (e_{di}, \ldots, e_{di-1}, e_{di+1}, \ldots, e_{dn})$. We have used the assumption in (26) that $E\{\tilde{C}_{di}(e_{di})\} = e_{di}^2$ and also the fact $\tilde{A}_i(\underline{e}_d, n) = 1$ precisely when firm i achieves the maximum in (2); otherwise $\tilde{A}_i(\underline{e}_d, n) = 0$.

We first evaluate the following expression in (26):

$$(27) \qquad EP = E\{[K_{pi}+h_{di}\tilde{Q}_{di}(e_{di})]\tilde{A}_i(e_{di}, \underline{e}_d^i, n)\} \quad .$$

EP represents the expected returns from the production stage as seen by firm i at the beginning of stage d.

We first note from (2) that

$$(28) \qquad \Pr\{\tilde{A}_i(\underline{e}_d, n) = 1\} = \Pr\{\tilde{Q}_{dj}(e_{dj}) \le \tilde{Q}_{di}(e_{di}) | \text{ for all } j = 1, \ldots, n\},$$

or using the assumed independence of $\{\tilde{Q}_{dj} | j = 1, \ldots, n\}$

$$(29) \qquad \Pr\{\tilde{A}_i(\underline{e}_d, n) = 1\} = \prod_{j=i} \Pr\{\tilde{Q}_{dj}(e_{dj}) \le \tilde{Q}_{di}(e_{di})\} \quad .$$

Thus, if $F_{dj}(q, e_{dj}) = \Pr\{\tilde{Q}_{dj}(e_{dj}) \le q\}$ is the cumulative distribution function of $\tilde{Q}_{dj}(e_{dj})$, we may write (29) as

$$(30) \qquad \Pr\{\tilde{A}_i(\underline{e}_d, n) = 1\} = \prod_{j \ne i} F_{dj}\left(\tilde{Q}_{di}(e_{di}), e_{dj}\right) \quad .$$

Finally, using (30), (27) becomes

$$(31) \qquad EP = \int_{-\infty}^{\infty} \left([K_{pi}+h_{di}\ x] \prod_{j \ne i} F_{dj}(x, e_{dj})\right) f_{di}(x, e_{di})\ dx,$$

where $f_{di}(x, e_{di})$ is the probability density function of $\tilde{Q}_{di}(e_{di})$.

In the exponential case considered here, (31) becomes

$$(32) \qquad EP = \frac{1}{q_{di}e_{di}} \int_o^\infty \left(\left[K_{pi}+h_{di}x\right] \prod_{j\neq i} \left[1-\exp\left(-\frac{x}{q_{dj}e_{dj}}\right)\right]\right) \exp\left(-\frac{x}{q_{di}e_{di}}\right) dx$$

Restricting attention to n = 1 or 2, we obtain

$$(33) \quad EP\ (n=1) = \frac{1}{q_{di}e_{di}} \int_0^\infty \left[K_{pi}+h_{di}x\right] \exp\left(-\frac{x}{q_{di}e_{di}}\right) dx = K_{pi} + h_{di}q_{di}e_{pi},$$

and setting $j \neq i$

$$(34) \quad EP(n=2) = \frac{1}{q_{di}e_{di}} \int_0^\infty \left(\left[K_{pi}+h_{di}x\right] \left[1-\exp\left(1-\frac{x}{q_{dj}e_{dj}}\right)\right]\right) \exp\left(-\frac{x}{q_{di}e_{di}}\right) dx$$

$$= \left[K_{pi}+h_{di}q_{di}e_{di}\right]\left(\frac{q_{di}e_{di}}{q_{dj}e_{dj}+q_{di}e_{di}}\right) \quad .$$

Comparing (33) and (34), it is interesting to note that for any given level of effort during the development stage the ex ante expected returns from the production stage, which we denoted EP above, are less for firm i if 2 firms compete for the production contract than if firm i alone is guaranteed the production contract.

Now, given (33)-(34), we may easily solve (26) for the optimal development effort $\hat{e}_{di}$, assuming the other firm's effort fixed at e_{dj}.

When n = 1, of course, there is no other competing firm and substituting (33) in (26) yields the following as the appropriate problem for firm i (if firm i is the only development firm):

$$(35) \qquad \max_{e_{di}\geq 0} \left[G_d - e_{di}^2 + K_{pi} + h_{di}q_{di}e_{di}\right],$$

which has the unique solution

(36) $$\hat{e}_{di} = \frac{h_{di}q_{di}}{2}$$

yielding overall profits for firm i of

(37) $$V_{di}(e_{di},G_d) = G_d + K_{pi} + \frac{h_{di}^2 q_{di}^2}{4} \quad .$$

When n = 2, matters are more complicated. Substitution of (34) in (26) yields

(38) $$\max_{e_{di}\geq 0}\left([(G_d/2) - e_{di}^2 + [K_{pi}+h_{di}q_{di}e_{di}]\left(\frac{q_{di}e_{di}}{q_{dj}e_{dj}+q_{di}e_{di}}\right)\right) \quad .$$

Taking first-order conditions in (38), while assuming e_{dj} fixed, we obtain

(39) $$e_{di} = \frac{K_{pi}q_{di}q_{dj}e_{dj}}{[2\Delta^2 - h_{di}q_{di}^2(\Delta+q_{dj}e_{dj})]}$$

where

(40) $$\Delta = q_{d1}e_{d1}+q_{d2}e_{d2} \quad .$$

We seek a Nash solution, defined by (8), which would be a simultaneous solution to (39) and the corresponding equation for firm j, i.e., to (39) and

(41) $$e_{dj} = \frac{K_{pj}q_{dj}q_{di}e_{di}}{[2\Delta^2 - h_{dj}q_{dj}^2(\Delta+q_{di}e_{di})]} \quad .$$

Assuming Δ fixed, and $h_{di},h_{dj} > 0$, the simultaneous solution to (39) and (41) is

(42) $$\hat{e}_{di}(\Delta) = \frac{-\Lambda}{[\Delta(2\Delta-h_{di}q_{di}^2)\ h_{dj}q_{di}q_{dj}^2+h_{di}K_{pj}q_{di}^3q_{dj}^2]}$$

(43) $$\hat{e}_{dj}(\Delta) = \frac{-\Lambda}{[\Delta(2\Delta-h_{dj}q_{dj}^2)\ h_{di}q_{di}^2q_{dj}+h_{dj}K_{pi}q_{di}^2q_{dj}^3]}$$

where

(44) $$\Lambda = [K_{pi}K_{pj}q_{di}^2q_{dj}^2 - (2\Delta-h_{di}q_{di}^2)(2\Delta-h_{dj}q_{dj}^2)\Delta^2] \quad .$$

Now, from (40) the Nash solution $\hat{\underline{e}}_d = \hat{\underline{e}}_d(\Delta)$ we seek must clearly satisfy (42)-(43) and

(45) $$q_{d1}\hat{e}_{d1}(\hat{\Delta}) + q_{d2}\hat{e}_{d2}(\hat{\Delta}) = \hat{\Delta} \quad .$$

Thus, multiplying (42) (resp., (43)) by q_{di} (resp., q_{dj}) and adding the results leads to (45), which in general is a polynomial of degree 6 in the variable $\hat{\Delta}$. Numerical solution procedures easily yield $\hat{\Delta}$ in general, and once $\hat{\Delta}$ is obtained so also is the desired Nash point $\hat{\underline{e}}_d$ from (41)-(42), from which all other desired information may be obtained. In this paper we will not proceed further with the general case. However, we discuss two cases which may be solved analytically.

(1) <u>The case $h_{di} = 0$ for all i:</u> In this case (39)-(41) can be solved directly to yield

(46) $$\hat{e}_{di} = T\sqrt{K_{pi}}\,, \qquad \hat{e}_{dj} = T\sqrt{K_{pj}}\,,$$

where

$$T = \frac{\left(\sqrt{q_{d1}q_{d2}}\right)(K_{p1}K_{p2})^{1/4}}{\sqrt{2}\left(q_{d1}\sqrt{K_{p1}} + q_{d2}\sqrt{K_{p2}}\right)} \quad (47)$$

In this case it can be shown that $\partial\hat{e}_{di}/\partial q_{di}$ has the same sign and $\partial\hat{e}_{di}/\partial K_{pj}$ has the opposite sign of $\left(q_{dj}\sqrt{K_{pj}} - q_{di}\sqrt{K_{pi}}\right)$. As expected $\partial\hat{e}_{di}/\partial K_{pi} > 0$ always holds.

(2) The case of two identical firms: When $q_{di} = q_{dj} = q_d$, $h_{di} = h_{dj} = h_d$, and $K_{pi} = K_{pj} = K_p$ we can again solve (39)-(41) explicitly, obtaining

$$\hat{e}_{d1} = \hat{e}_{d2} = \frac{3h_d q_d + \sqrt{9h_d^2 q_d^2 + 32K_p}}{16} \quad (48)$$

Here all the relative change effects are obvious and in the expected (positive) direction. An interesting point to note from (48) (or (46)-(47)) is that when $h_d = 0$, the amount of effort expended in development is independent of quality.

This concludes our discussion of Method 1 contracting (see (5)). Before considering further the government's problem in this regard, let us turn our attention briefly to Method 2 contracting (see (5')).

IV. Solution--Method 2

We continue to make the cost and distributional assumptions 1-5 of the previous section. In Method 2 contracting the stage p behavior of the production contracting firm, say i, is determined as a solution to (5'), except that we further restrict b so that $b \geq \underline{b} \geq 0$, with $\underline{b}$ being some minimal sharing rate set by Congress.[4] We assume the DoD utility function is specified linearly as

$$(49) \qquad U_D(C,CO,Q) = -g_1\, C - g_2\, CO + g_3\, Q,$$

where $g_i > 0$, $i = 1,2,3$. Then, for given $\alpha \in (0,1)$, we may write the problem (5') as follows:

$$(50) \qquad \underset{b,T_{pi},e_{pi}}{\text{Maximize}}\ EV = \alpha\, E\,\{\tilde{\Pi}_{pi}+\tilde{F}_i\} + (1-\alpha)\ E\{U_D(\tilde{C},\tilde{CO},\tilde{Q})\,|\,\tilde{Q}_{di} = Q_d\}$$

$$= \alpha\ [(a+b)T_{pi} - be_{pi}^2$$

$$+ (H_i + h_{di}Q_d + h_{pi}q_{pi}e_{pi})]$$

$$+ (1-\alpha)\ [-g_1\left(G_d + E\ \{\tilde{\Pi}_{pi}+\tilde{C}_{pi}(e_{pi})\}\right)$$

$$- g_2\left(G_d + E\ \{\tilde{\Pi}_{pi}+\tilde{C}_{pi}(e_{pi})\} - G\right)$$

$$+ g_3(Q_d + q_{pi}e_{pi})] \quad .$$

Subject to: (4) and $\underline{b} \leq b \leq 1$.

Note that the expected total project cost (to the government) and quality (given Q_d) are, respectively, $G_d + E\ \{\tilde{\Pi}_{pi}+\tilde{c}_{pi}(e_{pi})\}$ and $Q_d + E\ \{\tilde{Q}_{pi}(e_{pi})\} = Q_d + q_{pi}e_{pi}$. Now we note that

(51) $$E\{\tilde{\Pi}_{pi}+\tilde{C}_{pi}(e_{pi})\} = (a+b)T_{pi} + (1-b)e_{pi}^2 \quad .$$

Now, under our assumptions, (4) may be rewritten in the form (18). Moreover, as in section III, it may be shown here that for any fixed $b \in [\underline{b},1]$ the solution to (50) is on the boundary of the constraint set (18) provided only that[5]

(52) $$\alpha > \frac{g_1 + g_2}{1 + g_1 + g_2} \quad .$$

Condition (52) may be viewed as a lower bound on the bargaining power of firm i. We henceforth assume (52) so that (4) (i.e., (18)) holds as an equality. Just as in section III, we can now substitute (19) in (50) to obtain the final problem of interest:

(53) $$\underset{b,T_{pi},e_{pi}}{\text{Maximize}} \left\{(-\alpha e_{pi}^2+[\alpha h_{pi}+ (1-\alpha)g_3]\ q_{pi}e_{pi}+Q_d[\alpha h_{di}+ (1-\alpha)g_3] + TV(b)\right\},$$

Subject to: $T_{pi} \geq 0$, $e_{pi} \geq 0$, $\underline{b} \leq b \leq 1$,

where the term TV is independent of e_{pi} and Q_d and is given by

(54) $$\begin{aligned} TV(b) &= \alpha H_i - (1-\alpha)g_1G_d \\ &+ [\alpha-(1-\alpha)g_1]G_p \\ &+ [(1-\alpha)(g_1+g_2)-\alpha]k_{pi}(\gamma,b) \end{aligned}$$

We may first note that (52) implies $[\alpha-(1-\alpha)(g_1+g_2)] > 0$, and this coupled with (see (17)) $\partial k_{pi}/\partial b < 0$ implies that the optimal solution for b in (53) is $\hat{b} = \underline{b}$ (note that the only term containing b is $[\alpha-(1-\alpha)(g_1+g_2)]$

$k_p(\gamma,b)$). To obtain e_{pi} we take first-order conditions in (53) and find

$$\hat{e}_{pi} = \text{Min}\left[\frac{[\alpha h_{pi}+(1-\alpha)g_3]q_{pi}}{2\alpha}\ ,\ \left(\frac{G_p-k_p(\gamma,\underline{b})}{1-\underline{b}}\right)^{\frac{1}{2}}\right] \tag{55}$$

and $\hat{T}_{pi}$ is again found by substituting $\hat{e}_{pi}$ and $\hat{b} = \underline{b}$ into (19) to obtain

$$\hat{T}_{pi} = \frac{[G_p-k_p(\gamma,\underline{b}) - (1-b)\hat{e}^2_{pi}]}{(a+b)} \quad . \tag{56}$$

Substituting $\hat{b} = \underline{b}$ and $\hat{e}_{pi}$ in (55) into (53), we see that Method 2 leads to exactly the same form of solution value (see (24)) as Method 1 (where we use a ' to distinguish Method 2 values):

$$V'_{pi}(Q_d) = K'_{pi} + h'_{di}Q_d, \tag{57}$$

where for Method 2

$$K'_{pi} = -\alpha\hat{e}^2_{pi} + [\alpha h_{pi}q_{pi}+(1-\alpha)g_3q_{pi}]\hat{e}_{pi} + TV(\underline{b}) \tag{58}$$

and

$$h'_{di} = [\alpha h_{di}+(1-\alpha)g_3] \quad . \tag{59}$$

From this we see that the solution procedure and results for Method 1 in stage d are completely transferable to Method 2, with K'_{pi} and h'_{di} substituted everywhere for K_{pi} and h_{di}.

Before closing our analysis of Method 2 it is of interest to note, comparing (22) and (55), that effort expended in the production stage is always greater under Method 2 than under Method 1 contracting. More detailed comparative analysis of the other parameters and decisions will be explored in the next section via numerical analysis.

V. Illustrative Results

We illustrate the concepts and results of the previous chapters with a numerical example, solved in APL on the DEC System 10 at The Wharton School. We analyze the impact of the following parameters on the behavior of the firm and on the outcome of the project: variations in the risk sharing parameter (b) and partitioning of the (fixed) total government budget between the production budget (G_p) and the development budget. We consider three industry configurations: two identical firms, two firms with different levels of productivity, and a single monopolistic firm. The values of the parameters used in these experiments are given in Figure 1. One can interpret these figures by assuming that money is measured in dollars and that quality is measured in miles of range of the weapon (e.g., an aircraft or missile). Simulations are run for Method 1 and for Method 2 with $\alpha = .8$ and $\alpha = .9$. A sample of the output for the two identical firms with Method 1 appears in Figure 2. The remaining analyses are based on similar outputs for the other cases.

The impacts of the negotiation process (b) and budget allocated to production (G_p) on costs, quality, and the mean and variance of profit are shown in Figure 3. These relationships are identical across all three industry structures. The mean and variance of cost to the government is the same for Method 1 and Method 2, whatever the value of α. However, the expected quality and the expected cost to the firms are higher for Method 2 than for Method 1, and within Method 2 they are higher when α is at its lower value. In addition, as the expected cost of the firm increases from Method 1 to Method 2, the expected profit (including intangibles) decreases. These effects occur,

FIGURE 1: PARAMETERS IN EXPERIMENT

1. Firm Parameters

Parameters	Separate Firms: Firm 1	Separate Firms: Firm 2	Two Identical Firms and One Firm
q_p	1.6	1.5	1.55
h_p	12,000	10,000	11,000
h_d	1200	1000	1100
q_d	.8	.6	.7
σ	10^7	10^7	10^7
η	1500	1500	1500
δ	.7	.7	.7
μ	-10^6	-10^6	-10^6

2. Government Parameters

$G = 1.2 \times 10^8$; $g_1 = g_2 = 1$; $g_3 = 10^4$; $\gamma = .15$; $a = .1$

FIGURE 2: SIMULATION OUTPUTS FOR METHOD 1 WITH TWO IDENTICAL FIRMS

Value of b	Development Quality	Production Quality	Total Quality	Cost to Government	Standard Deviation of Cost to Government	Production Target
.1	4.242	11.627	15.869	110.64	9.00	0
.3	4.295	13.214	17.509	112.72	7.00	4.6177
.5	4.329	13.214	17.543	114.80	5.00	3.0770
.7	4.363	13.214	17.577	116.88	3.00	4.3847
.9	4.397	13.214	17.611	118.96	1.00	5.1692

Value of b	Cost to Firms	Profit of Firms	Standard Deviation of Profit of Firms	Intangible Profits	Development Effort	Production Effort
.1	88.92	151.73	16.1	130.01	4.0404	7.5011
.3	106.14	154.08	14.9	147.50	4.0903	8.5250
.5	106.68	155.65	13.8	147.53	4.1231	8.5250
.7	107.21	157.22	13.0	147.55	4.1556	8.5250
.9	107.75	158.78	12.5	147.58	4.1879	8.5250

Cost and profit are measured in millions of dollars, quality is measured in thousands of units, and effort is measured in thousands of units. $G_p = \$6 \times 10^7$ and $\gamma = 15\%$.

FIGURE 3: COMPARISON OF METHODS ACROSS INDUSTRY STRUCTURE

	Valid for any value of b and G_p		
Variable	Method 1	Method 2	
		$\alpha = .9$	$\alpha = .8$
Expected Cost to the Government	Same	Same	Same
Expected Total Quality	Low	Medium	High
Expected Cost to the Firm	Low	Medium	High
Expected Profits of the Firm	High	Medium	Low
Intangible Reward	Low	Medium	High
Variance of Profit*	High	Medium	Low
Variance of Cost to the Government	Same	Same	Same

*For the monopolistic industry structure, this variable is constant.

because Method 2 gives the government more bargaining power than Method 1, and this bargaining power increases with decreasing α. Thus, we obtain highest expected cost of firm and lowest expected profit at $\alpha = 0.8$.

The impact of the risk sharing parameter (b) and the portion of the budget allocated to production (G_p) on these variables are shown in Figure 4. With regard to the risk sharing parameter, the results are what one would expect, with one exception. As b increases, for any industry structure, the development and production efforts of each firm increases as long as the production target of the firm is zero. The production effort remains constant, with increasing b, once the target becomes positive. That is, as b decreases, each firm attempts to respond by decreasing its target without changing its production effort. But as the target is constrained to be nonnegative, the firm meets the design-to-cost goal by decreasing its production effort. We also observe that when industry structure is monopolistic, development effort is independent of b. This occurs because the monopoly firm, assured of the contract, puts forth minimal effort at development stage to obtain intangible follow-on benefits. As a result, quality of the weapon cost to the government, cost to the firm, profit of the firm (including intangible rewards), intangible rewards, and target increase (weakly) with increase in b. In addition, the variance of the government cost decreases with increasing b, since the firm assumes more risk. However, the variance of the firm's profit also decreases as the firm assumes increasing risk and this is an interesting result.

The explanation of this counterintuitive result arises partly from the fact that production cost and quality are correlated (which introduces a negative term in the variance calculation whose derivative may be dominant)

FIGURE 4: COMPARISON OF VARIABLES ACROSS METHODS

Effects on variables as b and G_p change

Variable	As b Increases: Different Firms	As b Increases: Identical Firms	As b Increases: One Firm	As G_p Increases: Different Firms	As G_p Increases: Identical Firms	As G_p Increases: One Firm
Expected Total Quality	INC	INC	LIM	INC	INC	LIM
Expected Cost to the Government	INC	INC	INC	SAME	SAME	SAME
Expected Cost to the Firms	INC	INC	LIM	INC	INC	INC
Expected Profit of the Firms	INC	INC	INC	CHG	CHG	LIM*
Expected Intangible Rewards	CHG	INC	LIM	CHG	INC	LIM
Production Target	INC	INC	INC	INC	INC	INC
Expected Quality at Development	INC	INC	SAME	INC	INC	SAME
Expected Quality at Production	CHG	LIM	LIM	CHG	LIM	LIM
Variance of Cost to the Government	DEC	DEC	DEC	SAME	SAME	SAME
Variance of Profit of the Firm	DEC	DEC	DEC	INC	INC	SAME

*This applies only to Method 1. For Method 2, the profit increases and then decreases.

LEGEND

INC: increases
DEC: decreases
SAME: no change
CHG: increases for small values, followed by decrease
LIM: increases until T_p becomes positive, followed by no change

and partly from the assumptions and parameter values used in these experiments. We begin by noting that the variance of profit (including intangibles) for the firm is given by

$$VAR(\tilde{\Pi}_i) = b^2\sigma_{pi} - 2bh_{pi}\sigma_{pi}\eta_{pi}\delta + h_{pi}^2\eta_{pi}^2 + h_{di}^2 q_{di}^2 e_{di}^2 + VAR(\tilde{C}_{di})$$

and thus,

$$\frac{dVar(\tilde{\Pi}_i)}{db} = 2b\sigma_{pi}^2 - 2h_{pi}\sigma_{pi}\eta_{pi}\delta + 2h_{di}^2 q_{di}^2 e_{di}\frac{de_{di}}{db} + \frac{dVAR(\tilde{C}_{di})}{db}$$

The variance of profit to the firm will increase or decrease with b as the above result is positive or negative. For the parameter values used in these experiments, the result will always be negative as long as ω, the coefficient of variation of $\tilde{C}_{di}$, is below .7 and will always be positive for $\omega > 2$. For intermediate values, the variance of $\tilde{\Pi}_i$ will decrease for low values of b and will thereafter increase.

We also note that the variance of cost to the government is given by $(1-b)^2\Sigma_i\sigma_{pi}^2 p_i$, where p_i is the probability that the i^{th} firm will receive the production contract. When σ_{pi} is independent of i, which is the case here, the variance of cost to the government is $(1-b)^2\sigma_p^2$, and this will always decrease with b.

Because increases in the risk sharing parameter bring about strict increases in total cost and total quality, risk sharing allows the government to obtain a cost/quality trade-off consistent with its goals. However, one may expect that beyond a certain point, quality increases slowly with b (and in the case of the monopoly firm, will not increase at all), while cost continues to increase proportional to increasing b. This is the point where the target, or one or more of the targets for nonidentical firms, becomes positive.

The situation is more complex when the total government budget is partitioned between the development and production stages. We note that total quality increases as G_p increases, because an increase in G_p relaxes the design-to-cost constraint. But, expected cost to government and the variance of that cost remain constant. Thus, the incentive to the government is to make G_p as large as possible. However, there may be a limit to the size of G_p--that is, it may not be possible to let G_p equal G--because the firms may refuse to compete due to inadequate compensation during the development stage.

With regard to industry structure, in many cases variables such as cost, quality, and profit have the same relationship to each other for all values of b and/or for all values of G_p. This is illustrated in Figure 5. The government receives the highest quality weapon at the same or at lower cost when two different firms are competing for the contract, whereas it receives the lowest quality system at the same or at higher price when the industry structure is monopolistic. This is an expected result. Expected profit is highest for the monopoly firm and is lowest when the industry consists of two identical firms. The two-firm industry receives more profit when the firms are different, because one of the two firms is less productive than the other, and the decrease in expected profit for this firm is not offset by the increase in expected profit for the more productive firm. In general, one would expect the benefits of competition to diminish as the quality of the inefficient firm decreases. When the inefficient firm has low quality, the efficient firm will not perceive a credible competitive threat. So, increasing government's expenses on development does not repay in increased

FIGURE 5: COMPARISON OF INDUSTRY STRUCTURE ACROSS METHODS

	For all values of b			For all values of G_p		
Variable	Two Different Firms	Two Identical Firms	One Firm	Two Different Firms	Two Identical Firms	One Firm
Expected Quality	H	M	L	H	M	L
Expected Cost to the Government	S	S	H	S	S	S
Expected Cost to the Firm	H	M	L	F	F	F
Expected Profit of the Firms	M	L	H	M	L	H
Intangible Reward (Method 1)	H	L	M	H	M	L
Intangible Reward (Method 2)	H	M	L	F	F	L
Variance of Profit	H	M	L	H	M	L
Variance of Cost to the Government	S	S	S	S	S	S

LEGEND

H: high value
M: medium value
L: low value
S: same value
F: fluctuates

quality.

The results described above are based on the assumptions that all firms in the industry will compete for the production contract regardless of the expected profits and that the government will allow all firms in the industry to compete (by paying a fixed cost for development) regardless of the productivity of the firm. These assumptions do not give rise to anomalies within the parameter ranges used here, contrary to expectation. For example, we observe that an increase in G_p (and a corresponding decrease in the funds paid to the firms for their development efforts) results in an increase in quality with no change in the expected cost to the government, and also results in an increase in expected cost to the firms, regardless of industry structure. However, in reality, most firms have alternative uses for their resources (current and fixed assets, experienced managers, skilled workers, etc.), and some of them may decline to participate, once their expected profits do not compare favorably with those obtainable elsewhere. In fact, the existence of a negative constant term $K_{pi}(\gamma,b)$ in (23) can result in negative expect3d profits for suitable contract parameter values. This will almost certainly cause a firm to withdraw from participation at the development stage.

Generally, the selection of government contract parameters (G_p, γ, b, and a) must be compatible with the alternative earning opportunities of the firm. Such alternative market opportunities determine a set of contract parameters for each firm at which the firm would be willing to participate in the development effort and compete for the production contract. The government will desire a possibly different set of values for the contract parameters, for which the cost is low, variance of cost is low and the quality is high. The government must choose its values of G_p, γ, b and a from the set of contract paramater values which will guarantee prospective contractors earnings opportunities as attractive as their alternative market opportunities.

Figure 6 illustrates an example of this tradeoff. The figure shows a situation where the efficient and inefficient firms expect returns higher than $102,300,000 and $62,800,000, respectively. This expectation leads the firm to accept b and G_p/G only in specified ranges (as shown by the shaded area). The government has to choose its acceptable b and G_p/G depending on budget allocation, risk sharing and other parameters. If these parameter values of the government fall in the shaded area, the government can expect the firms to bid for the project. If not, the government may have to revise its policy.

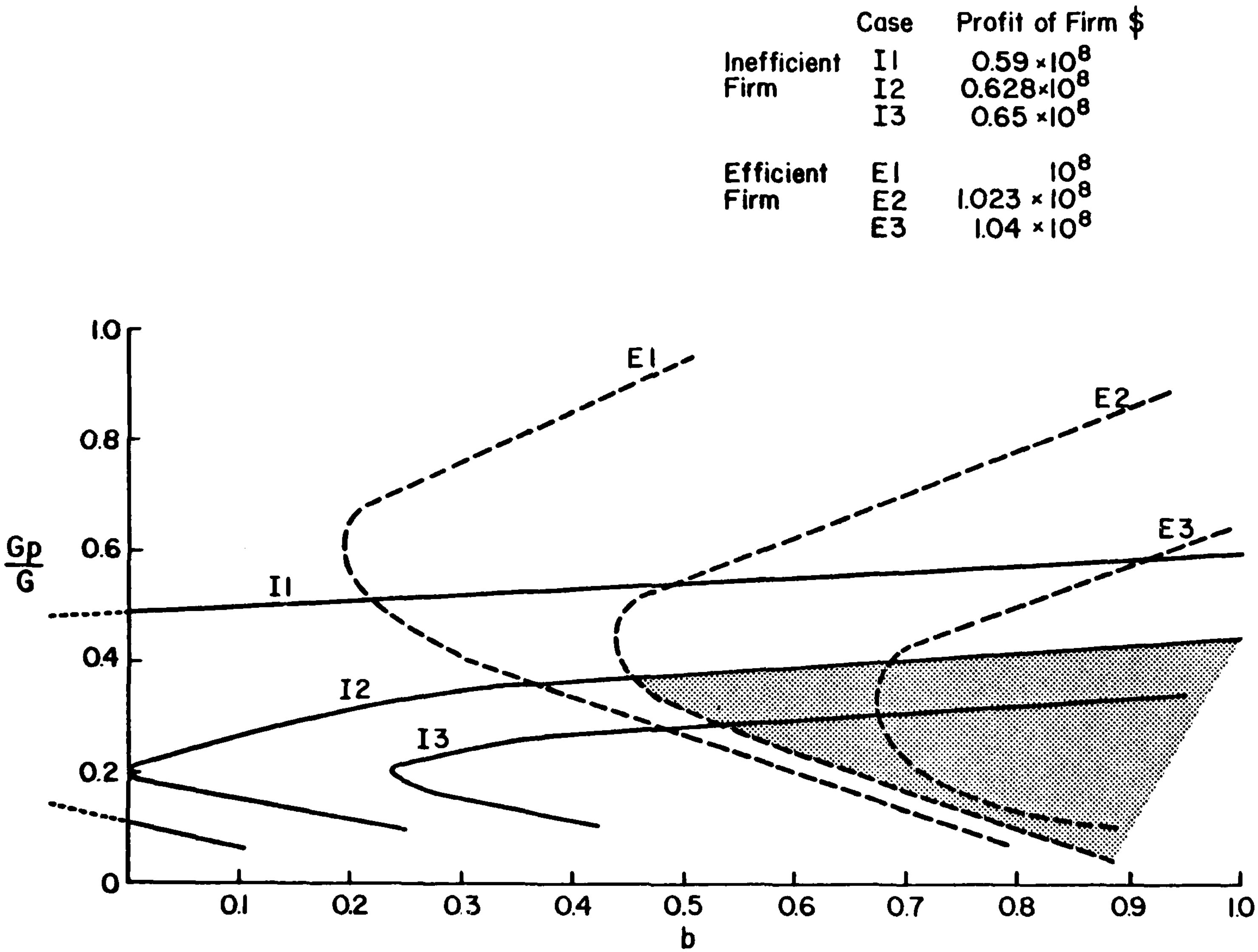

Figure 6: Areas of Firm Acceptability

VI. Conclusions and Further Research

We have examined the impact of dynamics and hierarchy, including industry structure, on government and industry behavior in a design-to-cost context, using a model of the weapons acquisition incentive process. Most of our results are a quantitative verification of what we would qualitatively expect. As risk sharing increases, the firms put forth more effort (except for the monopolistic firm during the development stage) and produce a better quality weapon at higher cost. The major counterintuitive result is that the variance of the government's cost decreases, and for some values of the economic and technological parameters, the variance of profit of the firm decreases as the risk sharing by the firm increases. In addition, the government receives a higher quality weapon for a fixed budget when it deals with competitive firms than it does when it must deal with a single monopolistic firm, and within limits, the quality increases when bidding firms are diverse in their capabilities. The government also receives a higher quality product when it invests a higher percentage of its budget in production (relative to development), unless the shift in investment causes some firms to withdraw from the competitive development phase of the acquisition process.

The interaction between government policy and industry structure suggests a productive direction for further research. Government policies influence industry structure and also affect the structure of the subset of the industry participating in the acquisition process and possibly in the long-term, the structure of the defense industry as a whole. In order to model the interaction between government policy and industry structure, we must determine three characteristics of the firms in the industry. The first characteristic, as mentioned in the previous section, is the spectrum of alternative earnings opportunities of the firms. The availability of these opportunities may lead some firms to withdraw from the development stage of the acquisition process. In contrast, the opportunities may lead other firms to participate in the hope that resources acquired during the project (skilled workers, experienced managers, etc.) may be useful in other areas, thus increasing the follow-on benefits of the project. The second characteristic is the range of risks that these opportunities present to the firms, which may lead some firms to decline to participate in the development phase of the project. The third is the firms' perceptions of future government actions (such as future projects, design-to-cost goals, and incentive parameters), and especially, of the uncertainty associated with these actions. It has been posited that a major blocking factor in industrial innovation is industry perception of the uncertainty in future government regulations and specifically that "the uncertainty of federal requirements, rather than their stringency, was perceived as the most important blocking factor."[6] Thus, government parameter setting behavior, established during a sequence of projects, may induce perceptions and uncertainties about future government actions that will influence significantly the attractiveness of defense contracting to individual firms and thereby the structure of the defense industry.

Footnotes

1. We discuss below the consequences of the nature and number of firms involved in the project.

2. Method 1 was analyzed by McCall [11] for a static problem and neglecting (4). He showed the possibility of a bias in favor of inefficient firms arising from opportunity cost considerations. Such effects are largely ignored here, though briefly considered
spirit of Cane [3] and Cummins [4], who also did not consider any constraint similar to (4).

3. We ignore discounting here for notational convenience.

4. See also Canes [3], for a similar assumption and a discussion of some rationale for establishing such a lower bounding sharing rate.

5. When (53) does not hold, the solution to (51) appears to be somewhat complicated as the solution need no longer be on the boundary of (18). Details for this more general case have not yet been worked out.

6. See Myers and Sweezy [13], page 29, for the quotation.

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