IMPROVING SPACE PROJECT COST ESTIMATING WITH ENGINEERING MANAGEMENT VARIABLES

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Abstract
Current aerospace parametric cost models attempt to predict space project costs using regression equations. The equations typically relate the historical cost of projects to key technical variables, such as weight and power. While improvements in parametric cost modeling have been made, there is still significant variability in the estimates. This is particularly true when estimating the costs for complex systems. Part of this variability may be due to the models inability to capture the impacts of the engineering management systems required to develop these complex systems. This paper lays the groundwork for the introduction of engineering management variables into current cost models in an effort to improve their predictive capabilities.

Background
This paper extends work presented at the 2001 ASEM National Conference, "Improving Space Project Cost Estimating with Engineering Management Variables" (Hamaker 2001). In that work, the Recommendations for Further Study suggested that efforts be undertaken to collect additional engineering management data on specific space projects. It was recognized that the major obstacle to such a continued study would be the research required to obtain credible and documented information on engineering management sufficient for a quantitative analysis. This paper reports on the status of that continuing research.

Introduction
The aerospace industry, both in the contractor community and the government organizations such as NASA and the Department of Defense, utilize parametric estimating methods for early predictions of the cost of space projects. Because these estimates form the basis for commitments to project stakeholders such as Corporate Boards, NASA and DoD management, the Office of Management and Budget and Congress, it is imperative that the parametric methods be as accurate as possible. Current space cost models employ cost estimating relationships (CERs) based on historical projects, which regress technical variables of these past projects against the known cost of the past projects. This approach, the current state of the art, works marginally well. But the CERs typically have large variances, which leads to wide prediction intervals around any estimate. For example, one commonly used model (Exhibit 1) shows a percent difference between actual and estimated costs of up to 89% (Hihn 2004) when used on historical space flight missions.

Exhibit 1. Cost Model Variance

Reference Mission	± Percentage difference between actual costs and estimated costs
Mission 1	-19.0%
Mission 2	-2.3%
Mission 3	-8.2%
Mission 4	-1.6%
Mission 5	-5.5%
Mission 6	16.2%
Mission 7	53.1%
Mission 8	0.4%
Mission 9	23.2%
Mission 10	89.5%
Mission 11	89.4%
Mission 12	-45.6%
Average	15.8%
Std. Dev.	41.75%

It is the continuing thesis of this work (both in this paper and its predecessor) that some significant part of the variance in the historical cost of space projects that is not being adequately treated in current cost models could be caused by engineering management differences between the projects that is not being captured in the traditional cost models.

Current Research
The 2001 ASEM paper analyzed a database of 64 space projects. The database included a highly heterogeneous set of projects:

- Earth orbiting satellite missions such as the Hubble Space Telescope Project
- Planetary missions including both orbiting satellites (such as the Mars Global Surveyor Project) and planetary landers (such as the Mars Pathfinder Project)

- Launch systems such as the X-34 Project (an experimental rocket), and the stages of the 1960s Saturn moon rocket (the S-1C Project, the S-II Project and the S-IVB Project)
- Human rated spacecraft such as the Shuttle Orbiter and the Skylab (NASA's first space station of the 1970's era)

While the results were promising, the very fact that such a heterogeneous sample was used tended to complicate the analysis. A large number of control variables had to be introduced (to account for earth orbital versus planetary, to account for satellites versus launch systems, to account for human rated versus non human rated, etc.). This in turn obscured the influences of engineering management on cost. Also, most of the data used in the 2001 paper were projects from the early 1990s and prior. These projects did not reflect the Aerospace industry's most recent attempts to improve its project management and cost performance.

This paper outlines current work that is more carefully parsing the database into families of like missions and is also using very up to date missions (many late 1990's missions and many flying in the 2000 to 2004 timeframe). The current database contains 150 missions but these are all either earth orbital or planetary spacecraft. Launch systems and human rated missions have been dropped from the study. (However, it is logical to presume that any engineering management influences on cost that can be discovered in the current more homogeneous data set can probably be extrapolated to these other types of missions. This also has the advantage of leaving fertile ground untouched for future research papers!).

Regression analysis (regressing the technical and engineering management variables against cost) is planned as the primary analytical approach. Other approaches were considered. For example, a complexity rating approach has been used in similar work (Bearden 1999, Bearden 2000, and Bearden 2001). Bearden's approach collapses a number of individual variables to one complexity variable that is then regressed against cost. This method, while feasible and still under consideration, but is not a primary approach. The Bearden approach weights all variables equally while the authors believe that the variables in this study are probably not equal. Another approach considered was to use existing commercial off the shelf cost models. In such an approach, the models could be calibrated to the data set assembled in this study and used to predict cost effects. However, such an approach was rejected because 1) the model are "black boxes" (the cost equations are not all known) but more to the point, the models do not include a wide set of management variables (the reason for this research in the first place).

Probably the most important improvement being made in the current analysis over the 2001 work is that of performing much more thorough researching of engineering management practices. And, as predicted in the 2001 paper, this aspect of the analysis is proving to be the most challenging due to the two major difficulties of 1) finding definitive historical documentation of the management practices of the missions and 2) once found, being able to quantifiably rate the management practices as variables suitable for a regression analysis.

Substantial progress has been made on the first problem above (though it is still far from complete). Three principle sources of information are being utilized to attempt to find definitive historical documentation of the management practices of the missions.

First, the NASA History Office in Washington has been immensely helpful. They have made available many documents that speak to the management approaches of NASA projects (a good example being the *Issues in Program and Project Management* series) in which senior managers, often the PM himself/herself writes about the way particular projects were managed.

Secondly, the NASA Lessons Learned Information System (http://llis.nasa.gov/) contains well-written discussions of lessons learned on projects. While many of these lessons learned are focused on technical issues, many also cover management subjects as well.

Thirdly, the Internet has been invaluable. Essentially all NASA missions since the mid 1990's have active official home pages (those hosted by the government project office and those hosted by the contractor and university community that have participated in the project). On many of these sites there are accounts of how the project was managed, organization charts, explanations of roles and responsibilities, cost and headcount information, etc. For just one outstanding example, go to the Advanced Composition Explorer website at CalTech (http://www.srl.caltech.edu/ACE/). On that site, one may obtain a document of ACE project Lessons Learned (http://www.srl.caltech.edu/ACE/ASC/DATA/pdf_docs/LessonsLearned.pdf) that provides detailed documentation of how the ACE was managed and even compares the ACE cost outcome to NASA historical norms. In addition to these official project websites, there are several private websites that contain excellent information on aerospace projects. One of the best is the *Encyclopedia Astronautica* (http://www.astronautix.com/index.htm). For a typical example of project documentation on that site, see the Contour Project. Two other excellent sites that document the technical and management history of space projects include http://nssdc.gsfc.nasa.gov/ and http://msl.jpl.nasa.gov/home.html.

The first problem of finding definitive information on how projects were managed is slowly being beaten down using the resources above and numerous others. The second problem mentioned above, that of being able to quantifiably rate the engineering management practices as variables suitable for a regression analysis is being approached by first examining what taxonomy of what engineering management practices or "variables" might be investigated for the 150 projects in the database. There is a rich vein of books, journal articles, studies, briefings, Internet sources and the like on suggested improvements in space project management. Over the past 6 months, a fairly exhaustive review of these sources has been conducted. The result of this research is the taxonomy of management practices shown in Exhibit 2. The left side of the table lists a number of engineering management variables that have been suggested by various authors—the authors being listed in the columns of the table. The body of the table tallies which authors suggested which engineering management variables. For convenience, the engineering management variables have been organized into 4 categories (Organization, Project Manager and Team, Tools and Processes, and Environment).

The research to date has focused on finding documentation for the 150 projects being considered which establishes that the engineering management variables of Exhibit 2 were used on the project. While it is well and good to find documentation that Project X utilized such and such an organizational structure, utilized risk management practices (or not), employed concurrent engineering (or not), had a team of great depth and experience (or not), had stable funding (or not), and other such management variables, it is quite another thing to be able to rate this in any quantifiable and defensible way, even using an ordinal scale in preparation for using dummy variables in the regression analysis.

Exhibit 2. Taxonomy of Engineering Management Variables Based on Various Authors

		Kerzner	Couillard	NAFCOM	Bender	Ammeter	Leising	APPL	McCarthy	Shenhar	Connell	Elrod	Needy	Ammeter	Prince	Smart	Hihn	Rosenberg
Organization																		
	Org structure--product, functional, matrix, skunkworks	x	x								x					x	x	
	Flatness of structure	x																
	Size of customer project office	x																
	Count of interfacing organizations	x													x			
	Count of integrating activiites	x		x														
	Count of total no. of customers, primes and 1st tier subs			x														
	Small, medium or large project compared to the norm	x								x								
	Count of reviews, TIMS, etc.	x																
	Customer rep on contractor site?	x																
	PM Reporting (to top mgt?)	x																
	High level sponsorship/visibility of project					x												
Project Manager and Team																		
	PM authority	x															x	
	Was PM a generalist or specialist?	x																
	Degree that PM delegates	x																
	PM behaviors (goal/values communication, fosters work ethic, enables "real team", status communication)													x				
	Cherry picked team	x																
	PM and team experience		x	x	x							x				x	x	x
	Sense of mission ownership at outset	x				x								x				
	Team stability (low turnover)				x			x										
	Teamwork, espirit de corp and and degree of team decision making	x			x							x		x				
	Communication and frequency team meetings					x												
	Effectivness of human capital usage via critical skills inventory, training, etc.												x					
	Stress or burn out level of team	x																
	Use of rewards, bonues and/or and team perks					x												
	Co-location or isolation of team					x										x		
Tools and Processes																		
	Adequacy of up front planning accomplished, requirements definition & flowdown	x	x	x											x		x	
	Was a PRA performed?																	
	Risk management, degree used	x		x											x			
	Degree to which backup strategies/off-ramps were defined at outset	x																
	Who did the planning, the team or a planning group?	x																
	Adequacy of initital cost, sched and perf margin at outset	x					x											x
	Level of planning (milestones only or detailed uisng CPM, PERT)	x	x						x									
	EVM usage																	
	Electronic tools usage (CAD, Requirments Def, Config Mgt, CPM/PERT, Calendaring, Email)	x																
	Degree to which Concurrent Engr and IPTs used	x						x								x		
	Quality Mgt system	x																
	Prototyping; rapid prototyping				x											x		
	Design to cost and/or CAIV usage															x		
Environment																		
	Externally driven requirements volatility	x						x								x	x	
	Was project cost capped?																	
	Funding Stability			x	x													
	Was project international?	x																

In the event that the above approach of accurately rating of the variables in Exhibit 2 turns out to be infeasible, another approach may be needed. In reading the project management histories of many of the 150 projects in the database, another way to classify the projects has surfaced. This approach was also suggested by the book, *Faster, Better, Cheaper: Low-Cost Innovation in the U.S. Space Program* (McCurdy 2001).

McCurdy argues that complexity demands coordination and coordination is achieved via project management and systems engineering. He further argues that there are two extremes in NASA project management/systems engineering to achieve this coordination. One extreme is the classic Apollo style systems management approach with much effort put into coordination using reviews, CPM/PERT, configuration control, formal risk management, formal documentation, etc. The other extreme is a team-based approach where much of the coordination is achieved via team members coordinating between themselves as required with fewer formal reviews (substituting "table top" and peer reviews), less documentation (documenting only what is really important), etc.

McCurdy's idea could be extended to examine the data to see if those projects that used more of the classic systems management approach would have recorded more of their budgets tied up in the project management and systems engineering accounts. Projects that used more of a team-based approach would have hypothetically spent less money in these accounts (their coordination activities would have been achieved at lower levels of the WBS and would not show up in the top level project management and systems engineering accounts). Correlation could be spot checked because there are a few dozen projects in the database that were very clearly documented as having used a team based approach. Other projects were clearly managed using strict systems management approach. If the data cooperates, the analysis should see corroboration in the project management and systems engineering percentages.

Another aspect to this a possible correlation between complexity and the management approach. One would surmise that the really complex projects might not be as amenable to the team-based approach (just too much coordination is required). Good examples might be Mars Observer (which was lost due to a tank pressurization problem compounded by a radio communication problem) and Mars Climate Orbiter (lost due to an English to metric conversion mistake). The data might show that such missions were too complex for the level of team-based management that was used.

Based on the above, an alternative taxonomy of engineering management variables suggests itself. This taxonomy can be separated into two major categories. The first can be termed Engineering Management Environment Variables. These are variables that logically would seem to drive space project cost and schedule, though they are to a large extent not too controllable by the project manager. Rather they are variables that represent the environment that is often "handed to" the project manager. Such Engineering Management Environment Variables might be found to include:

1. Budget constraints—whether the project has a capped budget at the outset or worse, a budget constrained after the project has been given authority to proceed.
2. Requirements volatility—the degree, to which the top-level requirements of the project have been determined, documented and stabilized.
3. Number of customers--the number of government sponsors such as NASA, DOD, NOAA etc.). More customers would hypothetically complicate the project and drive cost and schedule.
4. Team experience--the experience of both the customer team, which is usually the government project office as well as the experience of the contractor team on similar projects.
5. Heritage of the systems—the extent to which off-the-shelf hardware and software can be harvested from predecessor projects and reused or partially reused again.
6. Schedule pressure—the date by which the project is to be ready for initial operating capability in relation to the start date. Projects that are either required too quickly or are stretched out too far will presumably suffer budget inefficiencies.
7. Number of prime contractors involved (usually one but sometimes more)—the involvement of more than one prime contractor generally is thought to add time and money to projects.
8. Number of science organizations involved—likewise, the number of science organizations involved in the development of the instruments logically might be found to correlate to cost and schedule.
9. International partners—the existence of international partners is often cited in the literature as a complicating factor that drives cost and schedule.
10. Size of the project relative to the median—the dollar value of the project can be used to rank

the scope of the project relative to the median project in the database. Hypothetically, larger projects cost more and take more time just because of the complications of their scope.

The second category of this possible taxonomy of Engineering Management variable could be the Engineering Management Approach. As suggested by McCurdy, this could be a binary selection:

1. Classic systems management approach—in which full configuration management is used, a formal risk management plan is devised, full use of Interface Control Documents, full documentation, formal reviews, etc.).
2. A team-based management approach—in which coordination relies on person-to-person communication and coordination).

Prototype Model

A prototype model is being planned as a way to examine the above taxonomy of Engineering Management Environment Variables and Engineering Management Approach Variables. The prototype model will make use of some subset of the total planned database of 150 projects. This will be used to decide if this line of research shows promise or not for statistically explaining space project costs.

Once a suitably large subset of the 150 projects have been researched (say, 30 to 50 of the 150) and all the variables in the above taxonomy have been established, a regression analysis will be performed to determine if the variables are statistically correlated to project cost.

In addition to the above Engineering Management Environment and Approach variables, the model will include the usual set of technical variables that are used in current space project cost models. This is building on the work performed in Hamaker, 2001 but has been extended to include more technical variables. The set now includes spacecraft dry mass (kilograms), spacecraft volume (cubic meters), power (watts), type of power generation (silicon solar arrays, gallium arsenide arrays, nuclear radio isotopic thermal generators), battery type (nickel hydrogen, nickel cadmium, etc.), battery capacity (amp hours), spacecraft bus voltage, reaction control type (cold gas, monopropellant, bi-propellant, dual mode), number of thrusters (count), thrust (Newtons), apogee (kilometers), design life (years), launcher type (Shuttle or expendable launch vehicle), material complexity (aluminum or exotics), number of deployables (count), type of thermal control (active or passive), number of communications bands (count), type of stability (spinner or 3-axis control), type of navigation sensors (sun sensors, horizon sensors, star trackers), pointing accuracy (degrees), etc. This more exhaustive list of technical variables is being researched and cataloged in the 150 mission data base in order to develop the best possible "control model" of purely technical variables for explaining space project cost. This will be compared to a model in which the Engineering Management variables are then introduced. It is hoped that the goodness of fit statistics improve when the management variables then are added and that the variables are statistically significant.

If the results are encouraging, the research to complete the variable research on all 150 projects would seem warranted.

Conclusions

The problem of measuring how engineering management influences project cost is nontrivial. The work begins by establishing the accuracy of existing cost models that use technical variables only. Then, engineering management variables that may impact cost are researched and proposed. The database used to support this work is the historical files of past NASA space flight projects, supplemented by a questionnaire to obtain additional data from project staffs.

Ultimately, this work will be extended to introducing EM variables into the model using either quantitative measures or qualitative measures using pseudo variables. The set of EM variables could be extensive such as those listed in Exhibit 2 or they could be collapsed to the second taxonomy proposed above which is more succinct in terms of the systems management approach versus the team-based approach. Either way, if it can be concluded that the EM variables statistically contribute to explaining cost, then further research is warranted to develop a cost model that contains these EM variables. Inclusion of EM variables into space project cost models would not only reduce the variability of the models (actual versus estimate) but would serve to provide project management with a tool to proactively apply advantageous engineering management practices to projects. It has been established that current cost models need improvement to explain all the variability in the space project cost database. A hypothesis has been established that EM variables could explain some of this variability and thus, if introduced into the models, improve cost estimating of space projects. (Actually, to be precise, the null hypothesis will be H_o: Management variables had no effect on cost and the alternate hypothesis will be H_1: Management variables had an effect on cost).

Preliminary research has been undertaken and alternate approaches for measuring engineering management have been suggested. The next steps are to develop a prototype model to determine if the line of research is showing promise.

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