IMPROVING THE PREDICTIVE CAPABILITY OF SPACECRAFT COST MODELS

by

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A DISSERTATION

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Submitted by Joseph W. Hamaker in partial fulfillment of the requirements for the degree of Doctor of Philosophy in Industrial and Systems Engineering and accepted on behalf of the Faculty of the School of Graduate Studies by the dissertation committee.

We the undersigned members of the Graduate Faculty of The University of Alabama in Huntsville, certify that we have advised and/or supervised the candidate on the work described in this dissertation. We further certify that we have reviewed the dissertation manuscript and approve it in partial fulfillment of the requirements of the degree of Doctor of Philosophy in Industrial and Systems Engineering.

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ABSTRACT

The School of Graduate Studies
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Current space project cost models predict costs using regression equations which typically relate the cost of projects to technical variables such as weight, power, thrust, data rate, pointing accuracy, etc. While improvements in space project parametric cost modeling have been made since its advent in the 1960s, there is still significant statistical error. This remains true even when a rich set of technical independent variables are used. Anecdotal evidence suggests that part of this variability may be due to the current cost models' inability to capture the impacts of the non-technical considerations required to develop space systems—non-technical factors that are under the control of project management. This dissertation investigates the feasibility of introducing non-technical variables into the cost models and analyzes the improvement in explanatory power from these additional variables. The study involved researching management influenced non-technical variables and constructing a data base of historical projects containing both technical and non-technical characteristics. Subsequently, an extensive multivariable regression analyses was performed to develop two new cost models, one with technical variables only, as a control, and one with both technical and non-technical variables. The predictive power of the two models was compared to assess any improvements in the predictive power of the new model containing both technical and non-technical variables compared to the more classic approach of focusing mainly on technical variables.

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Finally, I would like to thank my management at NASA Headquarters, Mike Griffin and Scott Pace, who afforded me crucial time off from the day to day whirlwind at NASA to complete the dissertation. Mike's admonition included the instruction: "Finish the dissertation--no excuses." Scott said: "I didn't want any ABDs in my office."

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CHAPTER 1

INTRODUCTION

The project cost estimate is a key piece of information that decision makers rely upon to gage the worth of any new project. The cost estimates are required early in the project life cycle and achieving an acceptable level of accuracy has proven difficult to accomplish for all types of major projects. For technologically challenging projects such as the typical space mission, the cost estimating approaches are plagued by especially high variability. Current cost estimation approaches for new space projects are often based on statistical models which relate the cost of projects to a number of technical variables. Any improvements in these models would be especially welcome.

A. Context

All projects need a project plan to be developed very early in the project life cycle. One of the key elements of any project plan is the cost estimate. Space projects are no different than other projects in this regard. But because space projects are among the most costly of human endeavors, decision makers typically consider the project cost as one of the major pieces of information they need to make evaluations about commitment to the project and how it should be technically and programmatically structured. Getting the cost right, or correct within acceptable tolerances, is of paramount importance (Aldridge 2004), (General Accounting Office 2004), (Gross 2001), (Moorman and Anderson 2002), (Shawcross 2003) and (Young 2003).

Most space projects today continue to be government funded. Once approval is sought for a government funded space project, serious commitments are made to the project stakeholders who include the sponsoring government organization (NASA, the Air Force, and the Intelligence Community), the White House and the Office of Management and Budget, the Congress and the Congressional Budget Office and the Government Accounting Office and other involved parties. Perhaps the most important stakeholder is the taxpayer. They all deserve a project cost estimate that is credible, reasonable and accurate.

A general issue in space project cost estimating is predicting the cost of projects early in their formulation phase in order to make accurate commitments on what the project is likely to cost before serious and irrevocable investments are made. Parametric cost models are used because in the early stages of project definition, not enough detailed information is known to perform other types of estimates such as a detailed engineering estimate which is based on a labor and material buildup of cost (Russo, Garvey and Hulkower 1998). The trade space for decisions regarding projects, particularly space projects, obviously includes many technical considerations (e.g., the mass budget for the spacecraft, the available onboard electrical power, the required data rate, the choice of stabilization method, the selection of structural materials, the level of redundancy, the level of autonomy that the spacecraft should posses, the type of reaction control, the type of propulsion system, the type of communication system, and many, many other such technical decisions). Managers and engineers are generally aware that their choices on these matters have large implications for the cost, schedule and risk of their missions.

Still, the statistical variability that remains in today’s best space project cost models remains distressingly high (Mackenzie and Addison 1999). Even when a large number of space project cost drivers are considered in the set of independent variables used by the best models, significant residual error is "left on the table." Most of the work that has gone on over the years to improve the models has been focused on adding technical cost drivers to try to explain the cost behavior of space projects (Bearden 1999). It seems the thinking has been that is enough engineering nuances are reflected by the cost models, the costs will line up on a regression line (so to speak).

All the while, many knowledgeable observers of the space project landscape have often been heard to wonder if "it's not the way they are managed" that has a lot to do with the cost outcome of space projects. There is much anecdotal belief that such is the case (Mandell 2005). It is an interesting theory.

B. Problem Statement

This study will investigate whether the introduction of non-technical variables into space project cost models shows promise for improving the accuracy and usefulness of the models. A positive result would point out the importance of the non-technical decisions that space project managers make in comparison to the technical decisions on which they have traditionally focused. As will be developed in this dissertation, these non-technical factors include the extent to which management insists upon sufficient up front formulation of the project prior to full scale development, the degree to which management insures that requirements are solidified and maintained after project start, the management attention necessary to advocate the availability of timely funding, the experience of the development team chosen by management, the management choice of the number of science partners, the management strategy for using new technology versus off the shelf designs, and other factors to be addressed. These non-technical variables are not now extensively considered nor modeled in existing space project cost models (Bearden 1999) and (Space Systems Cost Analysis Group 2005). If the non-technical factors are important cost drivers, then managers need to be able to access the impact of decisions in these areas every bit as much as the technical decisions that now dominate the trade space. This dissertation intends to investigate the oft heard premise that “The way the project is managed” is a significant cost determinant.

C. Approach

Existing space project cost models have concentrated on mainly technical variables to explain cost. When non-technical variables have been included, they have been limited in number and/or the basis for them has tended to be based on engineering judgment, or at the very least, the basis has not been explicit (SAIC 2002). There are no examples of space project cost models that have been developed with an extensive focus on the contribution of non-technical variables that are within the control of managers (Space Systems Cost Analysis Group 2005).

This dissertation addressed this gap by performing an extensive body of research on a number of historical space projects to tabulate both technical and non-technical variables. The set of technical variables was based on those already widely used in space project cost models. The set of non-technical variables was based on those factors that have been suggested in the literature as having significant influence on project cost and factors that were mentioned as being substantially controlled by management decisions. These variables were researched and tabulated for a large data base of past projects. The technical variables were mostly quantitative in nature. The non-technical variables were mostly categorical and were quantified for regression analysis using indicator variables.

A thorough regression analysis was conducted to first develop the best possible model using only technical variables. This served as a control. Then management variables were introduced and checked for significance. The best model using both technical and non-technical variables was compared to the control model which used only the more common technical variable approach to determine if the introduction of the additional non-technical variables improved the model.

In addition to examining whether there were management controlled non-technical variables that could be used to improve space project cost estimating, this work produced a new regression model which should be useful in its own right for estimating the cost of proposed space projects. While there are existing models, both commercial proprietary models and government developed models, it was a necessary part of this study to develop a new model for several reasons. First, access to the underlying data base was necessary for this study in order to gauge the effect of adding new variables to the model. This precluded the use of the commercial proprietary models which do not provide the user with access to the data. Secondly, the government models, which do provide access to their data bases, could not be used to perform this study because their data bases do not contain characterizations of most of the non-technical variables that were of interest to this study. Third, the existing models operated at lower levels of the work breakdown structure than was necessary or even desirable for this study which considered cost at the total project level. Fourth, the existing government models did not contain the very latest spacecraft missions which have flown in the last few years for which this study was be able to harvest top level data and use much earlier than the lower level government models were able to incorporate.

CHAPTER 2

BACKGROUND

The literature review was performed in two steps. First, the broader literature of project management was reviewed for insight into what potential non-technical variables that are influenced by engineering managers might be investigated for inclusion into a new space project cost model. This is reported in part A below. Part B of the literature survey was concerned with canvassing the more narrow body of literature on existing space project cost models to document the extent to which they addressed any of the non-technical variables found in Part A.

A. Literature Review of Non-Technical Variables

There is an incredibly rich vein of books, journal articles, studies, briefings, internet sources and the like on suggested improvements in project management. In preparation for this study, an extensive review of these sources was conducted; work reported in a paper in the June 2005 Engineering Management Journal (Hamaker and Componation 2005). That literature review focused on two major tasks. First, the paper tabulated non-technical aspects of projects that are both under the control of managers and were mentioned as having an effect on the cost efficiency of the project. Secondly, because the semantics of project management is not standardized, a concern of the work reported in the June 2005 paper was developing a systematic way to name and record potential non-technical variables. The 2005 paper "binned" the literature occurrences of the mention of potential variables into a list. For convenience, the list was divided into 4 categories (Organization, Project Manager and Team, Tools and Processes, and Environment). The result of that research is the taxonomy of management practices shown in Figure 2.1. On the left side of the table are listed a number of non-technical variables were suggested by various authors in the literature—the authors being listed in the columns of the table. The body of the table tallies which authors suggested which non-technical variables. Table 2.1 actually includes only a subset of the works reviewed. Those that made the table were those that most clearly and convincingly articulated that the particular variable was an important potential driver that this study might in turn develop into an independent cost variable.

Table 2.1 Taxonomy of Non-Technical Variables

	Aldridge 2004	Ammeter 2002	APPL 2004	Bender 2000	Connell 2001	Couillard 1995	Elrod 1999	GAO 2004	Gross 2001	HIhn 2004	Kerzner 1995	Leising 2004	Mandell 2005	Miller 1993	Moorman 2002
ORGANIZATION															
Organizational structure		x			x	x			x	x	x		x		
Flatness of structure											x			x	
Size of customer project office											x			x	
Number of total integrating activites/organizations											x		x	x	
Scale of project compared to the norm											x		x		
Dynamics of project team, parent org and customer	x										x			x	
High level sponsorship/visibility of project		x									x		x		
PROJECT MANAGER AND TEAM															
PM authority										x	x	x		x	
PM and team experience and age		x		x		x	x			x	x	x			x
Team stability			x	x											x
Teamwork and use of Product Development Teams		x	x	x			x				x	x			
Sense of mission at outset		x									x				
Effectivness of human capital usage (training, rewards, etc.)		x							x			x	x		
TOOLS AND PROCESSES															
Risk management, degree used								x		x	x	x			x
Level of planning (using CPM, PERT, WBS, EVM etc.)						x		x			x	x		x	
Quality Management system											x	x			
Electronic tools				x					x			x	x		
Fidelity of up front planning accomplished	x					x		x		x	x	x	x		
Initial cost, schedule and performance margin	x							x	x		x	x	x		x
Prototyping; rapid prototyping				x										x	
Design to cost and/or CAIV											x	x			
ENVIRONMENT															
Requirements stability or volatility			x								x	x	x		x
Funding Stability				x								x	x		
International project									x		x				
Business base					x							x		x	
MANAGEMENT CONCEPTS															
Motivation or Behavioral Theories											x	x		x	
Management Systems	x							x	x			x			
Reward-Based Theories														x	
Best Business Practices								x					x		

	NAFCOM Model	Needy 2002	Niehoff 2004	McCarthy 2004	Pine 2000	PMI 2004	PRICE MODEL	Prince 2002	Rosenberg 2004	SAIC 2002	SEER Model	Young 2001/2003	Smart 2004
ORGANIZATION													
Organizational structure					x							x	x
Flatness of structure												x	
Size of customer project office													
Number of total integrating activites/organizations	x					x				x		x	
Scale of project compared to the norm						x						x	
Dynamics of project team, parent org and customer													
High level sponsorship/visibility of project						x						x	
PROJECT MANAGER AND TEAM													
PM authority													
PM and team experience and age	x						x		x		x		
Team stability						x							
Teamwork and use of Product Development Teams						x							
Sense of mission at outset													
Effectivness of human capital usage (training, rewards, etc.)		x			x	x							
TOOLS AND PROCESSES													
Risk management, degree used	x					x		x		x		x	
Level of planning (using CPM, PERT, WBS, EVM etc.)				x		x				x		x	
Quality Management system						x						x	
Electronic tools					x	x					x		
Fidelity of up front planning accomplished	x					x		x				x	
Initial cost, schedule and performance margin						x			x			x	
Prototyping; rapid prototyping	x												x
Design to cost and/or CAIV													x
ENVIRONMENT													
Requirements stability or volatility						x				x	x	x	x
Funding Stability	x											x	
International project										x		x	
Business base						x							
MANAGEMENT CONCEPTS													
Motivation or Behavioral Theories						x							
Management Systems						x						x	
Reward-Based Theories					x								
Best Business Practices			x			x						x	

In the June 2005 paper, Table 2.1 suggested a total of 29 non-technical variables. Some of these were mapped into more than one variable in the final data base. Some were used directly. Others were found not to be researchable. As will be seen in the data base discussion in Chapter 4, about a dozen non-technical variables were ultimately identified and successfully researched for the 122 projects. In the end, as will be discussed in Chapter V, some of these were eliminated when the regression statistics are examined.

B. Literature Review of Non-Technical Variables in Current Cost Models

This part of the literature survey was concerned with canvassing the more narrow body of literature on existing space project cost models to document the extent to which they addressed any of the non-technical variables found in Part A. There are three major off the shelf parametric cost models in use in the aerospace industry that are widely discussed in the literature.

1. The NASA Air Force Cost Model (NAFCOM) is an in-house NASA model currently maintained by SAIC for NASA.
2. PRICE (specifically, PRICE H which is used for hardware cost estimating) is a commercial off the shelf model developed and marketed by PRICE Systems LLC.
3. SEER (specifically, SEER H which is used for hardware cost estimating) is a commercial off the shelf model developed and marketed by Galorath, Incorporated.

Each of these models, to some extent, deals with non-technical influences on cost. Table 2.2, Table 2.3 and Table 2.4 list the major non-technical variables in these models from descriptions in the open literature.

Table 2.2 NAFCOM Model Non-Technical Variables

Engineering Management
The Engineering Management input describes level of design changes, experience of the design team, and the environment of the design effort.

Funding Availability
Funding Availability reflects the appropriate anticipated funding availability. Choices for Funding Availability include: (1) Funding is assured - no delays, (2) Some infrequent delays possible, and (3) Funding is constrained - delays likely.

Risk Management
Risk Management reflects the amount of risk being accepted and indicated by the planned test program. Choices for Risk Management include: (1) High risk with minimum testing, (2) Moderate risk with qualification at prototype level, and (3) Low risk with qualification at the component level.

Integration Complexity
Integration Complexity reflects the expected number of interfaces involving multiple contractors and/or centers. Choices for Integration Complexity include: (1) Minimal major interfaces involving multiple contractors/centers, (2) Moderate major interfaces involving multiple contractors/centers, and (3) Extensive major interfaces involving multiple contractors/centers.

Pre-Development Study
Pre-Development Study reflects the magnitude of the study efforts that were conducted or are being conducted prior to the start of design and development. Choices for Pre-Development Study include: (1) Two or more study contracts in Phase A&B - Greater than 9 Months of Study, (2) One study contract - between 9 and 18 months of study, and (3) Less than 9 months of Pre-Phase C/D Study.

Table 2.3 PRICE Model Non-Technical Variables (copyrighted material used by permission of PRICE Systems, L.L.C.)

Engineering Complexity Factor--Complexity of Engineering
The experience, skill, and know-how of the assigned individuals or team, as applicable to the specified task. Is a measure of the complicating factors of the design effort.

Table 2.4 SEER H Model Non-Technical Variables (copyrighted material used by permission of Galorath, Incorporated)

Developer Capability & Experience
Rates the overall development team's engineering capability and experience with a similar design challenge.

Development Tools & Practices
Use of modern development practices, methodologies, processes and automated tools available. These streamline the development process and reduce some analytical and data costs of the program. This rating should reflect the state of design tools that are in place and being used at the time hardware development begins.

Requirements Volatility
Anticipated frequency and scope of changes to the system requirements baseline after the requirements analysis phase is complete. Minor changes include subsystem functionality changes or configuration changes that do not impact other Work Elements. Moderate changes include such things as tighter system performance requirements that do not impact other Work Elements. Major changes include such things as changes in system performance requirements that alter the system configuration throughout most Work Elements.

While all three models do treat non-technical factors in some way as a management variable, their implementations of how these variables influences cost were considered to be improvable by this study. This statement is not meant to be a criticism of the capabilities of any of the existing models. All three models are widely used and widely respected in the industry—PRICE and SEER are used in many industrial sectors besides space projects. The models were developed with a focus on parametric estimating in an environment where detailed technical information exists and trade studies are likely occurring at levels of the work breakdown structure where this technical differentiation is needed.

First, compared to NAFCOM, the model being developed by this dissertation operates at the total project level on automated spacecraft projects only and is meant to provide early and quick results on the likely effects of decisions on project cost while the project is in early formulation and adjustments can still be made relatively easily. NAFCOM, on the other hand, estimates a wider variety of space projects including space launch and transportation systems and human rated missions, requires more detailed information at the subsystem and major assembly level of the work breakdown structure which is usually not available so early. In addition, this dissertation has a different set of technical and non-technical variables than NAFCOM. For example, the model here uses power, design life and data rate as technical independent variables which are not explicitly part of NAFCOM independent variables. And the model here uses number of non-technical variables which are not used in NAFCOM. Also, the data base for this dissertation includes a more extensive set of automated spacecraft projects (122 versus roughly 70 for NAFCOM) and many of the projects are more current than the NAFCOM database. (Because NAFCOM is designed to operate at lower levels of the work breakdown structure than the model here, NAFCOM requires more time to analyze any given project, introduce it into the NAFCOM database, and revise the cost estimating relationships).

Compared to the PRICE Model, again the model developed in this dissertation operates at a higher level of the work breakdown structure and can generally be used earlier in the project life cycle. PRICE is designed to estimate a very wide range of project types. It generally offers only the Engineering Complexity Factor as the principal management influenced non-technical variable in Table 2.3 while the dissertation model here offers a more extensive list. This is not to be interpreted as a criticism of the PRICE Model—that model offers a much richer set of technical variables than the model here and is widely used throughout the industry for very detailed estimates at much lower levels of the work breakdown structure which is essential for detailed trade studies. Finally, the PRICE Model database and resulting algorithms are proprietary to PRICE Systems while the cost estimating relationships developed in this dissertation are transparent.

Compared to the SEER, the model here also operates at a level of the work breakdown structure that is higher than that of SEER. SEER is designed to estimate a very wide range of project types. SEER offers only the principal management variables of Table 2.4 while the model here offers a more extensive list. Once again, this is not to be interpreted as a criticism of the SEER model which is designed for different requirements than those being addressed by this dissertation. And just as with PRICE, the SEER model database and resulting cost estimating relationships are not open literature while the equations developed here are.

In summary, the model here has significant differences from the models in the literature. The model developed by this dissertation differs from models in the literature in the following ways:

- This dissertation model is focused on automated spacecraft projects only

- The database includes many very current space projects
- The model is designed to be used earlier in the project life cycle and at the total project level
- It has a transparent and auditable database and regression analysis
- It offers a different set of technical variables
- It offers a more extensive set of management variables

C. Academic Argument for Research and Approach

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. Current space cost models employ cost estimating relationships 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 cost equations typically have large variances, which leads to wide prediction intervals around any estimate.

One commonly used model at JPL (Table 2.5) shows a percent difference between actual and estimated costs of up to 89% (Hihn 2004) when used on historical space flight missions. While this model has an average error of 15.8% which perhaps does not seem all that bad, this statistic reflects the cancellations of positive and negative errors. The standard error provided by Hihn of 41.75% is probably a better value to describe the variability and such an error is cold comfort to a project manager having to depend upon the model to predict his or her project.

Table 2.5 JPL Cost Model Variability between Actual and Estimated Cost

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%

Smart (2005) provides a similar computation in Table 2.6 for NAFCOM. The statistics indicate that NAFCOM accuracy is, to the first order, no better than the JPL model in terms of estimated versus actual costs.

Table 2.6 NAFCOM Variability for Selected Data Points

	% Deviation		
	DDT&E	First Unit Cost	Total
FAST	-26.0%	-56.7%	-33.1%
Mars Observer	-9.4%	-20.1%	-11.1%
NEAR	12.9%	53.1%	23.9%
STEP 0	5.7%	-19.0%	0.2%
GRO	-30.7%	-18.5%	-28.7%
HST-SSM	-5.2%	-5.5%	-5.3%
TDRSS	-13.5%	41.3%	-8.0%
Spacelab	2.9%	2.7%	2.9%
COBE	18.3%	46.7%	24.1%
CRRES	18.7%	-1.8%	14.7%
Orbiter	2.4%	-0.1%	1.9%
ET	21.5%	36.0%	22.7%
SRB	-4.8%	54.4%	-1.2%
SRM	50.7%	28.3%	49.6%
IUS	-17.0%	-8.2%	-16.6%
Average	1.8%	8.8%	2.4%
Absolute Average	16.0%	26.2%	16.3%
Standard Deviation	20.9%	32.8%	21.9%

Tables 2.5 and 2.6 show that current space project cost models leave a very significant amount of variability unexplained. It is the thesis of this dissertation 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 non-technical differences between the projects that is not being captured in the traditional cost models.

The literature survey in Section A above found a rich discussion of the theoretical cost implications of non-technical factors on projects and project cost, in a qualitative sense. Yet, as discussed in Section B, the current cost models available to the aerospace industry do a less than totally satisfying job of relating management approaches to cost outcomes using non-technical variables. All the current models suffer from one or more of the following criticisms:

- A limited number of non-technical variables (all models)
- A requirement for a fairly mature, lower level definition of the project (all models)
- A limited and/or less than current database (NAFCOM)
- Proprietary database and algorithms (PRICE and SEER)

This dissertation sought to extend and improve upon the implementation of non-technical variables beyond the capabilities and utility offered by the existing models in the literature to give engineering managers a tool to access the cost consequences of decisions they make in these non-technical areas. This work attempted to develop a model that can be used very early in the project life cycle. The database and cost estimating relationship development will be transparent, statistically sound and not proprietary. These goals seemed to offer adequate justification for the effort.