

**THE SUPPLY OF NATURAL RESOURCES INFORMATION INFRASTRUCTURE:
ISSUES IN THE THEORY AND PRACTICE OF ESTIMATING COSTS**

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Abstract

The collection and analysis of information about natural resources, the environment, and weather places heavy reliance on physical infrastructure. Estimating the cost of infrastructure is difficult for many reasons; ensuring accurate estimates is even more difficult given the tendency for contracting mechanisms to induce downward biases. This paper has reviewed the conceptual and empirical literature on cost estimation and associated contract design to highlight some of these problems and outline possible approaches to ameliorating them.

I. Introduction and background

This paper offers perspectives on the challenge of cost estimation for public investment in infrastructure required for the collection of natural resources information. Costs substantially in excess of initial estimates for this infrastructure have long been problematic for the weather and earth science communities, federal budget experts, and the public at large. Examples include current concerns about the National Polar-orbiting Operational Environmental Satellite System (NPOESS) and the Geostationary Operational Satellite –R (GOES-R) system, and previous overruns on projects including other GOES systems, the Land Observing Satellite 7 (Landsat 7), the Cloud-Aerosol Lidar and Infrared Pathfinder Satellite (CALIPSO), Cloudsat, and the New Millennium Program Earth Observing –1 (NMP-EO-1).¹

The particular focus of this paper is cost estimation during the initial planning stage of a project, reasons why realized costs may grossly exceed estimated costs, and possible steps towards solving the tendency for cost estimates to be misleading as a basis for public governance. It is important to note that imperfect cost estimates or excessive actual cost overruns may still result in programs that are effective in serving the public. In other words, cost growth *per se* is not an indicator of a socially *undesirable* program, nor is a project that is completed within its anticipated budget necessarily an indicator of a socially *desirable* program.

¹ The problem of cost overruns on civilian space projects other than those associated with natural resource infrastructure, such as the Hubble Space Telescope, the James Webb Telescope, the International Space Station, the U.S. Galileo mission, or the implementation of the vision for space exploration are not considered in depth in this paper.

The control of costs during a project, although an important process, is outside the scope of the paper. Yet anticipated problems in cost control, such as whether the parties have a reputation of change orders, a history of delays in delivery schedules or payment, or whether the project is characterized by engineering uncertainty should in principal be factored into the initial cost estimation. Hence the concentration of this paper on the estimation itself.

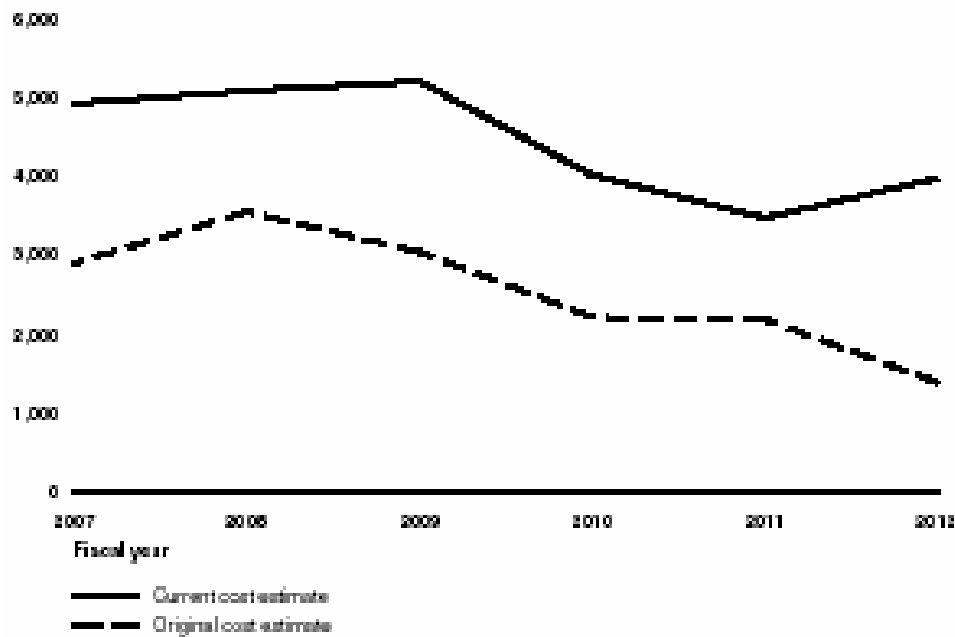
For many projects associated with the critical infrastructure to support the weather, earth sciences and space community, the problem of cost estimation seems particularly acute. The US General Accountability Office (GAO, formerly the US General Accounting Office) and the Congressional Budget Office (CBO) routinely review these program costs. Their reviews seldom find within-budget success. This result may reflect sample bias in that these agencies are requested to study troubled programs rather than smoothly functioning ones; nevertheless, overruns seem to be the rule rather than the exception and can be quite large relative to estimates promised at project start.

For instance, in 1989 the GAO reviewed cost growth and development delays in the GOES-NEXT US weather satellite program. The estimated program cost had increased from about \$294 million to \$725 million and was expected to exceed \$1 billion; the GAO quoted the former manager at the prime contracting company as acknowledging that cost overruns had reached “alarming proportions.” A subsequent GAO study of modernization and restructuring of the National Weather Service (acquiring and deploying several automated systems in addition to a GOES –NEXT procurement) found that the program was estimated in 1980 to cost under \$2 billion. Costs had more than doubled by the time of the GAO review in 1991. The NPOESS program was originally estimated to require \$6.8 billion, but completion costs today are estimated at \$11.1 billion (House Science Committee, 8 June 2006, at <http://www.spaceref.com/news/viewpr.html?pid=20049> accessed June 2007). New hearings on NPOESS cost issues are scheduled for June 7, 2008.

Cost overruns relative to estimates are not peculiar to natural resource information infrastructure, however. In a November 2006 report, *Space Acquisitions: DoD Needs to Take More Action to Address Unrealistic Initial Cost Estimates of Space Systems*, the GAO found current cost estimates had increased in the range of 44% to more than double original estimates for six ongoing space programs. In another, overall review of DoD space-related asset acquisition, GAO (2007) found that cost growth has approached or exceeded 100%, “causing DoD to nearly double its investment in the face of technical and other problems without realizing a better return on investment” (p. 2). Figure 1, reproduced from GAO (2007, p. 3), summarizes the report findings.

Figure 1: Comparison between Original Cost Estimates and Current Cost Estimates for Selected Major Space Acquisition Programs* for Fiscal Years 2007 through 2012

(Millions of 2007 dollars)



Source: GAO analysis of CDD data.

*Includes: Advanced Extremely High Frequency (AEHF) satellites, Evolved Expandable Launch Vehicle (EELV), Global Broadcast Service (GBS), Global Positioning System II (GPS II), Mobile User Objective System (MUOS), National Polar-orbiting Operational Environmental Satellite System (NPOESS), Space Based Infrared System (SBIRS) High, and Wideband Global SATCOM (WGS).

The concerns expressed by these budget experts have long been prominent in civil space activities. In a study, *NASA: Lack of Disciplined Cost-Estimating Processes Hinders Effective Program Management*, the GAO (2004) reports that

For more than a decade, GAO has identified the National Aeronautics and Space Administration's (NASA) contract management as a high-risk area – in part because of NASA's inability to collect, maintain, and report the full cost of its programs and projects. Lacking this information, NASA has been challenged to manage its programs and control program costs.

For more than half of 27 programs reviewed, the study finds that the development cost estimates have increased, and in some cases, by over 90%. A 2004 Congressional Budget Office report, *A Budgetary Analysis of NASA's New Vision for Space Exploration*, found wide disparities between projected and actual budgeted costs in over 70 space projects undertaken between 1977 and 2000. In eleven cases, the percentage change was negative (reflecting descoping of missions, often in response to possible cost overruns); in the remaining cases, percentage increases ranged from zero to 255%.

The difficulty of cost estimation is not unique to space-related infrastructure nor is a large ratio of actual to estimated costs necessarily unusual compared with those for other types of projects. For example, in a review of fourteen new mass transit projects under construction in the late 1990s, the GAO found that half of the projects had experienced increases beyond estimated costs and of these, three had costs significantly higher than expected – more than 25% over the estimates initially approved for funding. Quirk and Terasawa (1986) and references cited in their paper find the ratio of actual to estimated costs to be 1.26 in a review of 49 highway projects; 1.39 for 49 water-related projects; 1.63 for 15 building projects, and 2.18 for 12 major construction projects.

Nor are results such as these a recent trend. Engerman and Sokoloff (2006) have evaluated a dozen major US public works projects during 1817 to 2004, ranging from construction of the Erie canal, the interstate highway system, and the original Superdome to Boston's Big Dig (see table 1). The ratio of actual to project cost in these examples

ranges from about 1.1 to 20. For seven of the twelve projects, the ratio is greater than two. Engerman and Sokoloff find that the ratio has increased with more recent projects. However, in a comparison of major US weapons projects during the 1950s and 1960s, Quirk and Terasawa (1986) find the ratio of actual to estimated cost to be 1.89 for projects during the 1950s and 1.4 for projects during the 1960s.

Time period	Project	Ratio of actual to projected cost
1817-1825	Erie Canal	1.46
1824-1829	Chesapeake and Delaware Canal	1.63
1825-1835	Ohio and Miami canals	1.16
1835-1862	Enlargement and improvement of Erie Canal	2.42
1838-1843	Croton Aqueduct	1.35
1883-1926	Mississippi River Levee Line	Greater than 20
1902-1913	Panama Canal	2.06
1931-1936	Hoover Dam	1.12
1952-1953	Interstate highways	19.10
1966-1975	Louisiana Superdome	4.66
1971-1975	Renovation of Yankee Stadium	4.17
1991 – 2004	Boston Central Artery/Tunnel (“Big Dig”)	Greater than 5.21

Nor is the problem unique to the United States. Large cost overruns plagued construction of the Euro tunnel, the reconstruction of London’s Wembley Stadium, and the building of a large oil pipeline from the Caspian Sea to a Mediterranean port, a project undertaken by Azerbaijan, Georgia, and Turkey. In a study of 258 rail, road, and airport construction projects in 20 nations, Flyvbjerg and coauthors (2003) found substantial cost escalation to be the rule not the exception. And the Galileo navigation satellite project is encountering large cost overruns delaying its construction and deployment, leading the Commission on

European Communities to propose redesign and new financing mechanisms to the European Parliament and Council (see Commission on European Communities, 2007).

Is the challenge of cost estimation endemic to public works – canals, roads, and the space-based architecture for defense or weather and earth observations data? Is there no problem in projects undertaken by the private sector? Hardly. Ask commercial real estate developers. Or neighbors renovating their home or building a new one. Quirk and Terasawa (1986) study the construction costs of commercial nuclear power plants during 1965 to 1975. The majority of these plants were built by privately owned electric utilities. The results find consistently underestimated project costs, with the average percentage of final cost ranging from 103% to 484% of the average original estimate.

The common occurrence of cost underestimation among types and vintages of projects suggests that estimating costs, although for many reasons an art, may well involve systematic tendencies. The next section considers these, drawing from the large academic literature on the theory and practice of cost estimation. The section includes discussion of the problem of “engineering the uncertain,” the asymmetry of information between parties to transactions, the difficulty of monitoring costs to avoid inefficiency and waste, pressures to underestimate costs, the “winner’s curse,” the role of reputation among transacting parties, and the domino-like effect on costs when missions are extended beyond their useful lives. Section III briefly suggests possible guidelines and partial solutions, including use of third parties in cost estimation, an exhortation to discourage precision, the desirability of a public track record and rewarding good results, and whether the “Nunn-McCurdy” amendment is a fully workable alternative. Section IV summarizes the paper.

II. The theory and practice of cost estimation

Any attempt to deal seriously with the study of economic organization must come to terms with the combined ramifications of bounded rationality and opportunism in conjunction with a condition of asset specificity. Oliver Williamson, *The Economic Institutions of Capitalism* (New York: The Free Press, 1985, p. 2).

Cost estimates are usually the basis for a contract – that is, an agreement between parties to a transaction. Many of the problems of cost estimation are related to or result from the problems of contracts. As early as the very first “contract” ever made between parties in the world’s history (which historians cite as legal contracts from ancient Egypt (1800 BC) or early contracts from Mesopotamian civilization (2300 BC), most of these contracts were oral agreements entered into in the presence of witnesses.² Permanent records were sometimes created on issues such as sales and purchase, marriage and divorce, rental and land lease, annuities, loans and mortgages. But fully anticipating all contingencies and perhaps later, not sticking to the bargain have loomed large as problems for all parties to the agreement.

Oliver Williamson, one of the luminary scholars in the study of the organization of relationships and institutions within a market economy, summarizes in the passage above much of the voluminous theoretical literature on the coordination of activities between parties to a transaction. A fundamental assumption is that the parties each act according to their own interests or on behalf of a group to which they belong or represent – the reference by Williamson to bounded rationality and opportunism. The coordination problem is to determine what the transaction or agreement is, how it is accomplished, and who does what to carry it out. The motivation problem is to ensure that the parties do their parts, including reporting information accurately and acting as agreed.

The compact among the parties must describe the payments that flow among the parties, rules and procedures they will use to decide matters, and expectations for performance. Often in a market economy these arrangements take the form of a contract (leaving aside for our purposes the legal definition). The contract is voluntary, accepted only if the parties find it individually and mutually advantageous.

² http://nefertiti.iwebland.com/law_and_order/contracts.htm (accessed August 2006) and <http://www.fordham.edu/halsall/ancient/mesopotamia-contracts.html> (accessed August 2006).

A perfect, complete contract would specify precisely what each party is to do in all circumstances, at what cost, and at what benefit. The formal incorporation of the cost estimate in the contract takes into account the parties' expectations of delivering these specifications, including timing, responsibility, liability, and the allocation of technical and financial risk. In an examination of the problems encountered in Boston's central artery/tunnel project (the "Big Dig"), the National Academy of Sciences/National Research Council (2003) found an original estimate that was too low, along with numerous sources of contractual imperfection and incompleteness. These included inflation that accumulated during project delays, unanticipated costs of mitigation of environmental impacts, unexpected technical complexities, delays in making decisions, and design changes during construction.

A list of problems such as these is commonplace for all kinds of projects, public and private, and different types of infrastructure. Even in the case of routine spacecraft design (aside from innovation in spacecraft bus, instrument suites, or launch technology), typical reasons for changes in mass --and associated cost and contract changes--include: design changes, out-of-scope modifications, errors in estimates (overlooked components), mass reduction required by launch, measured versus actual calculated values, and mass increases to save money, such as by substituting less expensive but larger mass fabrication material (Sugiyama and Yang 2006).

Particularly in the case of infrastructure required for natural resources information, the infrastructure itself is often an asset with varying degrees of uniqueness (a wholly new instrument using experimental techniques, or new designs in the spacecraft bus or launch system). For this reason, Williamson's concern about asset specificity is particularly noteworthy.

Taken together, these characteristics of contracts may go far in explaining the tendency for actual costs to exceed estimated costs. In practice, contracts typically allow for some degree of unexpected changes. For instance, instead of a "fixed price" contract, where the payment is simply the firm's bid, a contract may be "cost plus," adding a margin to cover

additional costs, or it may be an “incentive contract,” flexibly allowing the payment to depend on both the bid and the realized costs. Whether these provisions for the contracting parties to share the risks of overruns can in practice have the unintended effect of encouraging overruns has been the subject of extensive theoretical and empirical research, particularly in defense contracting (for example, Harris and Raviv, 1979, Laffont, 1987, and Weitzman, 1980 are among the comprehensive theoretical models; Crocker and Reynolds, 1993, Cummings, 1977, and Hiller and Tollison, 1978 apply these concepts to defense contracting).

The rest of this section summarizes in somewhat greater detail some of the results from contract theory to consider a variety of reasons for discrepancies between estimated and realized costs.

II.A. Engineering the uncertain

Uncertainty is inherent in technology (as well as management, but this is addressed below), with a lack of systematic and reliable knowledge making it difficult to estimate the costs of unknowns. Quirk and Terasawa dub the problem “pioneering bias in cost estimation.” Uncertainty by itself doesn’t imply bias in one direction (upward or downward), although Quirk and Terasawa find that the tendency is for engineers and other technical experts to underestimate the cost of developing and testing new technology. And of course, unexpected problems that increase costs arise even in dealing with proven technology (plumbing repairs in old houses, a highway corridor encountering a sacred ancient burial ground). It is also the case that the preponderance of analyses and actual outcomes of projects appear to result in cost overruns relative to expected costs, not cost underruns.

Cost increases may arise with engineering changes or system enhancements by the contractor; early designs are frequently modified. These actions may increase the realized cost of a project but presumably are included in the expectations that underlie the formulation of the initial estimate. It may be that the accuracy of estimates increases with expenditures incurred during engineering design in preparing the estimate; in other

words, it may be that estimating mission cost to within, say, 120% of actual cost requires performing 10% or more of the design work. For a mission with a cost of \$300 million, this example would require \$30 million on design work, whereas a few hundred thousand is more typical for a mission in this range of cost.³ One of the most difficult problems with technical uncertainty is that it can be used as a convenient excuse for cost growth (Porter 1983).

An example of a slightly different but analogous set of circumstances has been shown in the case of the estimated costs to achieve compliance with new regulations. Here, it might be expected that prospective regulatees might seek to overstate the costs of engineering and other technological adjustments required to meet the regulation. In a review of 25 environmental and occupational safety regulations, Harrington and coauthors find that estimates of the cost of compliance exceeded actual costs in 12 cases and the estimates were too low in only 6 cases. The authors found that in some cases, overestimation is due to errors in the quantity of control achieved by the rule. For instance, in the case of a regulation to reduce emissions, if fewer emissions are attained, then costs of attainment may be less than expected. On the basis of per-unit of emissions reductions, however, the authors find that estimated costs tend to exceed actual costs.

Much of the overestimation is attributable to technical innovations unanticipated at the time the rule is issued. There may also be a tendency for the regulated entity to overstate expected compliance costs to exaggerate the costs relative to purported benefits. By way of solutions, the authors suggest that regulatory agencies issue a range of estimates rather than a single estimate. They also suggest that regulatory agencies revise cost estimates if compliance-cost changes are made in the proposed statute during the rulemaking process. Both of these recommendations have a counterpart to some of the guidelines that might improve infrastructure cost estimation as discussed in section III below.

³ Bill Gail offered the observation of the role of mission design expenditures in influencing the accuracy of cost estimation.

II.B. Asymmetry of information among the parties to the transaction

An additional and typical problem arises from asymmetric information and inability to monitor the contractor. Acting on behalf of the public, government enters into a contract because the contractor has the information, specialized knowledge, equipment, and other required inputs. The problem is typical for situations in which the principal, the government, contracts with another, the agent, to carry out a project (the principal-agent research is quite extensive; seminal papers include Hart, 1995, Laffont, 1987, McAfee and McMillan, 1986, and Ross, 1973).

Does this problem require two or more parties? Not necessarily if “engineering the uncertain” characterizes the estimate. For instance, a single party may both conduct a cost estimation and encounter overruns as a result of engineering uncertainty. This imbalance leads to additional problems such as monitoring effort.

II.C. The difficulty of monitoring to avoid inefficiency and waste

These suspicions are at the very heart of contracts, whether for major weapons procurement, highway, construction, or an extra bathroom. The problem largely arises from asymmetric information and inability to monitor the contractor. For these reasons, what constitutes excessive profit, waste, fraud, and inefficiency is often a matter of “they said, we said.” In addition, the cost of legal investigation of these concerns may exceed their remediation.

The variations among types of contracts with respect to their allocation of cost sharing and risk (the fixed price, cost-plus, and incentive contracts noted in section I) represent attempts to encourage efficiency and internalize monitoring on the part of the agent. That is, cost-plus and other modifications of a fixed-price contract are intended to be incentive-compatible modifications to give the agent inducements to perform efficiently, reducing the need for the principal to monitor. However, researchers conclude that even these modifications are highly imperfect in the presence of significantly asymmetrical

information between the principal and agent. Moreover, cost-plus and other risk-sharing provisions may have the unintended consequence of rewarding cost growth in the presence of asymmetric information.

In a study of defense contracting, Terasawa, Quirk, and Womer (1989) consider cost escalation during 1971 to 1982 in a major weapon system, the UH-60A (Black Hawk) helicopter (the first new helicopter developed by the US Army since the 1960s). They consider the effects of changes in order quantities, one of several reasons for “turbulence” by which they mean fluctuations over time in product specifications, delivery schedules, and other aspects of procurement. Turbulence in order quantities can result from Congressional budgeting, agency decisionmaking in response to differences in perceived threats (hence changes in demand for the weapons system), and other random and nonrandom factors. Changes are not necessarily undesirable, but they find that the use of renegotiation by the Department of Defense and use of cost-plus contracts tended to overcompensate the contractor for turbulence, creating incentives for contractors to seek to increase turbulence during execution of the project. The authors further speculated that turbulence in the form of reducing the quantity ordered might be politically attractive as an alternative to project cancellation.

In “Digging the Dirt at Public Expense,” based on an historical series of data for public projects during 1817 – 2004, Engerman and Sokoloff find support for their conjecture about the tendency for waste and inefficiency to characterize modern-day public projects. These projects have higher ratios of actual to expected costs than 19th century projects. The authors do not distinguish among types of contracts for these projects, but assuming their data set represents the range of risk-sharing approaches that have evolved in modern times, their findings are all the more discouraging. They conclude (pp. 116-117):

The straightforward interpretation, one for which we have already expressed support, is that the governance, or control over the use, of public funds was stricter during the early nineteenth century than it is today. It is difficult to explain the more substantial cost overruns during the modern day era, in particular, without acknowledging either that the processes of vetting these public works projects were badly flawed (if not

dishonest) or that oversight by the public authorities was so poor as to permit grossly inefficient use or private extraction of public resources.

They comment, “the source of this contemporary institutional failure is not easily identified, but cost overrun ratios during the late twentieth century that seem routinely very high by early nineteenth-century standards imply that public officials (or the taxpaying electorate) have lost control” (p. 117).

II.D. Pressures to underestimate costs

A firm may provide a low estimate in order to win a contract – known as “buy-in.” Under cost-reimbursable contracts, the firm will be assured of not losing money on the contract. Under a fixed price contract, the firm may be willing to lose money if it expects to be the only supplier or will have a superior bargaining position in the future. In many cases, if the firm loses money the government may be willing to offer compensation or lower performance requirements if the firm or the project is deemed vital to national interests (Porter 1983).

Pressures to underestimate costs can arise among competing programs within an agency or in the agency’s relationship in advancing proposals before congressional funders. The GAO has found repeatedly in its interview-based and other studies that program managers “produce optimistic estimates in order to gain approval for funding.”

In their review of cost overruns in transport projects, Flyvbjerg and coauthors (2003) found “grossly inaccurate” estimates over 70 years of data and write a strongly worded conclusion – that the inaccuracy was by and large due to “strategic misrepresentation, that is, lying.” A researcher at the Harvard Business School offers a more gentle description of this tendency, with is prevalent in the private sector as well, labeling it “self-serving bias.”

These pressures for cost competitions to lead to awards based on the lowest plausible estimate in and of themselves would not lead to a problem without additional conditions. One is the competition among agencies for budget dollars, creating an incentive to solicit

low bids that can be provided to legislatures. Altshuler and Luberoff (2003; see also Engerman and Sokoloff) quote one of the RAND Corporation's leading scholars in urban transportation planning, Martin Wachs:

I have interviewed public officials, consultants, and planners who have been involved (in transit projects) and I am absolutely convinced that the cost overruns and patronage overestimates were not the result of technical errors, honest mistakes, or inadequate methods. In case after case, planners, engineers, and economists have told me that they had to 'revise' their forecasts many times because they failed to satisfy their superiors. The forecasts had to be 'cooked' in order to produce numbers that were dramatic enough to gain federal support for projects whether or not they could be fully justified on technical grounds.

Another contributing factor is when the awarder of a contract either will not or can not commit to an award other than one based on "cost plus contracting." The awarder cannot say "this is your bid, this is all you get," because the bidder can always declare bankruptcy and refuse to complete the project, causing costly delays. In short, a winning bidder can act opportunistically, a point returned to below under "reputation."

In a review of differences between estimated and actual costs in the construction of nuclear power plants, Quirk and Terasawa (1986) find statistically significant tendencies towards cost underestimation. They attribute this result in part to a bias towards low cost estimates to boost prospective profitability. They conclude that observing cost overruns is the logical outcome if project selection is biased towards projects with cost underestimation. In other words, there may be cost estimation that is highly accurate, but their observations are based on a sample of projects actually undertaken, and the sample itself reflects cost underestimation.

Quirk and Terasawa point out that a review by the RAND Corporation (Morrow 1988) of post-World War II projects undertaken by the US Army Corps of Engineers finds a ratio of actual to estimated costs of close to one (.998). The absence of cost underestimation bias in these projects may support the problem of sample selection. If Corps projects are chosen based on their Congressional district locations, then greater randomness is

brought to bear on selection rather than a potential bias to select projects on the basis of lower estimated costs. The authors emphasize that this is a conjecture, and they also cite that the period for which the data were collected (1954-1965) was one of generally stable prices.

II.E. The winner's curse

The “winner's curse” is a result in some types of auctions in which the highest bidder wins, but the amount bid is to some extent larger than the amount the item is worth. Procurement procedures often result in awarding a project to the lowest bidder. By similar reasoning to the winner's curse in an auction, the winner will have tended to bid an amount less than the cost of the project. The severity of the curse increases with the number of bidders because the more likely it is that some of them have underestimated the actual cost of the project. The tendency to bid low in order to win the procurement is thus another possible cause of actual cost overruns relative to cost estimates, but the result is due to the desire to win rather than necessarily due to poor cost estimating.

II.F. Does reputation matter

If a contractor repeatedly produces low cost estimates and incurs large overruns in actual costs, customers can spread the word.⁴ The effect of reputation as a means of enforcing good performance by both the principal and the agent is intuitively appealing and is in fact prominent in the research literature (for instance, Baker and coauthors, 2002, Levine, 2003, McMillan and Woodruff, 1999).

However, if choice among contractors is limited, or government program managers repeatedly underestimate costs and contracts are difficult or expensive to terminate, then the market discipline of a good reputation is limited. Consolidation has indeed lessened competition among suppliers within the traditional industry that supplies space-based

⁴ Learning-by-doing may cause the cost of the first project to be underestimated and the costs of a subsequent project to be better estimated; the reputation effect would be

infrastructure, reducing choice and blunting the effect of the chance to choose among suppliers based on reputation. During the two largest waves of mergers, between 1980 and 2001, 76 defense and aerospace companies consolidated to form 5 large conglomerates (see *Aviation Week and Space Technology*, 3 December 2001, p. 50, based on information from Credit Suisse First Boston).

The International Traffic in Arms Regulations (ITAR) may also result in limited choice, although this effect may be outweighed to the extent ITAR enhances national security. ITAR is a set of U.S. government regulations controlling the export and import of defense, aerospace, and telecommunications parts and services. Although US federal procurement has always tended towards domestic procurement, the effects of ITAR may be to increase the cost of US products and services, if the regulations limit the opportunity of US firms to expand to global markets or restrict competition from international markets.

II. G. The domino effect of extending missions beyond their nominal lives

Physical capital – and once launched, space-based infrastructure in particular -- often continues to operate beyond its nominal or expected lifetime. With the approach of the nominal end-of-life, a decision to prolong a mission may have a domino effect in delaying and increasing the cost of a successor. A taxpayer may conclude that it is good to get mileage from existing assets rather than replace them. However, if the extended assets have met their science goals or if the assets support instruments that have become obsolete in the wake of technological advance, it may be appropriate to terminate the mission.

If there is credence in “the social contract for science,” then this contract may also offer a standard by which to judge mission extension. The argument is often advanced that scientists enter into a social contract with the general public in exchange for federal

expected to dampen the tendency to select the same contractor if underestimates are persistent beyond a reasonable expectation of learning-by-doing.

research support. (Vanevver Bush is said to have originated the concept behind the social contract in his report, *Science: The Endless Frontier*, but Guston (2000) suggests a different evolution of the idea). The “science social contract,” much like a contract, represents scientists acting on behalf of the public to carry out research for the public good. The public entrusts the research community to act in good faith in the allocation of the research expenditure.

This perspective could interpret “nominal life” rather strictly as indicating, in the best judgement of the science community, the appropriate length of operation of a mission. An agreed nominal life sets in motion expectations about research productivity and its timing associated with the mission, and planning for follow-on missions which may promise innovation in instrument design or the physical phenomena to be observed. The influential factors would likely include budgetary and technical constraints (such as the limits of the power supply and other on-board operating systems, or orbital mechanics or the timing of the process being observed). Factors might also include the anticipated window of interest of the observations or data collection such that at some point, hypotheses have been adequately tested and new questions, meriting a new mission, have arisen. Nominal life thus is one of the terms of implicit social contract. When nominal life has been reached, honoring the contract means termination even if the equipment is still functioning adequately.

A counterargument is that the incumbent mission may produce surprisingly good new or unanticipated science with the promise of more during an extended period. Scientific success may trigger operational requests to continue and extend missions. In fact, many NASA missions are in “extended period.”⁵ Or it may be desirable to continue the mission if planned replacement missions are delayed.

⁵ The controversy associated with NASA as an agency dedicated to research and development, with no agency dedicated to operating the missions as the next step after successful R&D, is of keen importance here but is outside the scope of this paper.

In a report, “Extending the Effective Lifetimes of Earth Observing Research Missions,” the National Research Council (2005) acknowledges that there may be scientific and operational reasons for extending a mission. Justifications based on science include extending a continuous data set, improving sampling, maintaining unique measurements, enabling unanticipated science, and achieving synergy among multiple instruments. Operational reasons include maintaining observations, demonstrating the usefulness of observations in anticipation of operations, and exploiting unanticipated operational applications.

But the report recognizes that these reasons to extend a mission must be weighed against new capabilities and new research missions. The report argues for a funded but flexible program that allows “near-last-minute” decisions regarding how to allocate funds between multiple missions that are candidates for extension. This practice would require retaining a separate budget allocation dedicated to this purpose rather than reallocating funds from new missions in order to extend an old one.

III. Possible guidelines and partial solutions

Involving expert third parties, discouraging “precision” in order to admit uncertainty, and publicizing and rewarding good results are among some possible guidelines for improving -- and strengthening incentives to improve -- cost estimation.

III. A. Use third parties

In a recent exchange reported between the administrator of NASA and the director of the National Research Council/National Academy of Sciences Space Studies Board (SSB), the administrator criticized the SSB for “lowballing” the cost of missions proposed for the next decade of earth observations. The administrator argued that the SSB should have used NASA Headquarters’ Office of Program Analysis and Evaluation (PA&E) to “prepare more realistic cost estimates” (“Griffin: Decadal Survey Cost Estimates are Unrealistic,” *Space News*, 16 March 2007). The SSB director pointed out that that the report used information from NASA’s Jet Propulsion Laboratory and Goddard Space

Flight Center. The director also urged that in the future, studies requiring cost estimates should be given the time and money to make use of outside expertise.

The NRC/NAS director points out that objectivity in cost estimation is essential. However, objectivity combined with sufficient expertise to understand space-based infrastructure may be difficult to find. Porter (1983, p. 21) discusses use of third parties for cost estimation and expresses the concern that the estimators, “to free themselves from institutional pressures to bias their estimates, (will) have effectively removed themselves from the process.” He predicts that the estimates of the contractors, program managers, and others directly involved in the project would be given more weight.

However, a deliberate decision by policymakers to give weight to the experts, much like that accorded the independent Base Realignment and Closure process to reorganize US military bases, could alleviate Porter’s concerns. In this case, engaging teams of private sector analysts may be workable, involving individuals with their own professional reputations at stake but insulated from political bias and accorded appropriate authority. Like the BRAC commissioners, the names of these individuals could be placed on the public report. Similarly, the project and contract managers supplying information to inform the estimates could also have their names placed on the report (much as under the new Public Company Accounting Reform and Investor Protection Act of 2002, known as “Sarbanes-Oxley,” the chief executive officer now personally signs and certifies financial reports).

IV. B. Discourage precision and consider the median not the lowest

Cost estimation and its related domain of contract theory have some counterintuitive results. For instance, there are circumstances under which an incomplete contract (and provisional cost estimation) is a good idea (Crocker and Reynolds, 1993, Salanie, 1997). In this case, the parties to a contract prefer not to iron out all the details – that is, all the variables that may affect the conditions of the contractual relationship. In a study of the procurement of aircraft engines, researchers found that the cost of writing and enforcing a

contract to cover all contingencies and eventualities in long-run projects was simply too expensive. The best contract leaves open some issues for future negotiation.

In addition, any estimate has a probability distribution of final costs; any point estimate is likely to be off by some amount (Porter 1983). A median estimate that fulfilled the criterion as the estimate at which there is equal probability of either a cost overrun or underrun, and the probability distribution itself, would be more informative. Program managers, agency heads, budget managers, and Congress could refuse point estimates and narrow ranges of estimates. They could evaluate funding requests based not on the lowest plausible estimate but on the median value. They could tolerate and even demand uncertainty, requiring agencies to apply decision software and analytical approaches that transparently communicate confidence intervals and other related measures (a specific list of decision criteria is promulgated by the GAO (see GAO 2004)). What are the greatest risks in a project and how will they be managed? Much like a mutual fund manager, can government better act on behalf of the taxpayer to demand explanation of the upside and downside of public investments?

An alternative approach also makes use of probability. Mission planners could provide a cost and a probability of meeting that cost. Proposers with missions that are closely derivative of a previous mission might have a higher probability of estimation accuracy. New proposals might have a lower probability. If the mission cost cap is \$200 million and a mission is proposed for \$100 million with low cost reliability, the mission may be viewed more favorably than a proposed \$195 million mission with high cost credibility.

IV. C. Maintain a public track record

Another means of improving the accountability of project management, discouraging pressures to underestimate costs and ameliorating the difficulty of monitoring, rests on exercising more fully the effect of reputation. Reforms typically address problems associated with the contractor. However, which government and contractor program managers continue to validate projects with large cost overruns and which deliver better

ratios of actual to projected costs should also be of keen interest and importance to decisionmakers and the public at large.

IV.D. Reward good results

When projects come in under budget, savings are siphoned off for other expenditures. For NASA centers, this perverse incentive could be eliminated by establishing a virtual bank in which projects that come in under projected cost keep the savings. These funds could be carried forward for other investments within the particular scientific domain – for example, savings on one earth observing system would go into a pool to finance the next generation system. Researchers have experimented with the design of such a procurement system (Healy and coauthors 2007). They find that the contractor (in this case, the NASA center carrying out the work) has an additional incentive to innovate to reduce costs since it keeps a portion of the savings. This benefits NASA headquarters as well, since it also re-appropriates some of the savings. NASA headquarters shares in the cost of reasonable even if unsuccessful attempts to engage in cost-reducing innovation and this encourages the center to innovate more, to the benefit of both parties. The ability to retain a portion of the cost savings allows both parties to save funds for future “bad luck,” a form of insurance. Additional funds are automatically released to reduce the incidence of delay when unexpected cost increases occur.

IV. E. Nunn-McCurdy as an approach?

As part of the Defense Authorization Act for Fiscal Year 1982, Senator Sam Nunn and Representative David McCurdy included a provision intended to limit the growth in the cost of major weapons programs. Under the Nunn-McCurdy amendment (10 U.S.C. 2433), Congress must be notified if the costs of a project grow by 15% above the original estimate. A program is to be terminated if its total costs grow by more than 25% above the original estimate. However, there are several conditions under which the program can continue despite cost growth. The original legislative provision listed these as if the project is deemed a “critical system” by the Secretary of Defense or if the growth in costs is attributable to certain types of allowable changes in the project. Subsequently, the provisions have come to include additional circumstances under which a project may be

continued: if there is no viable alternative to the program, and if the problems leading to the cost overrun are shown to be under control.

Because NPOESS is a joint project of the Department of Defense and the Department of Commerce, the Nunn-McCurdy provision was applied in December 2005 in the wake of cost overruns in excess of the threshold. The result has been to reduce the number of spacecraft, sensors, and provisions for research and analysis. The weather and earth sciences communities have expressed significant concern about these changes in capability (for instance, National Research Council 2007).

Application of the amendment has many of the problems of asymmetric information and potential biases identified above in section III. For instance, the amendment allows program managers in some instances to increase their baseline cost estimate before the threshold for recertification is reached if there have been major changes to the scope of the program, but the justification can be subject to interpretation and judgement.

Proposed changes suggested by some Congressional members (Singer 2005) would require personal involvement of the Secretary of Defense in “signing off” on programs before the start of preliminary design work. The secretary would not be able to delegate this responsibility and would have to certify that the program likely will meet its cost goals and likely accomplish its mission. The members also express concern about a lack of formal training or career development programs for cost analysts within some branches of the military, and understaffing of cost analysts within the acquisition branches.

V. Summary

The collection and analysis of information about natural resources, the environment, and weather places heavy reliance on physical infrastructure. Estimating the cost of infrastructure is difficult for many reasons; ensuring accurate estimates is even more difficult given the tendency for contracting mechanisms to induce downward biases. This paper has reviewed the conceptual and empirical literature on cost estimation and

associated contract design to highlight some of these problems and outline possible approaches to ameliorating them.

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