Contracting inside an organization: an experimental study*

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Abstract

In this paper we propose and test a contracting mechanism, Multi-Contract Cost Sharing (MCCS), for use in the management of a sequence of projects. The mechanism is intended for situations where (1) the contractor knows more about the true costs of various projects than does the contracting agency (adverse selection,) and (2) unobservable effort on the part of the contractor may lead to cost reductions (moral hazard.) The proposed process is evaluated in an experimental environment that includes the essential economic features of the NASA process for the acquisition of Space Science Strategy missions. The environment is complex and the optimal mechanism is unknown. The design of the MCCS mechanism is based on the optimal contract for a simpler related environment. We compare the performance of the proposed process to theoretical benchmarks and to an implementation of the current NASA 'cost cap' procurement process. The data indicate that the proposed MCCS process generates significantly higher value per dollar spent than using cost caps, because it allocates resources more efficiently among projects and provides greater incentives to engage in cost-reducing innovations.

1 Introduction

Many projects that provide a benefit to an entire organization are assigned to a specialized division for management while being funded through budgets at the headquarters level. Examples include the research division of a corporation, a team from a construction firm assigned to a building project, or a group of engineers and scientists assigned to develop a space mission. Often the division has better information about the eventual cost of the project than does headquarters. When multiple divisions compete for the assignment of a project, an adverse selection problem exists because each has an incentive to understate its cost estimations. This may lead to an inefficient allocation and cost overruns during the execution of the project.

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In many cases, the application of greater effort on the part of members of the division can reduce the cost or increase the value of the project. However, the level of the division's effort may not be observable to others, and only the final observed cost of the project may be contractible. If effort cannot be monitored and there are exogenous sources of cost uncertainty, cost reductions due to effort cannot be distinguished from other variations in costs. A moral hazard problem exists because the organization as a whole would like the division to exert a different level of effort than may be optimal for the division individually.

Both adverse selection and moral hazard create friction between headquarters and the divisions. These frictions can lead to a significant loss in performance – less is accomplished for the same dollars spent – if the appropriate relationship cannot be found. If the division (or more generally, the agent) and headquarters (the principal) are profit maximizers, then the structure of the optimal relationship or contract is well known.[1] We summarize this theory in Section 2. Under appropriate assumptions on the distribution and timing of information, the optimal contract can be implemented by the headquarters by offering a menu of linear contracts to the division such that for each possible realized cost value, there is exactly one optimal contract for the division. Thus, the division self-selects its contract in such a way as to reveal its true cost level. The contract then specifies the percentage of costs to be shared between the division and the headquarters. When used in government procurement with private contractors, cost-sharing contracts have generally met with success.[2]

Most situations in which a headquarters and a division need to establish a good relationship are not well suited to the pure theory described above. Consider as evidence the following stylized facts. (1) Within a firm, government body, or other organization, retaining profits at the level of a division is not always possible and the organization must employ incentives other than the profit motive.[3] (2) The goals of headquarters and the division are often much more aligned than in the canonical principal-agent problem with profit maximizers. This is partly because the relationship lasts over many periods and success today may breed more work tomorrow. (3) Information often arrives in bits over time as it is learned by the division instead of being available at the beginning of the process. The particular setting of interest, NASA's Mission Acquisition process, features these three complications, among others. The process is detailed in Section 3.

In this paper, we consider the problem of the headquarters-division relationship and ask whether we can exploit features of the solution to the canonical model in order to improve the outcome in the more realistic environment. We propose a new contracting process, called Multi-Contract Cost Sharing (MCCS). Under this system, headquarters offers a small number of linear cost-sharing contracts to the division. Since the the fully optimal solution features an infinite menu of linear cost-sharing contracts, the MCCS is a simplified approximation to the full solution. We then compare the MCCS process to the "cost cap" system currently in place at NASA. Under this system, the headquarters assigns a cost cap to each project and fully refunds any reported costs up to the cap. The moral hazard problems created by the cost cap rule are obvious, and we conjecture that the MCCS process will significantly improve welfare.

Because the MCCS process is only an approximation of the optimal solution and because the environment of interest differs from the canonical model, it is not immediately clear that the MCCS process would improve welfare. Although the cost cap system may appear inferior, it is has evolved in the NASA environment and was put in place by actors with very large stakes in the project outcomes. This implies that the existing process has properties that at least some parties view as desirable. Furthermore, decision makers may exhibit biases, errors, and learning effects not captured by the standard model, making the simple cost cap system the better choice. For these reasons, we turn to experimental methods to compare the outcomes under the MCCS process to the outcomes under the cost cap system. By simulating these processes in the lab, we can directly test our hypotheses and reach conclusions where theory remains inconclusive.

This research is of independent interest to experimental economists because it provides one possible roadmap for using experiments in the design of real-world institutions. In particular, when existing theory cannot provide a complete solution to a given problem, simplified approximations to the solutions of similar models may capture the desired incentive effects. It is then the goal of the experimentalist to test whether or not these effects survive the differences in environment and the simplifications of the solution. In that sense, experiments on institutional design can be thought of as robustness checks of existing theory. Theoretical solutions that are shown to be robust to the idiosyncrasies of real-world environments then become useful tools for practical implementation problems.

2 The Theory

In this section we review the standard model of contracting in the presence of adverse selection (asymmetric information about costs and abilities,) and moral hazard (asymmetric monitoring of effort.) The model and extensions are presented in Laffont and Tirole [11, Chapters 1,4]. This theory provides the foundation for our proposed system.

The firm, or 'implementing center' in the current context, faces a cost of production $C(e; L) = L - e$, where $L \in [\underline{L}, \overline{L}]$ is the firm's private 'luck' parameter and and $e \geq 0$ is the level of effort exerted by the firm. The cost to the firm of a given effort level e is $\psi(e)$, where $\psi(0) = 0$, $\psi'(e) > 0$ and $\psi''(e) > 0$ for each $e > 0$, and $\lim_{e \to L} \psi(e) = +\infty$.[4] The principal, or headquarters in our story, does not observe L directly, but has a prior belief given by the distribution $F(L)$ with density $f(L)$.[5] The firm is fully reimbursed by the principal for the final cost of the project and receives an additional transfer $t(C)$ that may depend on the realized cost C, but not on the unobservable level of effort. The overall profit of the firm is given by $U(e;L) = t(C(e;L)) - \psi(e)$.

The principal has a fixed value of S for the completed project. The total funds transferred from the principal to the firm is $t(C) + L - e$. The opportunity cost of these funds is given by $\lambda > 0$, so the net surplus to the principal is $S - (1+\lambda)(t(C) + L - e)$. In this model, the principal represents either the headquarters of a large organization or a regulator interested in overall welfare. Therefore, the principal's *ex-post* payoff is

$$\begin{aligned} V(e;L) &= S - (1+\lambda)(t(C(e;L)) + L - e) + U(e;L) \\ &= S - (1+\lambda)(L - e + \psi(e)) - \lambda U(e;L) \end{aligned} \tag{1}$$

The principal maximizes expected payoff by selecting the optimal transfer function t. By the revelation principal, the search for the optimal mechanism can be restricted to those incentive compatible direct mechanisms in which the firm is incentivized to announce its true luck parameter L.

Under complete information, the principal would maximize (1) subject to individual rationality constraints by requiring the level of effort e^* that solves $\psi'(e^*) = 1$ and setting $t = \psi(e^*)$ so that $U(e^*;L) = 0$.

With incomplete information, we look for a second-best solution by considering direct revelation mechanisms. In such a mechanism, firms announce any $\hat{L} \in [\underline{L}, \overline{L}]$ to the principal, who then requires that the observed cost equal some value $\tilde{C}(\hat{L})$ and pays a transfer $\tilde{t}(\hat{L})$. Requiring $C(e;L) = \tilde{C}(\hat{L})$ is equivalent to requiring $e = \tilde{e}(\hat{L};L) \equiv L - \tilde{C}(\hat{L})$ and can be enforced by penalizing the firm if the actual cost $C(e;L)$ does not equal the required cost $\tilde{C}$. Thus, $\tilde{U}(\hat{L};L) \equiv \tilde{t}(\hat{L}) - \psi(L - \tilde{C}(\hat{L}))$ represents the firm's profit under this scheme when its true luck parameter is L and it announces $\hat{L}$. Incentive compatibility requires that $\tilde{U}(\hat{L};L)$ be maximized at $\hat{L} = L$. Letting $\tilde{U}(L) \equiv \tilde{U}(L;L)$, Laffont & Tirole [11, Proposition 1.2] show that

$$\tilde{C}'(L) \leq 0 \tag{2}$$

and

$$\tilde{U}'(L) = -\psi'(L - \tilde{C}(L)) \tag{3}$$

are necessary and sufficient conditions for the mechanism $\{\tilde{C}(\hat{L}), \tilde{t}(\hat{L})\}$ to be incentive compatible. Since $\tilde{U}'(L) \leq 0$ under these two conditions, requiring $\tilde{U}(\overline{L}) \geq 0$ is sufficient to guarantee that individual rationality will be satisfied for all $L \in [\underline{L}, \overline{L}]$.

Integrating (3) gives the value of $\tilde{U}(L)$ that must obtain in any incentive compatible scheme. Defining $\tilde{e}(L) \equiv \tilde{e}(L;L) = L - \tilde{C}(L)$, the expectation of $\tilde{U}(L)$ with respect to $F(L)$ is

$$\int_{\underline{L}}^{\overline{L}} \tilde{U}(L)\, dF(L) = \int_{\underline{L}}^{\overline{L}} \frac{F(L)}{f(L)} \psi'(\tilde{e}(L))\, dF(L).$$

The principal's problem of maximizing the expected value of equation (1) subject to incentive compatibility is given by

$$\begin{aligned} &\max_{\tilde{e}(\cdot)} \int_{\underline{L}}^{\overline{L}} \left[S - (1+\lambda)(L - e + \psi(e)) - \lambda \tfrac{F(L)}{f(L)} \psi'(\tilde{e}(L)) \right] dF(L) \\ &\text{s.t.} \quad \tilde{e}'(L) \leq 1, \end{aligned} \tag{4}$$

where the constraint is simply equation (2), replacing $\tilde{C}(L)$ by $L - \tilde{e}(L)$. The unconstrained solution to (4) is given by

$$\psi'(\tilde{e}^*(L)) = 1 - \frac{\lambda}{1+\lambda} \frac{F(L)}{f(L)} \psi''(\tilde{e}^*(L)), \tag{5}$$

where $\tilde{e}^*(L)$ represents the optimal choice of $\tilde{e}(L)$. Recall that under complete information, $\psi'(e^*) = 1$, so the second term on the right-hand side represents a distortion due to asymmetric information. The assumptions of the model guarantee that $\tilde{e}^{*\prime}(L) \leq 0$, so the constraint in (4) is satisfied at the global solution. Plugging $\tilde{e}^*(L)$ into the right-hand side of (3) and integrating the result gives the firm's profit under this mechanism,

$$\tilde{U}^*(L) \equiv \int_{L}^{\overline{L}} \psi'(\tilde{e}^*(l))\, dl. \tag{6}$$

Using the definition of $\tilde{U}(L;L)$, we have

$$\tilde{t}^*(L) = \psi(\tilde{e}^*(L)) + \tilde{U}^*(L), \tag{7}$$

which identifies the optimal transfer function $\tilde{t}^*(L)$.

Since $\tilde{C}^*(L)$ is strictly increasing, the inverse function $L^*(C)$ is well-defined. By replacing L in equation (7) with $L^*(C)$, the above direct mechanism can be replaced by an equivalent indirect mechanism with transfer function $\tilde{t}^*(L^*(C))$. Laffont & Tirole [11, p 68] show that $\tilde{t}^*(L^*(C))$ is strictly convex in C, so it can be characterized by a continuum of tangent lines, one for each C (or, one for each $L^*(C)$.) Instead of offering the convex transfer function $\tilde{t}^*(L^*(C))$, the principal can ask the agent to announce $\hat{L}$ and then offer the linear contract represented by the tangent to $\tilde{t}^*(L^*(C))$ at $\tilde{C}^*\left(\hat{L}\right)$. Specifically, this linear contract is of the form

$$\tilde{T}^*\left(\hat{L}, C\right) = \tilde{t}^*\left(\hat{L}\right) - \psi'\left(\tilde{e}^*\left(\hat{L}\right)\right)\left(C - \tilde{C}^*\left(\hat{L}\right)\right). \tag{8}$$

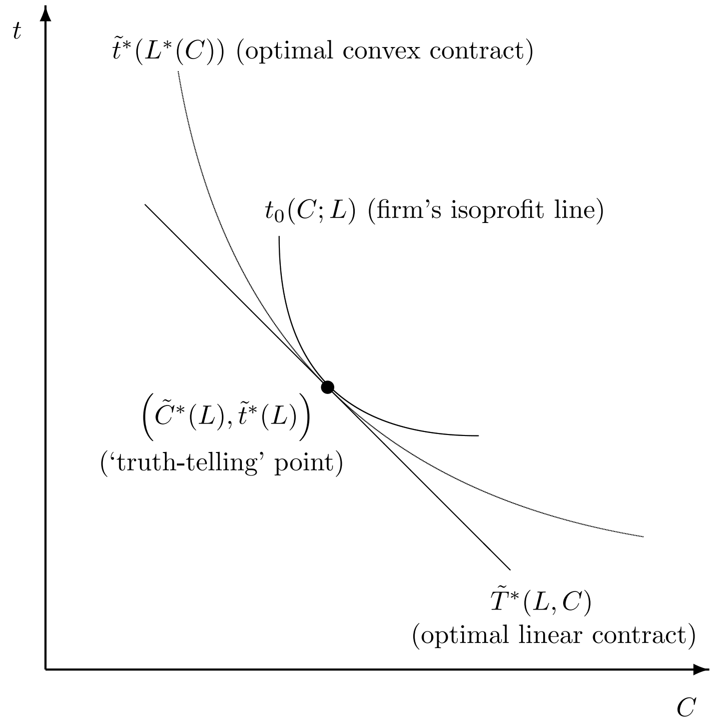

Figure 1: Both the convex contract $\tilde{t}^*$ and the linear contract $\tilde{T}^*$ are incentive compatible. (Picture adapted from Laffont & Tirole [11, Figure 1.4].)

Refer to figure 1. Since $\psi'' > 0$, the firm's isoprofit line in (C,t)-space through $\left(\tilde{C}^*(L), \tilde{t}^*(L)\right)$, which is represented by the equation

$$t_0(C;L) = \psi(L - C) + \tilde{t}^*(L) - \psi\left(L - \tilde{C}^*(L)\right),$$

is also strictly convex in C. By incentive compatibility (and since the constraint in (4) does not bind,) t_0 must be tangential to $\tilde{t}^*(L^*(C))$ at $\tilde{C}^*(L)$. Therefore, it is tangential to the linear contract $\tilde{T}^*(L,C)$ at $\tilde{C}^*(L)$. This implies that $\tilde{T}^*(L,C)$ is also incentive compatible. By using this menu of linear contracts, the principal is able to induce the optimal effort choices from the firm just as well as with the convex contract.

Finally, the principal can use an equivalent *linear* indirect mechanism by asking for a cost estimate C^E instead of requiring the firm to announce $\hat{L}$. The transfer payment under this scheme is given by

$$T^*\left(C^E, C\right) = \alpha\left(C^E\right) - \beta\left(C^E\right)\left(C - C^E\right), \tag{9}$$

where

$$\alpha\left(C^E\right)=\tilde{t}^*\left(L^*\left(C^E\right)\right)$$

and

$$\beta\left(C^E\right)=\psi'\left(\tilde{e}^*\left(L^*\left(C^E\right)\right)\right).$$

This indirect mechanism simply recreates the linear transfer function in (8) by using incentive compatibility to guarantee that C^E will be chosen such that $L = L^*\left(C^E\right)$. The reader may verify that this follows from the first-order conditions of the firm's maximization problem, as does the choice of $e = \tilde{e}^*(L)$, confirming that (9) is an optimal incentive compatible mechanism.

The coefficient $\beta\left(C^E\right)$ is interpreted as a cost-sharing parameter. It indicates the percentage of the difference from the announced cost of the project that the principal bears. As C^E increases, $\alpha\left(C^E\right)$ decreases and $\beta\left(C^E\right)$ increases. For higher values of C^E, the contract resembles a 'cost-plus' contract where $\beta = 1$. For low values of C^E, the contract resembles a fixed-price contract with $\beta = 0$.

Laffont & Tirole [11, Chapter 7] analyze the same model with $n > 1$ firms. The firms are assumed to compete in an auction where each firm i 'bids' its luck parameter $\hat{L}_i$. The optimal incentive compatible auction awards the project with certainty to the lowest bidder and induces the same level of effort from the winning bidder as in the monopoly contract above. If $\mathbf{L} = (L_1, \ldots, L_n)$, $i = \arg\min_k L_k$, and $j = \arg\min_{k \neq i} L_k$, then firm i's profit equals

$$\tilde{U}_i^*(\mathbf{L}) = \int_{L_i}^{L_j} \psi'\left(\tilde{e}^*(l)\right) dl. \tag{10}$$

Comparing this amount to equation (6), we see that competition has driven down the rents accruing to the firm. In fact, as n grows to infinity, the firm's rent shrinks to zero and the equilibrium effort approaches the optimal effort under complete information (since $F(L)$ goes to zero in (5).) Thus, competition mitigates the market failures associated with information asymmetries.

3 Application: NASA Mission Acquisition

In this section, to describe in detail the system whereby the National Aeronautics and Space Administration (NASA) procures its Strategic Missions.[6] This is a particularly interesting example to study for two reasons. First, the informational asymmetry between principal and agent appears unusually severe. Costs of NASA missions are highly uncertain because new technology is typically required for their completion. Because the expertise required to build space missions is so specific, the informational asymmetry is very difficult to

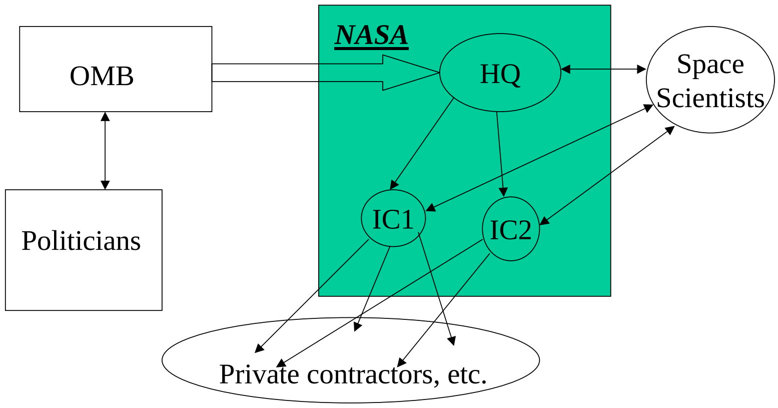

Figure 2: The NASA Mission Acquisition Environment.

resolve by monitoring. Since new technology is required for most missions, there are sometimes possibilities for significant cost-saving innovations on the part of contractors. However, in other instances, no such innovations are possible, even with great effort. It is not always a priori evident which situation one is in. Thus, drastic differences in cost can occur because of choices of effort level.

A second reason is that this application has many difficult features from which the theory usually abstracts. Divisions are cost-centers and not profit maximizers. There is a lot of uncertainly and the relevant distributions are not common knowledge. Although headquarters and the divisions spend a lot of effort trying to penetrate the technology and to get a better handle on costs, the 'cutting edge' nature of the projects makes it very difficult to make reliable estimates.

A final reason to study this particular application is that many parties at NASA view the current process as unsatisfactory.[7] Therefore, there is a reasonable likelihood that the proposal will be field tested and benchmarked against the current process.[8]

3.1 The NASA Mission Acquisition Environment

The organization of the main actors in NASA's mission acquisition process is given in figure 2. The three key players are the Office of Management and Budget (OMB), who oversees NASA's budget and approves mission requests by NASA, the Space Science Enterprise office at NASA headquarters (Associate Administrator and five Science Theme Directors), and the Implementing Centers (which can be thought of as divisions of the main NASA organization). In addition, the space science community at large and their committees and councils are involved as first line customers, the American public as the ultimate customer, and various levels of management in the organizations of the key three players participate in the decision processes.

We focus here on the relationship between NASA headquarters, who has the role of procuring new missions, and the Implementing Centers, who are the contractors, but who are also part of the overall NASA agency. The Implementing Centers manage the construction of missions, often subcontracting with the private sector. The four largest Implementing Centers for the Space Science Enterprise are the Jet Propulsion Laboratory, Goddard Space Flight Center, Marshall Space Flight Center, and Ames Research Center. These organizations rely on formal agreements and contracts to develop and manage NASA missions as their principal source of revenue, and although they have an interest in the overall success of NASA, they also have an interest in larger shares of the Space Science budget being allocated to their own part of the organization rather than to the other Centers.

3.2 The Current Process of Mission Acquisition.

Approximately every ten years, Committees of the Space Studies Board of the National Academy of Sciences publish reports on the state of space science and outline current scientific priorities. The Space Science Advisory Committee (SScAC) and its subcommittees contribute to the preparation of the Space Science Strategy. The Strategy is largely based on science and technology "roadmaps" prepared by each science theme director with the assistance of supporting centers and of roadmap teams staffed by science community representatives and center employees.

The Strategy, issued by the Space Science Enterprise at NASA Headquarters every three years, "translates" the space science priorities into the missions on which NASA will focus. These are missions that, under the leadership of headquarters senior management, have been studied and "costed", at various levels of definition, by one or more of the Implementing Centers. The assignment to the Implementing Center is made by the Associate Administrator, on the recommendation of the cognizant Theme Director. This recommendation, in turn, is based on the Center's established role and skill base.

As the study of a mission progresses and the cost estimates become more defined, the Space Science Enterprise staff at Headquarters communicates with the science community, OMB and congressional staffers, and cost targets are tested for viability in the budgetary process. As a result, the center is given a Cost Cap, a maximum dollar figure that can be spent on a mission, with an understanding that respect of the cap is a condition for mission approval.[9] Figure 3 illustrates the payment structure of a cost cap. The contractor is exactly reimbursed for his costs up to a ceiling level[10].

As the studies of the mission become more detailed — and more expensive — it often appears that the preliminary estimates were optimistic. If this is the case, either of the following may occur: (1) the cap is respected and the mission is descoped, (that is, the goals of the mission are scaled back), or tests, analyses,

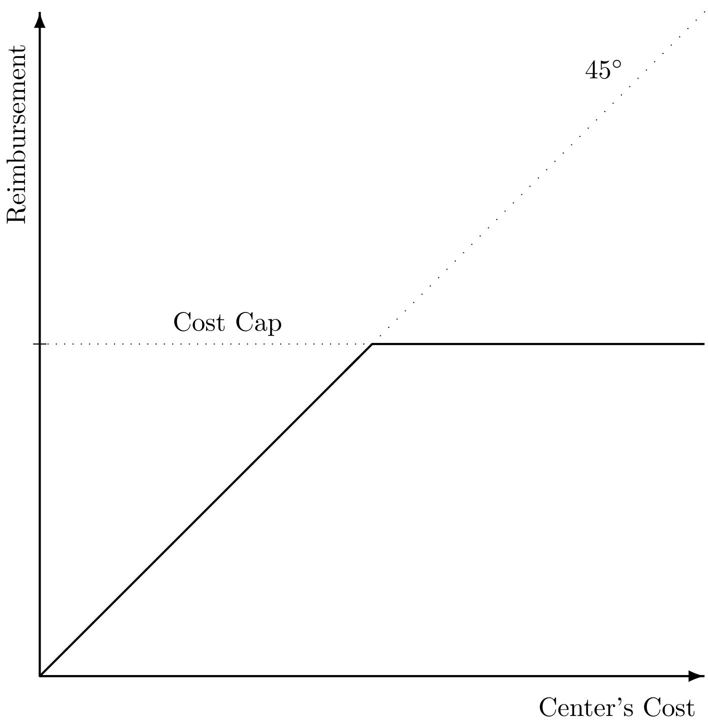

Figure 3: "Cost Cap" reimbursement schedule.

and/or redundancies are deleted with the consequence that the risk of failure (that is, that the space craft is unable to complete its mission) increases, (2) the cap is deemed unfeasible and an augmentation is requested by the center, or (3) the mission is cancelled or abandoned.

When descoping occurs, the science community is unhappy, but, generally, accepting of the circumstances, as long as the science content is above an agreed "floor". When the floor is reached, only by accepting increased risk can one reduce costs. This situation is difficult to manage well because risk management is not a familiar discipline in the community, the ability of the stakeholders to understand and communicate the level of risk and its implications is inadequate, and the stakes are high (both for money and visibility). In unlucky instances increased risk results in failures that are embarrassing and costly because of investigations, replanning, and stand–downs.

When the Implementing Center requests an increase in its cap, NASA Headquarters has the choices of: (a) canceling the mission and requesting authority from Congress to reprogram the funds for other purposes, (b) requesting an authorization to transfer funds from another mission, which typically requires delay or cancellation of the other mission, or (c) requesting, from the OMB first and then the Congress, an increase in budget authority with explanations of why the earlier estimates were in error. This is viewed as highly embarrassing and the proposed budget changes may not be approved. There is also the possibility that Congress would not only deny the augmentation, but that it would then also cancel the mission and order the unspent funds to be returned to the Treasury.

3.3 The Current Dilemma

Cost caps are established on the basis of preliminary information both at the Implementing Centers and at Headquarters. There is a dilemma for Headquarters. On the one hand it should not use caps that are too tight and result in funding a proposal that cannot be implemented without taking an unacceptable risk, resulting in failure, or in a request for augmentation when cost growth occurs. It was a series of failures under cost caps that caused questions to be raised, which led to our study to find, if possible, better alternative practices. On the other hand, Headquarters must also avoid caps that are too generous, and forgo the opportunity to use cost pressure to induce creative thinking. This was one of the real problems under a regime of cost capped contracts. Headquarters might find itself in a situation where it wastes public money, and offers an expensive, less appealing and less popular science program. This may ultimately lead to a permanent loss of funding for space science. The dilemma for the Implementing Centers is between accepting a low cost cap and taking on excessive risk of cancellation, delay or failure, or holding out for a higher cost cap and risking the loss of the mission assignment.

These differences in objectives between Headquarters and the individual Implementing Centers belie the popular view that there is a common interest between all units at NASA. There are differences in goals and risk attitudes between Headquarters and the Implementing Centers. There is an asymmetry in information between the two sides during the study and development process, with the Implementing Center more aware of cost data. Furthermore, there is competition between the Implementing Centers. At times it takes the form of direct competition for the contract to build a particular mission, but more generally there is competition for larger shares of the fixed annual budget that Headquarters has earmarked for mission acquisition.

4 The Proposed Process – MCCS

Can we create a Pareto-superior improvement (a win-win change) in the process by which NASA manages its Mission Acquisition process? We look to the theory in section 2 to give us guidance in the development of a new mechanism. In particular, we use the insight that a menu of linear contracts can provide incentives for both the revelation of cost information and for inducing second-best effort levels. We do not, however, use a continuum of linear contracts. Instead, we limit the menu to three. We call our proposal the MCCS contracting process. The process is intended for use in environments, such as those of NASA described in section three, in which final cost is observable to both parties, and the final cost depends on the effort of the agent as well as on exogenous random variables. The agent knows the realizations of the random variables, but neither the effort level nor the realization of the exogenous variables are known to the principal.

4.1 Description of MCCS

The MCCS process consists of the following steps.

1. The principal and agent negotiate a baseline cost C_B to complete the project. The principal can also negotiate with multiple agents before choosing the agent to whom the project is awarded and agreement on the baseline cost is reached.

2. An algorithm, which is known before negotiations begin and is common knowledge, calculates two other values C_L, and C_H, a "low" and a "high" cost estimate (requiring that $C_L < C_B < C_H$) and three linear contracts, called $T(C_F, C_k)$ with $k \in \{L, B, H\}$, representing "low", "baseline", and "high" cost estimates and C_F representing the final cost. For example, C_L and C_H could be computed as fixed percentages above and below C_B. $T(C_F, C_k)$ denotes the monetary transfer from principal to agent under contract k when C_F is the final cost. T has the functional form:

$$T(C_F, C_k) = \alpha_k + \beta_k (C_k - C_F) \tag{11}$$

Further, C_L, C_H and T must satisfy the following incentive compatibility constraints: there exist C^* and C^{**} such that $C_L < C^* < C_B < C^{**} < C_H$ and

$$T(C_F, C_L) > T(C_F, C_k) \;\; \forall k \neq L \text{ if } C_F < C^* \tag{12}$$

$$T(C_F, C_B) > T(C_F, C_k) \;\; \forall k \neq B \text{ if } C^* < C_F < C^{**} \tag{13}$$

$$T(C_F, C_H) > T(C_F, C_k) \;\; \forall k \neq H \text{ if } C_F > C^{**} \tag{14}$$

Equations (12)-(14) require there to exist a range of cost realizations for which each contract provides the highest dollar payment to the agent.[11] Satisfying this condition requires that $\beta_H > \beta_B > \beta_L$. The low contract resembles most closely a fixed price contract, while the higher contract is closer to a cost-plus contract. If one of these conditions is not satisfied, then one might as well replace the two adjacent contracts with a single contract since one of them will be irrelevant.

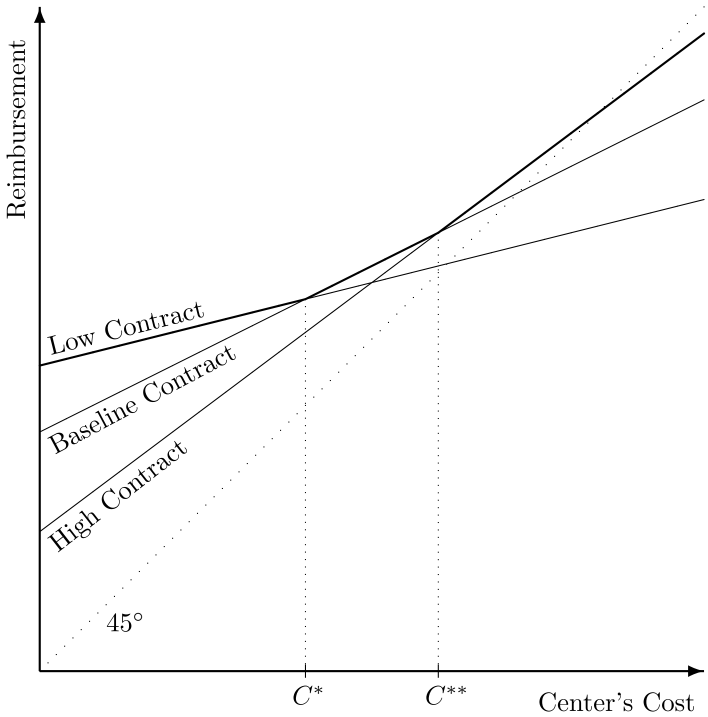

Figure 4: MCCS reimbursement schedule.

3. At a later stage after the project begins, when the private cost estimates of the agent presumably become more precise, the agent selects one of the three contracts under which to operate.

4. After completion of the project and observation of final cost, the agent receives a payment equal to $T(C_F, C_k)$, where $k \in \{L, B, H\}$ indicates the contract chosen at stage 3. The difference between T and C, if positive, can be carried over by the agent into the future as profit or, in the case of non-profit firms or divisions of organizations, as a credit to offset the cost of future projects. If the difference between T and C is negative, the agent must pay the principal from retained profits or, in the case of non-profit firms or divisions of organizations, from the credits from previous contracts.

A hypothetical example of such a system of contracts is shown in figure 4. The agent's cost of completing the project is shown on the horizontal axis and the reimbursement received from the principal is given on the vertical axis. Notice that, as required, each of the three contracts is optimal for the agent for a range of cost realizations.

4.2 Differences Between the Optimal Contract and Our Process

There are two main differences in the actual cost-sharing mechanism we use and the one implied by the solution to the theoretical model. These are guided by practical implementation considerations in the typical application in which a new contracting system would be proposed, and the typical absence of precise information about the distribution $F(L)$ and the function $\psi(e)$.

The first major difference is that there are just three contracts in the menu rather than an infinite number corresponding to the number of types. A small number of contracts is more practical for implementation since it simplifies the decisions of the parties involved.[12] Also, the contracts are not necessarily optimal since $F(L)$ and $\psi(e)$ will generally not be common knowledge in applications. Even if an infinite number of contracts were specified, the contracts would, therefore, in general not correspond precisely to the optimal menu.

The second major difference is that the specification of C_B comes about as a result of a bargaining process between principal and agent(s).[13] In many cases a division of an organization possesses some specific human capital or other innate advantage over other alternatives, perhaps because of past work in this same area, so that really is a bargaining problem in which both sides possess some power. When there is more than one potential contractor, the method of choosing the agent to whom to award the contract is left unspecified. The principal is free to negotiate a level of C_B with each of the potential contractors, and does not necessarily need to choose the lower offer. We consider both the 1 division and 2 division cases in our analysis below.

5 The Experiment

5.1 The environment

In our experiment, subjects have one of two roles, Headquarters (hereafter HQ) or an Implementing Center (hereafter IC). Each experimental session is made up a series of periods, in which one HQ interacts on a repeated basis with either one or two IC's. In each period there are two potential missions, A and B, each of which can be assigned to an IC to construct. Each mission can be designed in three ways: labeled as A1–A3, and B1–B3.[14] Thus with two IC's, in each period HQ can procure two of six different possible products from the IC's.

Missions are characterized by a value $S_j > 0$ and a reliability level $R_j \in [0, 1]$. The reliability of a mission is the probability that the mission is a "success"; that is, that it actually yields S_j. The value of a mission in the NASA context represents the benefits of its scientific output. There is a target value $\underline{S}_j$ that a mission must contain to be viable. If the mission does not have a value of at least $\underline{S}_j$, it is not considered complete.

In the event that the mission fails, there is a cost of failure F_j, equal to $3\underline{S}_j$, paid by both HQ and the IC that built the mission. The value of failure in the NASA context represents the losses, political and otherwise, associated with such outcomes. S_j and F_j are denominated in points, which are convertible to dollars that the participants in the experiment can take home with them at the end of the experimental session. This convertibility to dollars is how experimenters create the same incentives for subjects that exist for the NASA actors they represent.

There are two units of account: the points above and "francs," an experimental currency, that are not convertible to dollars at the end of the experimental session. Budgets and expenditures are denominated in francs.[15] All francs that a subject may have accumulated over the course of the experimental session disappear at the end. No incentive is created for subjects to retain or save at the end of the session. That is, no incentive exists for Headquarters to allocate less than its entire budget to missions, or for the Center to spend less than its entire budget over the course of the session. Of course, HQ still benefits from keeping costs down for the missions it procures so that the savings can be used for other missions.

There is a cost function, denominated in francs, for each design of each mission. The cost function for mission/design j is of the form

$$C_j\left(S_j, R_j, e_j\right) = a_j S_j^2 + b_j \ln\left(1/\left(1 - R_j\right)\right) + e_j + L.$$

The lower the value of coefficient a_j, the cheaper it is to add value to a mission. The lower the value of coefficient b_j, the cheaper it is to increase the mission's probability of success. e_j represents the amount the IC spends pursuing a new technology that might reduce the cost of the mission. Expending e_j yields an innovation with probability

$$P = 1 - z_j^{-e_j}.$$

An innovation decreases a_j by 1/3 from its current level. L is a random variable that has an expected value of 0 and may be positive or negative. L represents that information about costs that is not known a priori but will be learned as the project is actually developed. The cost functions have the property that each design is the lowest cost method for attaining some levels of S_j: design 3 for relatively low S_j, design 2 for intermediate levels, and design 1 for high levels. The coefficients a_j, b_j and z_j for each mission and each design are given in table 1.

When the mission is completed, the IC can deliver the mission for "launch". If the mission is launched and is successful, HQ and the IC constructing the mission each receive S_j points. If a mission is not launched, the payoff for the mission is zero to all parties. If the mission is launched, R_j is the probability that it is

Mission	a_j	b_j	z_j	S_j	F_j	CE_j	y_j
A1	.003200	60	1.010	500	1500	980	500
A2	.004375	20	1.005	400	1200	760	0
A3	.004750	30	1.005	200	600	280	0
B1	.001400	60	1.010	1000	3000	1580	500
B2	.002400	20	1.005	500	1500	660	0
B3	.007500	30	1.005	200	600	390	0

Table 1: Cost parameters for each design of each mission.

successful and $1 - R_j$ is the probability that it fails after launch. A "Contractor Bonus" for mission j, denoted as y_j, equal to 500 francs, is awarded to an IC every time a design 1 mission it builds is successful.[16] There is no contractor bonus awarded for design 2 or 3 missions. Thus the expected payoff, in points, of a mission at the time of launch is equal to

$$E\left[\pi_{HQ}\right] = R_j S_j - \left(1 - R_j\right) F_j$$

for HQ and

$$E\left[\pi_{IC}\right] = R_j \left(S_j + y_j\right) - \left(1 - R_j\right) F_j$$

for the IC that built the mission. The target value, the cost of failure, and the contractor bonus for each design and mission are given in table 1.

5.2 Timing

Each experiment runs for 5 periods. At the beginning of a period, the following information is common knowledge. There are 2 potential missions that can be constructed by any IC. There is an initial publicly posted estimate for the cost of completing the mission under each possible design. It is calculated as $C_j^E\left(\underline{S}_j, 0.95, 0\right)$ and is shown in table 1. HQ receives a budget B at the beginning of each period for the procurement of missions. B is equal to 1500 francs.

To differentiate the timing and structure of information we let $L = \sum_k L_{ij}^k$. Each component is independently and identically distributed according to a probability distribution function, $F(L_{ij}^k)$. The center will learn the components over time. HQ does not see or know the values of the L_{ij}^k, only the possibilities from $F(L)$, unless honestly informed by the IC. Initially, in each period, each center i will have a private cost estimate for each mission, c_{ij}, which is equal to the commonly known C_j^E plus L_{ij}^1. L_{ij}^1 represents private information that each center has about its own cost that is not contained in C_j^E. This represents "luck"

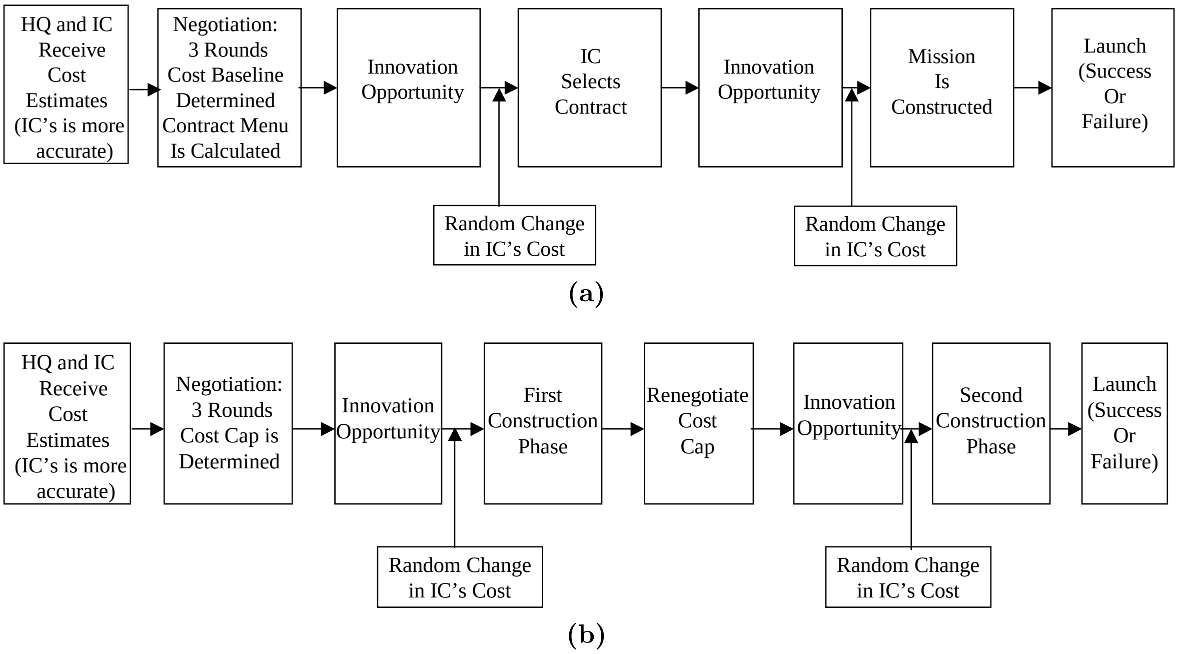

Figure 5: Timing of (a) the MCCS process and (b) the Cost Cap process.

to the center in the sense that the center has a stroke of good luck if the publicly available cost estimate happens to be higher than its current belief about its own cost.

After the contract to construct the mission is awarded, there is an opportunity for the IC building the mission to obtain an innovation, which is a cost reduction due to effort. Afterwards, there is another independently drawn value from $F(L)$, L_{ij}^2, which is added to the IC's cost estimate. This represents an exogenous cost shock. Later on during the construction process there is one more opportunity to innovate and another privately observed exogenous cost shock, L_{ij}^3. When the mission is completed, the IC chooses whether or not to deliver it for launch.[17] If the mission is not delivered, both parties receive a payoff of zero for the mission. If the mission is launched, everyone learns whether it succeeds or fails and is rewarded accordingly. Success and failure do not affect the budget HQ has in each period, though they may of course affect HQ's budget allocation policy toward IC's in later periods.

5.3 The Multi-Contract Cost Sharing Process

Implementing the MCCS system in the experimental environment described above yields the sequence of events during a single period illustrated in panel (a) of Figure 5. Activity in each period can be divided into a series of stages.

		Low Variance			High Variance		
Mission	Contract	C_k	α	β	C_k	α	β
A1	H	1180	1180	.916	1280	1280	.928
	B	980	1016	.633	980	980	.755
	L	780	927	.349	680	827	.433
A2	H	831	831	.872	985	985	.905
	B	780	791	.544	780	809	.610
	L	729	776	.216	575	692	.315
A3	H	340	340	.883	390	390	.911
	B	290	301	.565	290	301	.783
	L	240	283	.248	190	283	.474
B1	H	1781	1781	.853	2080	2080	.902
	B	1580	1620	.605	1580	1639	.763
	L	1379	1537	.388	980	1217	.445
B2	H	710	710	.885	960	960	.938
	B	660	668	.670	660	685	.835
	L	610	643	.405	360	459	.553
B3	H	440	440	.905	490	490	.874
	B	390	400	.610	390	405	.708
	L	340	379	.315	290	348	.361

Table 2: Menu of Contracts Generated by Cost Sharing Algorithm: All Missions and Designs.

Stage 1 The initial cost estimate $C_j^E = C_j(\underline{S}_j, 0.95, 0)$ is displayed for each design of each mission. Both HQ and the ICs know this. Center i receives private cost estimates for each mission $c_{ij} = C_j^E + L_{ij}^1$, where L_{ij}^1 is drawn independently each period.

Stage 2 Negotiation Phase: IC proposes a design and a baseline cost, in "francs" for one or more missions. HQ responds with a counteroffer, which may include a proposal for a different mission or the use of a different design. There are three total rounds of offers and counteroffers at this stage. After the third round, HQ assigns missions and specific designs to IC's. HQ also assigns a cost baseline C_a for each mission. Once C_a is agreed upon, the menu of contracts is calculated.[18] These are given in Table 2 for each design of each mission. The "Low", "Middle", and "High" contracts yield the highest transfer from HQ to IC for different ranges of final costs. The headings Low and High variance are explained later in this section.

Stage 3 First Innovation Phase: IC chooses e_1, a level of expenditure on innovation effort and realizes an innovation with probability $P_1 = 1 - z^{-e_1}$. An innovation benefits only the mission with which it is associated. If an IC receives an innovation associated with mission j, a_{ij} decreases by one-third. The expenditure on effort represents a monetary expense in francs that the IC incurs.

Stage 4 IC experiences an independent cost shock L_{ij}^2 from $F(L)$. After observing its own shock, IC chooses one of the contracts from the menu.

Stage 5 Second Innovation Phase: IC chooses e_2, the level of expenditure on innovation effort, and realizes an innovation with probability $P_2 = 1 - z^{-e_2}$. If IC receives an innovation associated with project j, a_{ij} decreases by one-third from its level after stage 3.

Stage 6 Construction Phase: IC builds the mission by spending francs on S_j and R_j in accordance with the cost function for the mission. Before it does so, IC experiences an independent cost shock L^3_{ij} from the same distribution as L^1_{ij} and L^2_{ij}.

Stage 7 After S_j and R_j are selected, IC chooses whether or not to deliver for launch. If launched, the mission is successful with probability R_j. If successful, both HQ and IC receive a payoff of S_j points. If the mission fails, both HQ and IC receive a payoff of $-F_j$ points. If the mission is not launched all parties receive a payoff of zero for the mission.

Stage 8 The IC is reimbursed $t(C_F, C_k)$ francs, where

$$C_F = C\left(S_j, R_j, e_1 + e_2 + \sum_{k=1}^{3} L^k_{ij}\right) - I\left(S_j\right),$$

where $I(S_j)$ equals the cost savings from innovation. $t\left(C_F, C_k\right) = \alpha k + \beta k \left(C_F - C_k\right)$, where k corresponds to the contract selected in stage 4. The amount $t(C_F, C_k) - C_F$, if positive, is credited to an account denominated in francs, that the IC can spend on missions in subsequent periods. If $t(C_F, C_k) - C_F$ is negative it is deducted from the balance of the account.[19]

5.4 The Single Contract Cost Sharing Process

In order to isolate the effect of the multiple contracts, we also designed a simpler type of cost sharing mechanism, the single-contract cost-sharing process (SCCS). The sole difference between this process and the process outlined in section 5.3 is that only the baseline contract is available. In stage 2, when C_a is agreed upon, the IC is required to operate using the baseline contract. Of course, this eliminates stage 4 in section 5.3. All other stages in the SCCS process operate as described in section 5.3.

5.5 The Cost Cap Process

To provide a standard of comparison to our proposal for MCCS, we implement a stylized version of the current contracting process used at NASA for mission acquisition in the context of our experimental environment. The sequence of events in a period of the Cost Cap process is summarized in panel (b) of Figure 5. There are eight stages of activity, two of which are different from the stages in MCCS. There are two building stages (instead of one) and no cumulative reimbursement or carryover of costs.

Stage 1 This is identical to stage 1 described in section 5.3.

Stage 2 First Negotiation Phase: IC proposes a design and a budget to complete a mission. HQ responds with a counteroffer, which may include a proposal for a different design. There are three total rounds of offers and counteroffers. After the third round, HQ assigns missions to ICs and specifies the designs and cost caps k_{ij}, where k_{ij} is the maximum that center i can spend on mission/design j. HQ is constrained by the global budget B so that $\sum_{i,j} k_{ij} \leq B$, where B is the total amount of funds available for projects in a period. B is equal to 1500 francs in every period of the experiment.

Stage 3 First Innovation Phase: This is identical to stage 3 in section 5.3.

Stage 4 First Construction Phase: IC experiences an independent cost shock L^2_{ij} from $F(L)$. After learning L^2_{ij}, IC begins construction of its assigned mission according to the agreed upon design. After this phase the mission has a current value S^1_{ij} and a current reliability level R^1_{ij}. At the end of this stage the IC has spent $a_{ij}(S^1_{ij})^2 + b_{ij}\ln(1/(1 - R^1_{ij})) + L^1_{ij} + L^2_{ij} + e_{ij}$.

Stage 5 Second Negotiation Phase: This is similar to stage 2 except that there is one round of offer and counteroffer. Here HQ can cancel, contract new missions, or change the design of previously assigned missions. If the design is changed, 50% of the science and reliability level of the previous design transfers to the new design. That is, if design j is changed to k, $S^1_{ik} = S^1_{ij}/2$ and $R^1_{ik} = R^1_{ij}/2$.

Stage 6 Second Innovation Phase: This is identical to stage 5 in section 5.3.

Stage 7 Second Construction Phase: IC can spend money to add more value S^2_{ij} and reliability R^2_{ij}. Value and reliability are cumulative so that $S_j = S^1_{ij} + S^2_{ij}$ and $R_j = R^1_{ij} + R^2_{ij}$. Beforehand, IC experiences another cost shock L^3_{ij} from the same distribution as but independent of L^1_{ij} and L^2_{ij}.

Stage 8 After S_j and R_j are selected, IC chooses whether or not to deliver for launch. If launched, the mission is successful with probability R_j. If successful, both HQ and IC receive a payoff of S_j points. If the mission fails, both HQ and IC receive a payoff of $-F_j$ points. If the mission is not launched all parties receive a payoff of zero for the mission.

There is no cost reimbursement here. All expenditures in Stages 4 and 7 were required to be less than or equal to the cost caps negotiated in Stages 2 and 5. Any excess francs at this point are removed from the experiment: neither the IC nor HQ may keep them.

5.6 Principal differences between environment of model and experiment

There are some major differences in the environment described here and the assumptions of the theoretical model described in section 2. Properties of the NASA environment described in section 3 guided the differences.

1. In the experiment, Center i learns the components of the productivity parameter L_i as the game proceeds, and does not know the full realization of L_i at the beginning of the process. There are three independent shocks that comprise L_i, two of which are incurred after the first negotiation phase, and one of which occurs after the second negotiation phase, in contrast with a single negotiation phase after the single shock in the theoretical model. In the model the adverse selection (drawing of L_i) occurs before the moral hazard (choice of e_i). In the experiment, adverse selection problems and moral hazard opportunities occur in overlapping stages during the process.

2. In the experiment, greater effort yields lower cost stochastically. By spending money on innovation, the agent makes an investment that yields a reduction in cost with a probability that is increasing with the expenditure, but predetermined in magnitude.

3. The use of the transfer t is restricted in the experiment. It can be used, if at all, only to fund missions in subsequent periods. The contractor can get no benefit by retaining it as profit. The utility of the transfer to both sides, which is equal to the opportunity cost of the funds, thus differs from a model in which the funds may be used for many other purposes.

4. The agent and the principal both receive utility from the completion of the mission. This represents the fact that in our application both principal and agent are members of the same organization. In the NASA example, the engineers and scientists working on construction of a mission often use the scientific output from the mission in their own research, and thus are also consumers of the science the mission generates.

5. In the experiment, multiple missions may be contracted simultaneously in a period. One mission may be assigned to each of two IC's or two missions may be assigned to the same IC. The presence of multiple designs for each mission means that there are also group-level incentives for the two parties to coordinate on the most cost-effective design. The appropriate design can differ from period to period because of the exogenous randomness in costs.

6. In the experiment, there are global budget constraints that limit how much can be spent on a collection of missions. However, because the contractor cannot shift budgets between missions, each contract is

independent except for the fact that they must be paid for by HQ out of one global budget. In the NASA example, this represents the typically binding budget constraints imposed by OMB during the appropriations process.

7. The good the contractor in the experiment delivers is a lottery, since it consists of a value and a probability of success/failure. In the theoretical model, there is no uncertainty about the final payoff the principal receives from the delivery of the good.

5.7 Experimental design, treatments, and sessions

There are three factors that are systematically varied in the experimental design. The first factor is the contracting process. One of the three contracting procedures described above is in effect. As detailed below, the second factor is the number of Centers (either 1 or 2), and the third is the distribution of cost shocks (Low Variance and High Variance).

One vs. two IC's: The 1IC treatment involves two subjects paired in the roles of one HQ and one IC. The 2IC treatment consists of groups of three subjects, one in the role of HQ and two in the role of competing ICs. We study both cases because the incentives of the actors differ qualitatively in the two situations, and both situations are relevant to our field application. In the situation of 1IC, the incentives of HQ and the IC are, other than the presence of the bonus to the IC from successful completion of design 1 missions, perfectly aligned, and therefore the interaction has many properties of a common interest game. Both parties have common incentives to allocate budgets optimally across missions and across time. However, in the 2IC case, there are two ICs competing for the same funds and thus each IC's incentives are not perfectly aligned with HQ and are in conflict with the other IC. Recall that each IC does not receive any earnings for missions completed by its competitor.

Variance of cost shocks: The distribution of the cost shocks $F(L)$ was varied systematically. In the Low Variance (LoVar) treatment all cost shocks were drawn from uniform distributions with support on the interval $[-200, 200]$, on average 16.6% of the initial cost estimate, for design 1 missions and $[-50, 50]$ for design 2 and 3 missions (7.1% and 15.3% of average initial cost estimates for design 2 and 3 missions respectively). In the High variance treatment (HiVar), cost shocks were drawn from uniform distributions on the intervals of $[-500, 500]$ for design 1 missions, $[-300, 300]$ for design 2 missions, and $[-100, 100]$ for design 3 missions. These amount to on average 41.3%, 42.5%, and 30.0% of the initial cost estimates for design 1, 2, and 3 missions respectively.

There were 58 independent series of periods where the same pair or group of subjects interacted. Each series consisted of five periods. Subjects were recruited from the graduate student population at Purdue

Number of Centers	Variance of Cost Shocks	Number of Periods Collected					
		Cost Caps		MCCS		SCCS	
		Inexper.	Exper.	Inexper.	Exper.	Inexper.	Exper.
1	Low	5	10	30	5	0	20
1	High	30	15	20	15	0	0
2	Low	20	5	25	5	10	20
2	High	20	10	20	5	0	0
Total		75	40	95	30	10	40

Table 3: Amount of data gathered.

University. The experiment was entirely computerized. The program, which was developed specifically for this experiment, was written in Perl, ran on a UNIX server accessible from the Internet, and subjects interacted with the program through a web browser. The instructions for the experiment are available from the authors. There were up to three pairs of agents in the 1IC treatment and up to two groups in the 2IC treatment interacting in the laboratory simultaneously, though each group was completely independent of the others and at no time became aware of the decisions taken in other groups. Each subject remained grouped with the same person(s) for the entire session.

In Experienced sessions all subjects had participated in a previous experiment in this study. This meant that they were familiar with the environment. In Inexperienced sessions no subject had previously participated in an experiment of this type. In each Inexperienced session, there were three practice periods and in each Experienced session there was one practice period, before the five periods that counted toward subjects' earnings began. Participants were not paid for any earnings accrued during practice periods. Inexperienced sessions averaged approximately three hours in length, and experienced sessions averaged approximately 90 minutes. Table 3 describes the amount of data available under each treatment.

6 Results

6.1 Performance of the Multi-Contract Cost Sharing Process

Figures 6 through 9 indicate the average values of two measures of performance of the three processes, with both experienced and inexperienced subjects. The measures of performance of the processes in the experiment are the period payoff to HQ, defined as $\pi_{HQ} = \sum_i \sum_j [R_j S_j + (1 - R_j) F_j] x_{ij}$ and the period payoff to IC$_i$, defined as $\pi_{IC} = \sum_j [R_j (S_j + y_j) + (1 - R_j) F_j] x_{ij}$. x_{ij} equals 1 if IC i is assigned mission j and 0 otherwise. The figures illustrate the average level of π_{HQ} by period as well as the average by period of the total π_{IC} of all ICs.

In the figures, the observed payoffs from the three processes described in section 5 are compared to two benchmark outcomes. The two benchmarks are the payoffs that would result if parties made optimal decisions and maximized their average payoff $(\pi_{HQ} + \pi_{IC})/2$. The first benchmark, called the No Carryover Benchmark, is calculated by solving the following optimization problem:

$$\max_{\{x_j, R_j, S_j\}} \sum_j x_j \left[R_j S_j - (1 - R_j) F_j + y_j/2\right] \tag{15}$$

such that

$$S_j \geq \underline{S}_j \ \forall j \tag{16}$$

$$x_j \in \{0, 1\} \ \forall j \tag{17}$$

$$\sum_j x_j C_j^E (S_j, R_j, 0) \leq B \tag{18}$$

$$x_{A1} + x_{A2} + x_{A3} \leq 1 \tag{19}$$

$$x_{B1} + x_{B2} + x_{B3} \leq 1 \tag{20}$$

where $x_j = 1$ if mission/design j is assigned to any IC and 0 otherwise.

The solution to (15)-(20) represents the value resulting from an optimal allocation of 1,500 francs over one period. (16) requires the value of each mission to be at least the target level, (17) constrains missions to be allocated in integer quantities, (18) requires that the budget is not exceeded, and (19)-(20) ensure that at most one A and one B mission are allocated. For simplicity, it is assumed that $L_{ij} = 0$ and $e_i = 0$ for all i and j. That is, every cost shock is equal to zero, and no innovation effort is exerted. The No-Carryover benchmark for HQ payoff, 672.2 points, is equal to $\sum_j x_j^*[R_j^* S_j^* + (1 - R_j^*)F_j]$, where x_j^*, R_j^*, and S_j^* are the solution to (15)-(20). The No-Carryover Benchmark for IC, 1160.2 points, is equal to $\sum_j x_j[R_j^* S_j^* + (1 - R_j^*)F_j + y_j^*]$.

A second benchmark we compare to the performance of our three processes is the Carryover Benchmark. It is calculated by solving the optimization problem in (15)-(20), but replacing (17)-(20) with:

$$x_j \in \{0, 1, \ldots, 5\} \ \forall j \tag{21}$$

$$\sum_j x_j C_j^E (S_j, R_j, 0) \leq B \tag{22}$$

$$x_{A1} + x_{A2} + x_{A3} \leq 5 \tag{23}$$

$$x_{B1} + x_{B2} + x_{B3} \leq 5 \tag{24}$$

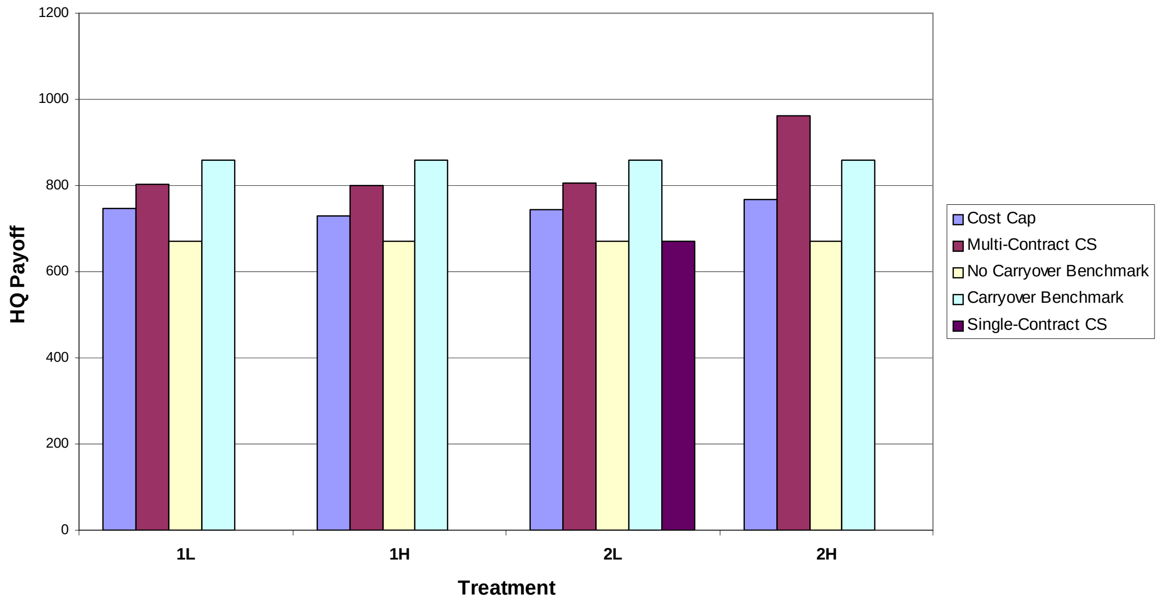

Figure 6: Average period payoffs to HQ in sessions with inexperienced subjects.

The Carryover Benchmark assumes that funds can be borrowed from or carried over into the future during a five period horizon. In other words, it represents the optimal allocation of five yearly budgets, a total of 7,500 francs, over five periods. The difference between the Carryover and No-Carryover benchmarks provides a measure of the effect on earnings of the ability to carry over savings from period to period. This difference is 188 points for HQ and 94 points for the IC's. As we argue below in Observation 1, the MCCS process both outperforms the Cost Cap process and generates higher payoffs than both benchmarks. Both parties, HQ and IC's, are better off under MCCS than under Cost Cap or at the benchmarks.

Observation 1 *The payoff to both HQ and the IC's is (a) greater under MCCS than under Cost Cap and (b) greater under MCCS than both benchmark payoff levels.*

Support. For each measure, we can compare MCCS and Cost Cap under eight different and independent treatment cells ([1IC and 2ICs] * [Experienced and Inexperienced Subjects] * [High and Low Variance]). If the two processes on average generate the same value of the measure, the probability that the average value of the measure for one contracting system exceeds the other for all 8 comparisons is .0039. Therefore, we can reject the hypothesis that the two processes generate identical average values of the measure at the $p < 0.005$ level, if the value of the measure is greater for one process than the other in 8 of 8 comparisons. The figures show that MCCS yields higher average values of both π_{HQ} and π_{IC} than Cost Cap under all

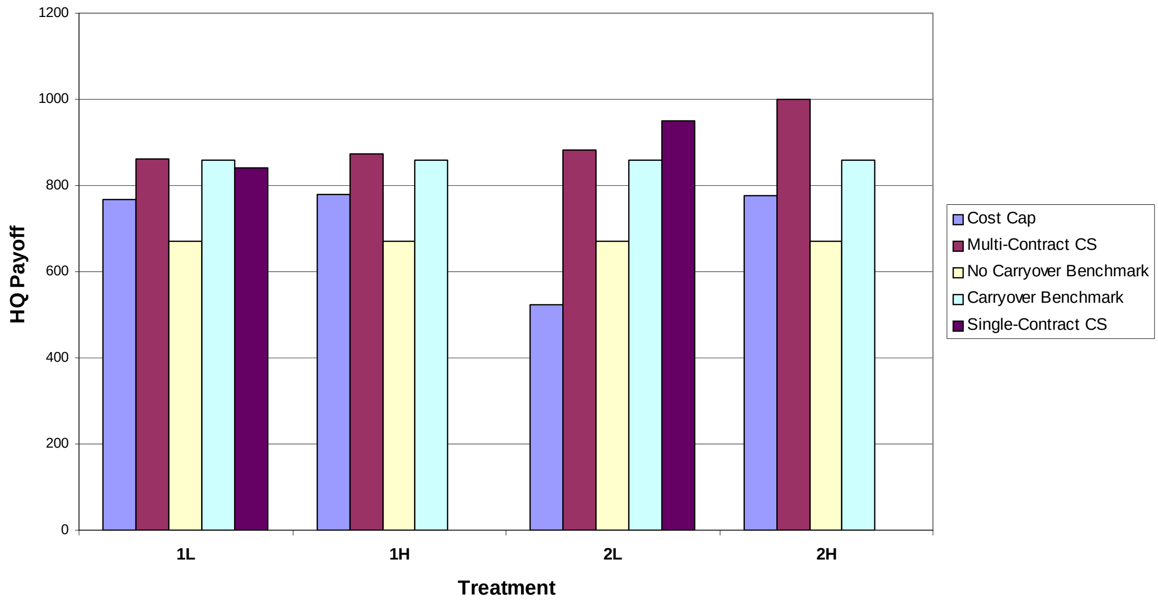

Figure 7: Average period payoffs to HQ in sessions with experienced subjects.

treatments and for both experience levels (in eight out of eight comparisons between treatment cells). With experienced subjects, the MCCS process outperforms the No-Carryover and the Carryover benchmark from the point of view of both parties in eight of eight treatment pairs ([HQ and IC] * [LoVar and HiVar] * [1IC and 2IC]).[20] ■

Thus both HQ and the IC receive gains from a change from Cost Cap to MCCS.[21] There is little improvement with experience under the Cost Cap system, but there is considerable improvement with experience under MCCS. The Cost Cap system appears to be simpler and subjects reach the limit of how well the system can do more quickly than under MCCS. In only four of eight treatment cells ([HQ and IC]*[LoVar and HiVar]*[1IC and 2IC]) are average payoffs higher among experienced than among inexperienced subjects under Cost Cap. On the other hand, under MCCS, in 8 of 8 cases, average payoffs are higher in experienced than in inexperienced sessions. The relative advantage of MCCS is greater under 2IC and under High variance conditions. It may be the case that MCCS becomes relatively more effective in the presence of competition between agents.

The superior performance of MCCS relative to Cost Cap is not merely due to the ability to carry over funds between periods, which relaxes the constraint that the budget must balance at the end of every period. There are two pieces of evidence that support this contention. The first piece is a comparison of the difference

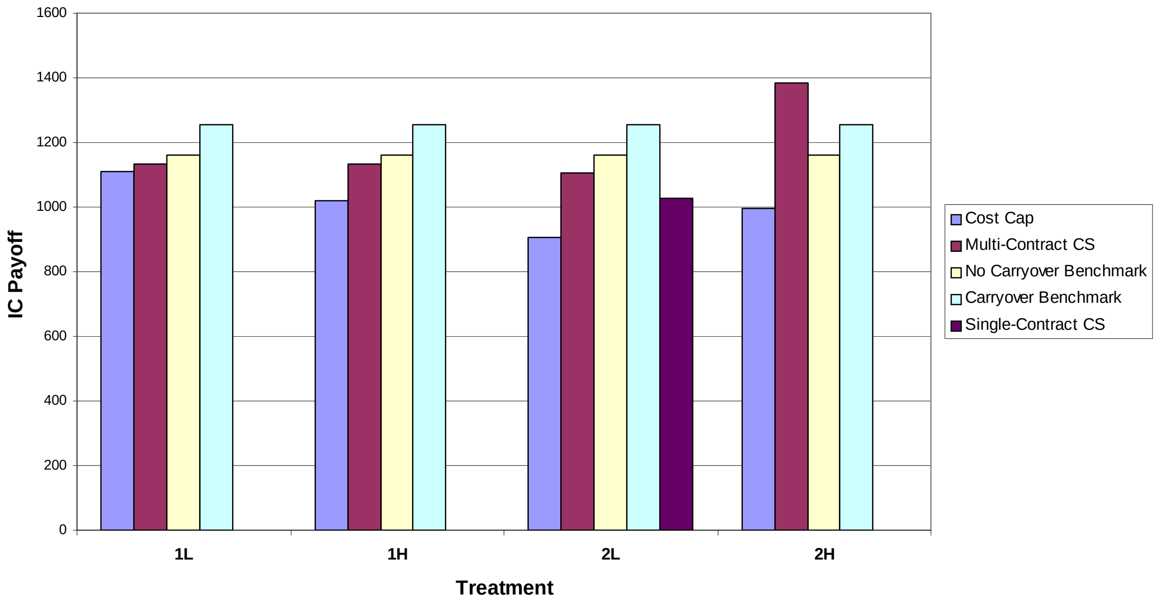

Figure 8: Average period payoffs to the ICs in sessions with inexperienced subjects.

in payoff between Cost Cap and MCCS to the difference in payoff between the Carryover and No-Carryover benchmarks. For experienced subjects, the difference in total payoff ($\pi_{HQ} + \pi_{IC}$) between MCCS and Cost Cap is greater than the difference in the two benchmarks in all four treatments. This indicates that the benefit of MCCS is not merely the fact that it relaxes the constraint that budgets must be spent in the current period.

The second piece of evidence comes from comparing the single-contract cost sharing process (SCCS) with the multiple-contract version. The single-contract process includes the ability to carry over and borrow funds across periods like the multi-contract version. Differences between multi and single-contract cost sharing cannot be attributed to carryover and indeed not to cost sharing itself. In the three treatment cells in which it was applied, SCCS outperforms Cost Cap, but does not do as well as MCCS. The total payoff ($\pi_{HQ} + \pi_{IC}$) is greater under MCCS than under SCCS, and in turn is greater under SCCS than under Cost Cap, in the 2IC LoVar treatment with both experienced and inexperienced subjects and in the 1IC LoVar treatment with experienced subjects. This indicates that the multiple contract structure and IC self-selection themselves promote high payoffs when added to cost sharing and carryover.

The Cost Cap process yields higher payoffs than the no-carryover benchmark for HQ in seven of eight instances but in zero of eight instances for IC. The shifting of rent from IC to HQ under the Cost Cap

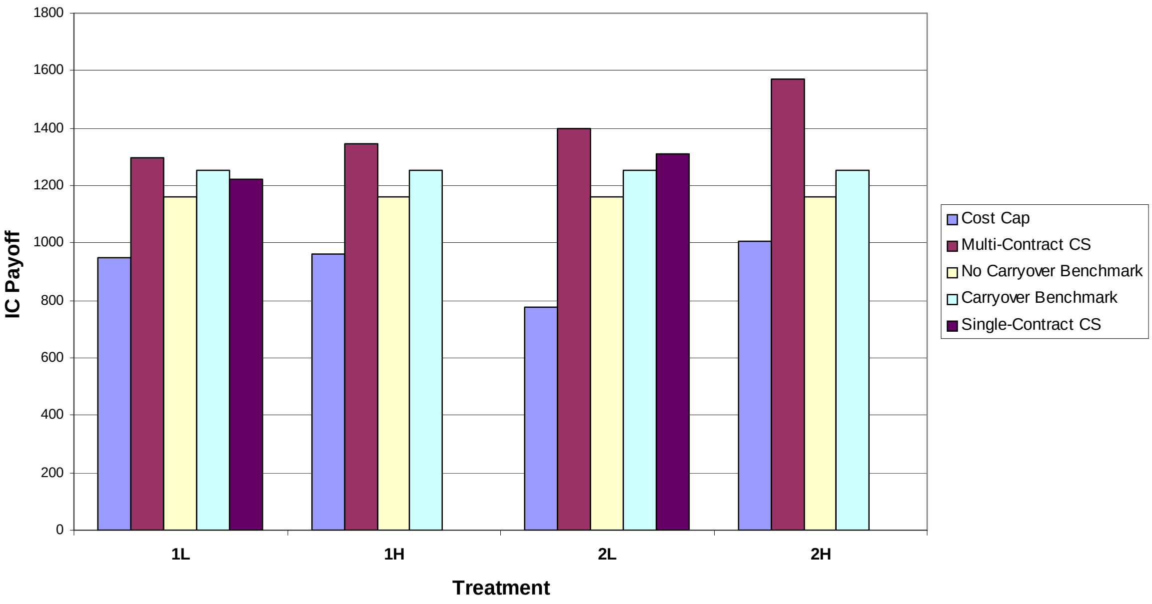

Figure 9: Average period payoffs to the ICs in sessions with experienced subjects.

process relative to the benchmark process may be due to HQ's ability to unilaterally specify caps at the end of the negotiating process, giving HQ more bargaining power than ICs. Since MCCS realizes higher value than optimal decision making when luck and effort are set to zero, it must be the case that MCCS is able to induce a level of effort that on average reduces costs, and/or allocates resources toward missions and IC's who have experienced favorable exogenous cost shocks. Observation 2 below summarizes differences between the two systems in measures that are typically of interest in field applications: final costs, the probabilities of non-delivery and failure, and the number of innovations realized.

Observation 2 *On average, there is more innovation, lower final cost and less frequent non-delivery of projects under MCCS than under Cost Cap.*

Support. The data in table 4 show that there is more innovation per mission under MCCS than under Cost Cap in seven of eight treatments (and an equal amount in the eighth treatment). The non-delivery of contracted missions is more frequent under Cost Cap than under MCCS for each of the eight relevant comparisons. Average cost relative to original estimated costs are lower under MCCS than under Cost Cap for eight of eight possible comparisons, even when the missions that are not delivered (which occur more frequently under Cost Cap and which tend to have unfavorable cost shocks) are censored from the data. ■

It appears that MCCS yields more innovation than Cost Cap because of the ability of IC's to

	Number of ICs	Variance of Cost Shocks	(Overall / Experienced Only) Cost Caps	MCCS	SCCS
% of Missions Not Delivered	1	Low	12.5% / 10%	4% / 0%	4.50%
	1	High	23.7 / 23.1	1.9 / 0	–
	2	Low	23.4 / 50.0	0 / 0	7.8 / 0.0
	2	High	25.4 / 25.0	2.8 / 14.3	–
C_F/C_j^E (Avg. of completed missions)	1	Low	1.15 / 1.20	1.00 / 1.11	1.042
	1	High	1.05 / 1.04	0.98 / 0.80	–
	2	Low	1.20 / 1.34	0.99 / 1.01	1.01 / 1.00
	2	High	1.05 / 1.06	0.88 / 0.95	–
Reliability R_j (Avg. of completed missions)	1	Low	97.1% / 99.3%	96.7% / 98.1%	95.60%
	1	High	98.1 / 95.9	95.8 / 98.2	–
	2	Low	96.1 / 95.4	93.4 / 97.1	95 / 95.73
	2	High	98.0 / 97.5	95.3 / 96.1	–
Number of Innovations per Period	1	Low	1.07 / 1.40	1.2 / 1.4	0.7
	1	High	0.89 / 0.73	1.49 / 1.6	–
	2	Low	0.64 / 0.80	1.0 / 1.0	0.87 / 1.10
	2	High	0.63 / 0.10	1.2 / 1.6	–

Table 4: Summary of results for all periods.

appropriate cost savings and the provision by HQ of insurance against unsuccessful innovations. There tends to be more innovation under multi-contract than under single-contract cost sharing especially in 1IC treatments. The multiple contract version of cost sharing induces better incentives to innovate during the first innovation opportunity than the single contract version. Under MCCS, the steeper cost share coefficients for the high contract provide more insurance against unsuccessful innovation. The relatively flat coefficients in the low contract mean that the IC can appropriate a greater share of the savings from innovation.

Under Cost Cap, the incidence of non-delivery is not reduced by experience, so there is no evidence that it is a transitory phenomenon that would disappear with learning. Non-delivery is more common under HiVar and when there are two IC's. High variance creates an additional inability to complete missions on time when "bad luck" occurs. With two IC's, the phenomenon of "buy-in", a strategy on the part of an IC to negotiate a low cost cap in order to win the contract but in anticipation of a later renegotiation to increase the cap, causes contracts to often be awarded at budgets too low to allow them to be completed.

Final costs are roughly 15% lower for completed missions on average under MCCS than under Cost Cap. Under all of the mechanisms, conditional on completion, average costs are lower under HiVar than under LoVar. This is because if there is a tendency for projects with relatively good cost draws to be assigned, and the expected cost to the low-cost IC of the most cost effective mission is lower under HiVar. Average final costs are similar under SCCS and MCCS, and costs under SCCS are lower than under Cost Cap in each of the three treatments where SCCS is applied. The cost per mission shows little tendency to decrease over time under any of the processes, but the composition of missions changes over time in MCCS to shift to higher value missions, leading to increases in payoffs.

6.2 Where does MCCS under-perform?

In the preceding section, we have argued that the MCCS process is a significant improvement over Cost Caps, the current process in use for our application. The experimental data, however, allow us to identify three systematic biases in decision-making by participants in the MCCS system. The modification of MCCS in ways that would reduce these biases could further improve the performance of the system.

Bias 1 *MCCS exhibits a tendency toward overinvestment in effort relative to optimal behavior.*

Support. Optimal investment in innovation is defined as the level of investment that minimizes the expected cost of completing the mission at the target value S_j. Under MCCS and 1IC, 81.8% of design 1 missions were characterized by greater than optimal effort; while 12.8% had lower than and 5.4% had exactly the optimal level. Under 2IC, 54.2% of design 1 missions included overinvestment, 41.7% had underinvestment and the rest were optimal. Under SCCS 80% of design 1 mission innovation opportunities are characterized by overinvestment with 2IC's. Under 1IC, the comparable figure is 56.3%. ■

Bias 2 *In the 2IC treatment of MCCS, there is some tendency to award contracts to the IC that does not have the lowest estimated cost at the time of the award.*

Support. Under MCCS, only 65.5% of missions were awarded to the IC with the lowest initial cost estimate. With SCCS, only 58.8% of contracts were awarded to the IC with the lowest cost estimate. Most inefficient allocations appear to be due to a tendency for HQ to try to distribute the missions evenly between the ICs, even though this means often not awarding missions to the lowest cost suppliers. Although an even distribution of contracts may be a goal of NASA in practice, there were no direct incentives in the experiment for this to occur. Nevertheless, it often happened. ■

Bias 3 *At the levels of science and reliability chosen by the IC's, the marginal return on expenditure tends to be lower on science than on reliability. In other words:*

$$\frac{\partial E\pi}{\partial C_j}\frac{dC_j}{dS_j} < \frac{\partial E\pi}{\partial C_j}\frac{dC_j}{dR_j} \tag{25}$$

This means that expected payoffs to IC's would typically be higher if marginal expenditures were substituted from science to reliability. In all but 6 of 37 completed missions under MCCS in which $S_j > S_j$, the marginal return on R_j was greater than on S_j (in the missions where $S_j = S_j$, equation (15) does not necessarily indicate a bias because the marginal expenditure on S_j allowed the threshold level S_j to be attained). Of the 6 exceptions, 5 were under 1IC. Under SCCS, the marginal return to the IC is higher on R_j than on S_j for every single mission, including the eleven missions that had the property that $S_j > S_j$. In contrast, under Cost Cap, in 50 out of 103 missions in which $S_j > S_j$, 48.5%, the return of the marginal franc spent on reliability exceeded that spent on increasing the value of the project. Since a change in the contracting process removes the bias toward insufficient spending on reliability, bias three appears to have its origin in the MCCS process itself rather than in the underlying preferences of agents.

7 Discussion

We have used the theory of optimal contracting under moral hazard to guide us in proposing and constructing a procurement system, Multi-Contract Cost Sharing, for use in contracting applications. Our experimental data show that the MCCS system performs well compared to benchmark algorithms and compared to an alternative mechanism, Cost Cap, a version of which is currently in use in NASA Mission Acquisition, an environment with a structure similar to the experimental environment. Both principal and agent are better off under MCCS than under the Cost Cap system, and therefore no party should have a stake in opposing implementation. Comparison of MCCS with an alternative, SCCS, suggests that the menu structure of contracts and the ability for the agent to delay choice of contract improve the performance of the system over simpler linear cost sharing systems.

Some of the properties of MCCS that appear to enhance its performance are the following. (1) The agent has an additional incentive to innovate to reduce costs since he keeps a portion of the cost savings. This benefits both parties because the principal also re-appropriates some of the savings. (2) The principal shares in the cost of sensible but unsuccessful innovation attempts and the presence of this insurance encourages the agent to innovate more, to the benefit of both parties. (3) The ability to keep a portion of the cost savings allows both parties to save money to compensate for future bad luck – another form of insurance. (4) Additional funds are automatically released to reduce the incidence of delays when bad luck occurs. (5) The agent is encouraged to select the relatively cheap "Low" contract when its costs are low and this reduces the incentive to spend additional money on a project unproductively. (6) The contract is chosen late in the process when cost estimates are more precise.

The experimental results reveal the weaknesses of a contracting system where costs are capped. A cost ceiling is not flexible enough to cope with unavoidable cost increases, which require an increase in the cap, or to efficiently exploit favorable cost shocks by lowering the level of reimbursement in such circumstances. It also only contains incentives to reduce cost for certain ranges of the exogenous variables; that is, when innovations increase the likelihood that the final cost is below the cap. If costs are sufficiently below the cap, or are unlikely to be reduced to below the cap even with great effort, the agent will have no strong incentive to exert effort to seek cost reductions.

Of course, the degree to which the experimental results presented here parallel those that would be observed in field applications cannot be known with certainty until the mechanism is implemented. There are three types of questions that arise with extrapolation from the laboratory to field applications, which typically involve higher stakes, a natural rather than a laboratory setting, and decision makers with different characteristics and training. The first question is whether behavior of humans changes when the monetary stakes are increased to levels that exist in field applications. Experiments in which the scale of payoffs is varied show that the scale of payoffs does not influence results qualitatively (see for example Smith and Walker [18]). Experiments in developing countries, (for example Kachelmeier and Shehata [8] and Cooper *et al.* [4]) in which large sums of cash are paid relative to subjects' overall incomes also show only minor differences in behavior from experiments with university students in developed countries. There is evidence that players are more risk averse at higher stakes (Holt and Laury [7]). However, increased risk aversion would likely improve the performance of MCCS relative to Cost Cap because under MCCS the IC does not bear exclusively the risk of attempting to innovate.

The second question is whether behavior differs inside and outside of the laboratory setting. Some recent experiments comparing behavior in the laboratory and on television game shows are useful in this regard, because the precise rules of the game show can be recreated in the laboratory. Several studies show similar behavior in the two settings (see for example Cason and Tenorio [3] or Healy and Noussair [6]).

The third question is whether behavior differs between untrained student subjects and professional practitioners who have though long and deeply about the strategic structure of the situation. The current evidence from professionals and students participating in identical experiments has not yielded any major differences. Examples include King *et al.* [9] who studied the behavior of experimental asset markets with stock traders as subjects and Bohm and Carlen [2] who studied negotiation in the laboratory with diplomats as subjects.[22]

As a final thought, in our experimental environment there was an incentive to spend the totality of the allocated budgets. That is, we have modeled a government agency without a profit motive. We have no reason to believe, however, that the treatment effects we observe, in particular the strong performance of the MCCS system, would not also be observed when a direct profit motive exists.

Notes

[1]This theory is due to Laffont and Tirole, [10] and [11].

[2]There have been several instances of the use of cost-sharing contracts in US government procurement. All have used different cost sharing rules than the MCCS process. The Air Force Peace Shield program contract had an incentive structure where there was an agreed upon baseline cost, the Air Force paid 75% of any overrun, and the contractor kept 75% of any underrun. In addition, the contractor received a $50 million bonus if the project was completed early, and incurred a $50m penalty for late delivery. There was a payment ceiling of 125% of the baseline cost. Another example is Lockheed Martin's contract for the F-117A in which the Defense Department and Lockheed Martin shared the cost of any overrun and savings from any underrun at a rate of 50%. 50-50 cost sharing also applied to the US Army's procurement of the Multiple Launch Rocket System (MLRS). In 1987, the GAO conducted a review of 60 DOD incentive contracts and found that the final costs of the majority of contracts were within 5% of target costs. 47% were below and 53% were above target. 21% exceeded the original ceiling price (US Army, [19]).

Cox et al. [5] compared cost sharing and fixed-price contracting in the laboratory. Their results indicate that cost sharing allows projects to be completed at lower cost than fixed price contracting. However, cost sharing is less efficient than fixed price contracting in the sense that the contract is less likely to be awarded to the lowest-cost contractor.

[3]This is especially true of many government agencies such as NASA who are constrained by Congress from transferring money between many budget categories.

[4]The additional technical assumption of $\psi''' (e) \geq 0$ is used to eliminate stochastic mechanisms and guarantee that the optimal choice of effort is nonincreasing in L.

[5]It is also assumed that $F(L)$ is is absolutely continuous and $f(L) > 0$ for each $L \in [\underline{L}, \overline{L}]$.

[6]There are have been several other research projects that have used experimental methods to focus on NASA-related economic issues. See Banks, Ledyard and Porter [1], Noussair and Porter [15] Ledyard, Noussair and Porter [13] and Ledyard, Porter and Wessen [12] for examples.

[7]This observation was made in 1999 when we began this project.

[8]There is follow up work currently underway at NASA to lead to exactly this.

[9]The capping of costs is very unusual for contracts in which new technologies are involved and the costs to the contractors are highly uncertain. In most such cases in the private sector, the contractor will typically only agree to a cost-plus contract structure, in which he is paid the full amount of his cost plus a fixed amount. At NASA, before 1993, cost-plus contracting was typical, and the current system of cost caps was put in place in response to a series of severe cost overruns under the cost-plus system.

[10]Note that the cost cap process differs from a fixed price contract. Under a fixed price contract, if the final cost to the contractor is less than the fixed price, the contractor keeps the difference. Under a cost cap system, the contractor must rebate the difference to the contracting agency. The cost cap system does not contain any positive incentive to reduce costs below the cap. There is an incentive to hold costs equal to the cap, because of the threat of cancellation of the mission, which is costly both because the Center values the mission, and because its reputation would then be damaged. It would then be less likely to receive contracts for future missions.

[11]The linearity of the contracts implies that at C^*, the Low and Baseline contracts yield the same transfer, and at C^{**}, the Baseline and High contracts yield the same transfer.

[12]One might wonder why not use just one contract. Below we describe the tests we conducted to study this alternative. As discussed in section 6 of this paper, we found that three is indeed better than one.

[13]This suggests that the appropriate "optimal contracting problem" is not the traditional one where the principal is given the ability to propose a take-it-or-leave-it contract. Instead we should look for contracts that are interim efficient subject to incentive compatibility and voluntary participation constraints on both the principal and the agent.

[14]Design 1 represents a design that yields high science value if the mission is successful, is expensive relative to other designs, and often requires a major technological innovation to be completed. Design 2 represents a standard design with "off-the-shelf" technology that yields lower science value than design 1, but is cheaper and can be infused with higher reliability (lower risk) at lower cost. However, it is very difficult to innovate and integrate new technologies within design 2. Design 3 is a low-budget, minimally acceptable design, which is at the "science floor" for the mission. It is also difficult to innovate within the framework of design 3, but it is inexpensive to ensure a high-likelihood of success. An IC can only be working on one design for a mission at a time. Payoffs can only be obtained for one A mission and one B mission in a given period, representing the fact that building two of the same mission, even if the design is different, duplicates the same scientific output.

[15]Expenditures will be constrained by budgets. How this is done is an organizational design choice and will be varied in the experiments. More details will follow.

[16]The contractor bonus represents future pecuniary and non-pecuniary rewards derived from the successful completion of a prestigious mission that required a break-through innovation. The design 1 missions in the experiment represent such missions.

[17]Non-delivery of a mission in our framework corresponds to the cancellation of a NASA mission. Cancellation may be done by an IC to sacrifice one mission to improve the chances of success for another.

[18]All negotiations were carried out through the experimental software so communication was limited. During the negotiation process, subjects have access to a computer screen that allows them to compute their hypothetical reimbursement for any baseline cost, any of the three contracts, and any final cost.

[19]At the end of a period, the account of an IC or HQ could have a negative balance up to -1000 francs, but at the end of period 5, the balance was required to be positive. If either of these rules were violated, the subject was required to pay a fine of 3000 francs, which was prohibitive given the earnings in the experiment. If the balance fell below -1000 before period 5, the subject was also required to leave the experiment.

[20]It might be argued that the payoff to HQ and the payoff to IC are not independent. If total payoff ($\pi_{HQ} + \pi_{IC}$) is measured rather than the payoffs to the separate actors, four comparisons of total payoff can be made between different processes [(LoVar and HiVar)*(1IC and 2IC)]. If this is done, then MCCS yields higher total payoff under all four comparisons for both experienced and inexperienced subjects. MCCS yields higher payoff than the two benchmarks under all four comparisons when subjects are experienced.

[21]The introduction of cost sharing affects the composition of the completed missions. Under Cost-Sharing, a greater percentage of the completed missions are the more innovative "Design 1" missions, for which IC receives extra payoff.

[22]In addition to the data reported in this paper, we conducted one session with senior managers from NASA Headquarters and from the two largest Implementing Centers. Six periods of data were generated, of which three were under the Cost Cap process and three were under the MCCS process. The relative measures of MCCS vs. Cost Cap were: HQPayoff averaged 753 under Cost Cap and 900 under MCCS. ICpayoff averaged 1086 under Cost Cap and 1400 under MCCS.

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