Correlation of Spacecraft Mission and Project Costs

Christopher Swan
Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA

Shawn Jarrett
University of Texas at Austin, Austin TX

Abstract

A key component of any cost risk analysis is the level of correlation between individual elements of cost. This analysis supplements the available historical records with the cost estimates from the JPL Advanced Design Team. The costs from actual JPL flight projects are then used to validate the results, clearly indicating that, on average, the correlation between elements of cost is between 0.4 and 0.7.

1.0 INTRODUCTION

Analyzing the cost risk of potential and ongoing projects is integral to both the design and effective management of major aerospace systems development. One of the most common methods for performing cost risk assessments of projects is to utilize a Monte Carlo simulation. A major component of such an analysis is the statistical correlation between the costs of each work breakdown structure (WBS) element. These correlation coefficients can have a significant effect on the results of the cost risk assessment as illustrated in Figure 1.

"The result of ignoring correlation is that the "tails" come in closer and management is given the incorrect view of risk and cost overrun potential." (Black, page 6)

Correlation Impact

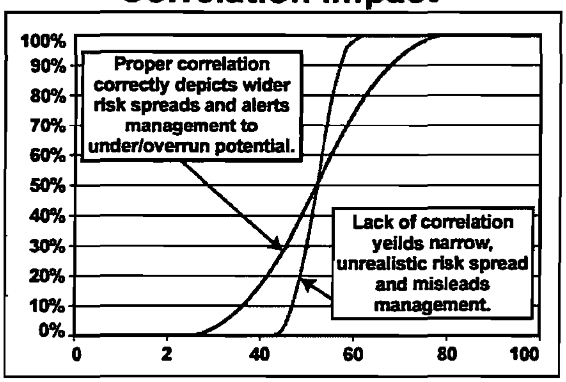

Figure 1. Sample impact of correlation on the results of a Monte Carlo cost risk analysis.

The difficulty of choosing appropriate values for the correlation matrix can vary, depending on many factors, even within the aerospace field. This study uses both historical project and design team data to provide a more concrete basis for choosing correlation values for one-of-a-kind robotic, aerospace projects.

2.0 METHODOLOGY

2.1 DATA COLLECTION

Due to a scarcity of historical cost information this study used data from both archived design studies and historical flight project cost data. Each data set was reviewed for completeness, consistency, and then grouped according to a variety of categories and cost element WBS. Because the cost data was collected from a variety of base year dollars, all cost data was normalized to Fiscal 2006 Dollars using a constant inflation rate of 3.1%. The effort resulted in three data sets from the design studies (Table 1) and one data set from the historical project cost data.

The design studies' cost information was obtained from the JPL Advanced Design Team (Team X) archive; the archive included over 100 studies during the period of 2003–2006. Team X is a concurrent design team that uses interconnected models to rapidly generate spacecraft and mission designs, complete with life cycle cost estimates. The team has performed more than 800 studies since it was founded in 1995 and their cost estimates have been validated against historical project costs within an average Δ of 5%, with a standard deviation of 22% (Carter and Rosenberg, page 3).

A careful review of each study was performed to remove studies that were either incomplete (cost estimates were not always performed) or performed multiple times (only solitary studies were included for this analysis). The cost information for each study was extracted and placed into one of three categories (identified in Table 1) according to the established Team X WBS (Tables 2 and 3).

Table 1: Description of Team X data sets

Team X Data Set	Description
Team X Projects	WBS level 2 costs for life cycle costs of entire projects
Team X Flight Elements	WBS level 3 costs for all spacecraft (including non-orbiting elements such as rovers)
Team X Orbiters	WBS level 3 costs for spacecraft which orbit a planetary body (subset of Flight Elements)

Table 2: Team X Project (level 2) WBS

Team X WBS
Project Management
Project System Engineering
Mission Assurance
Science
Instruments
Spacecraft
ATLO
Mission Operations
Launch Vehicle

The cost information for historical projects was obtained from the JPL Technical Cost Database (post-1990) and the JPL Cost Archive (pre-1990). This information was then grouped according to a WBS that encompassesd all of the missions (Table 3). In some instances, it was necessary to simplify certain WBS elements on more recent projects to accommodate the WBSs of legacy projects where elements such as flight software were historically carried under the computer and data handling accounts, while systems engineering, management, testing activity, and integration were traditionally charged to each subsystem. Unfortunately, due to the lack of available data for older (pre-1990) projects, further refinement of the mapping process was not possible.

Table 3: Subsystem (level 3) WBS of historical and Team X spacecraft.

Historical WBS (Level 3)	Team X WBS (Level 3)
Attitude and Control System	Spacecraft Management
Power	Spacecraft System Engineering
Propulsion	Attitude and Control Systems
Structures	Power
Thermal	Propulsion
Telecommunications	Structures
Command and Data Handling	Thermal
	Telecommunications
	Command and Data Handling
	Spacecraft software
	Testbeds

2.2 SOURCES OF ERROR

As with any statistical study, the main limitation is the source data; this analysis is no exception—the result being that the uncertainties in the WBS data for the older projects affected the comparison with Team X data. In addition to the differentiations in the data handling accounts and subsystem charging, another critical difference between the data sets existed, wherein project historical costs included expended reserves, while Team X data represents a current best estimate without reserves (they are carried separately). Again, because of the limited data available, determining where the reserves were expended was not possible.

2.3 METHOD: ANALYSIS

After the collected data was separated by category and WBS, it was correlated using the-Pearson Product-Moment Correlation method (Pearson's r). These calculations are outlined in equations 1-3:

$$S_x = \sqrt{\frac{\sum (X_i - \bar{X})^2}{n}} \qquad (1)$$

Standard Deviation of X

$$S_y = \sqrt{\frac{\sum (Y_i - \bar{Y})^2}{n}} \qquad (2)$$

Standard Deviation of Y

$$r = \frac{\sum \frac{(X_i - \bar{X})(Y_i - \bar{Y})}{n}}{S_x S_y} \qquad (3)$$

Pearson's r

$\bar{X}, \bar{Y}$ = Mean of X, Y data sample
n = Number of samples
X_i, Y_i = Value of X,Y
S_x, S_y = Standard Dieviation of X, Y

The resulting correlation matrices are included in the data appendices (Appendices 1, 3 , 5, and 7). Due to the size of the available data sets, it was important to determine which results were statistically significant. This was accomplished via a null hypothesis test. For the purposes of this study, we selected a probability of significance of 95% (or alpha = 0.05) using a two-tailed test, which resulted in the critical t values for each correlation data set listed in Table 4. Each correlation was then tested against the appropriate t value by using equation 4; the results are reported in Appendixes 2, 4, 6, and 8.

$$t = \frac{r\sqrt{n-2}}{\sqrt{1-r^2}} \quad (4)$$

Null hypothesis test for Pearson's r

Table 4. Critical t values for two-tailed null-hypothesis tests.

Degrees of Freedom	Two - Tailed with α=0.05
16	2.12
17	2.11
18	2.1
19	2.09
20	2.09
30	2.04
40	2.02
50	2.01
60	2.00
70	1.99
80	1.99

The final step in the data analysis was to aggregate the correlation data and the null-hypothesis test results. This was accomplished by averaging the values of Pearson's r that passed the null-hypothesis test. The results reported in Table 5 show a range of average correlation from 0.4 to 0.7.

3.0 RESULTS

There is significant variation in the comparison between model data sets and historical data sets at the WBS level. While the majority of correlation points (compared in all data sets) pass the null hypothesis test (see Appendixes 2, 4, 6, and 8), the differences between Team X flight elements and the historical project data at the WBS level are large and variable (Table 6). The Team X orbiter data is closer to the historical projects on average, but the variance (0.27) is similar to the flight element data set (0.31). This is most likely driven by the fact that the majority of the historical spacecraft are orbiters.

Another comparison exists at the aggregate level using the average correlation level across each data set (shown in Table 5). This removes much of the variability in the correlations observed at the WBS level and discards individual results that are not statistically significant..

4.0 DISCUSSION

The variability of the correlation results at the WBS element level makes recommending a specific matrix based on this data impossible. While the individual correlation of each data set appears to be statistically significant, comparisons between the sets are inconclusive. The aggregate correlations of each data set compare better and with more consistency than the WBS elements, which indicates that the results may be overly influenced by some of the stated source data issues. The variation of

Table 5: Averages of Pearson's "r" Range for Each Data Set

Data Set	Average r
Team X Projects	0.60
Team X Flight Element	0.41
Team X Orbiter	0.47
Average Team X	0 50
Historical Projects	0.70

Table 6: Comparison between WBS Level 3 Correlations for Each Data Set

Correlation Relationship	Team X Orbiters	Historical Projects	Team X Flight Element	Orbiter—Historical Difference	Flight Element—Historical difference
ACS—C&DH	0.53	0.69	0.42	0.15	-0.27
ACS—Power	0.68	0 91	0.33	0.23	-0.58
ACS—Propulsion	0.38	0.66	0.40	0.28	-0.25
ACS—Structures	0.63	0.77	0.34	0.14	-0.42
ACS—Telecom	0.34	0.78	0.49	0.44	-0.29
ACS—Thermal	0.72	0.60	0.25	-0.12	-0.35
Power—C&DH	0.66	0.78	0.47	0.12	-0.32
Power—Propulsion	0.53	0.58	-0.06	0.05	-0.64
Power—Structures	0.52	0.74	0.47	0.22	-0.26
Power—Telecom	0.38	0.83	0.38	0.46	-0.45
Power—Thermal	0.51	0.41	0.72	-0.10	0.30
Propulsion—C&DH	0.26	0.37	0.05	0.11	-0.32
Propulsion—Structures	0.45	0.28	-0.01	-0.17	-0.29
Propulsion—Telecom	0.48	0.75	0.33	0.27	-0.42
Propulsion—Thermal	0.36	0.76	-0.22	0.39	-0.98
Structures—Structures	0.49	0.56	0.20	0.07	-0.36
Structures—Telecom	0.42	0.49	0.24	0.06	-0.25
Structures—Thermal	0.65	0.27	0.63	-0.38	0.37
Telecom—C&DH	0.18	0.68	0.60	0.50	-0.08
Thermal—C&DH	0.54	-0.02	0.29	-0.56	0.31
Thermal—Telecom	0.42	0.58	0.27	0.17	-0.31
Bold/italics indicate one or more of the results did not pass the rule hypothesis.			Average	0.11	-0.28
			Standard Deviation	0.27	0.31

WBS data is the most likely culprit, as it has the potential to adversely affect the results of a WBS-specific correlation matrix, while having little impact on an aggregate correlation across a WBS.

Regardless of the WBS issues, the results of the aggregate correlation provide guidance for a range of coefficients (0.4–0.7) that are supported by historical results.

5.0 ACKNOWLEDGEMENTS

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6.0 REFERENCES

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I. DATA APPENDIX 1: PEARSON'S R CORRELATIONS FOR TEAM X FLIGHT ELEMENTS

COST Correlation	ACS	Power	Propulsion	Structures	Thermal	Telecom	C&DH
ACS	1.00						
Power	0.91	1.00					
Propulsion	0.66	0.58	1.00				
Structures	0.77	0.74	0.28	1.00			
Thermal	0.60	0.41	0.76	0.27	1.00		
Telecom	0.78	0.83	0.75	0.49	0.58	1.00	
C&DH	0.69	0.78	0.37	0.56	-0.02	0.68	1.00

II. DATA APPENDIX 2: CRITICAL VALUE, NULL HYPOTHESIS TEST FOR TEAM X FLIGHT ELEMENTS

COST Null Test	ACS*	Power*	Propulsion*	Structures*	Thermal*	Telecom*	C&DH
ACS	1 00						
Power	21.39	1.00					
Propulsion	4.46	3.37	1.00				
Structures	7.17	6.20	1.16	1.00			
Thermal	3.64	1.92	6.88	1.11	1.00		
Telecom	7.82	10.66	6.53	2.48	3.41	1.00	
C&DH	5.09	7.83	1.65	3.13	-0.06	4.81	1.00

* Shaded cells indicate t values above the required critical values for significance (1.99 per Table 4)

III. DATA APPENDIX 3: PEARSON'S R CORRELATIONS FOR TEAM X ORBITERS

COST Correlation	S/C Bus Management	S/C Bus Engineering	ACS	Power	Propulsion	Structures	Thermal	Telecom	C&DH	S/C Software	Testbeds
S/C Bus Management	1.00										
S/C Bus Engineering	0.24	1.00									
ACS	0.17	0.18	1.00								
Power	0.25	0.05	0.33	1.00							
Propulsion	0.01	0.04	0.40	-0.06	1.00						
Structures	0.19	0.12	0.34	0.47	-0.01	1.00					
Thermal	0.19	0.07	0.25	0.72	-0.22	0.63	1.00				
Telecom	0.08	0.15	0.49	0.38	0.33	0.24	0.27	1.00			
C&DH	0.25	0.47	0.42	0.47	0.05	0.20	0.29	0.60	1.00		
S/C Software	0.21	0.09	0.11	0.41	-0.06	0.41	0.45	0.37	0.38	1.00	
Testbeds	0.28	0.14	0.53	0.55	0.17	0.31	0.38	0.53	0.60	0.37	1.00

IV. DATA APPENDIX 4: CRITICAL VALUE, NULL HYPOTHESIS TEST FOR TEAM X PROJECTS

COST Null Test	S/C Bus Management*	S/C Bus Engineering*	ACS*	Power*	Propulsion*	Structures*	Thermal*	Telecom*	C&DH*	S/C Software	Testbeds
S/C Bus Management	1.00										
S/C Bus Engineering	4.81	1.00									
ACS	3.39	0.96	1.00								
Power	5.63	1.04	9.29	1.00							
Propulsion	3.04	0.54	3.22	5.28	1.00						
Structures	3.45	2.90	7.54	5.16	4.10	1.00					
Thermal	3.93	3.11	10.75	5.04	3.06	8.04	1.00				
Telecom	4.27	0.86	2.85	3.19	4.51	3.76	3.67	1.00			
C&DH	5.73	3.47	5.45	8.68	2.04	4.65	5.64	1.33	1.00		
S/C Software	-0.02	0.99	0.58	1.63	3.17	2.38	2.40	1.27	1.40	1.00	
Testbeds	5.09	0.63	8.69	7.62	3.20	3.91	6.00	2.89	6.70	1.42	1.00

* Shaded cells indicate t values above the required critical values for significance (1.99 per Table 4)

V. DATA APPENDIX 5: PEARSON'S R CORRELATIONS FOR TEAM X PROJECTS

COST Correlation	S/C Bus Management	S/C Bus Engineering	ACS	Power	Propulsion	Structures	Thermal	Telecom	C&DH	S/C Software	Testbeds
S/C Bus Management	1.00										
S/C Bus Engineering	0.50	1.00									
ACS	0.39	0.13	1.00								
Power	0.54	0.14	0.68	1.00							
Propulsion	0.36	0.07	0.38	0.53	1.00						
Structures	0.40	0.35	0.63	0.52	0.45	1.00					
Thermal	0.44	0.37	0.72	0.51	0.36	0.65	1.00				
Telecom	0.46	0.12	0.34	0.38	0.48	0.42	0.42	1.00			
C&DH	0.55	0.40	0.53	0.66	0.26	0.49	0.54	0.18	1.00		
S/C Software	0.00	0.13	0.08	0.21	0.37	0.30	0.30	0.17	0.19	1.00	
Testbeds	0.51	0.09	0.67	0.63	0.38	0.44	0.56	0.35	0.59	0.19	1.00

VI. DATA APPENDIX 6: CRITICAL VALUE, NULL HYPOTHESIS TEST FOR TEAM X PROJECTS

COST Null Test	S/C Bus Management*	S/C Bus Engineering*	ACS*	Power*	Propulsion*	Structures*	Thermal*	Telecom*	C&DH*	S/C Software	Testbeds
S/C Bus Management	1.00										
S/C Bus Engineering	4.81	1.00									
ACS	3.39	0.96	1.00								
Power	5.63	1.04	9.29	1.00							
Propulsion	3.04	0.54	3.22	5.28	1.00						
Structures	3.45	2.90	7.54	5.16	4.10	1.00					
Thermal	3.93	3.11	10.75	5.04	3.06	8.04	1.00				
Telecom	4.27	0.86	2.85	3.19	4.51	3.76	3.67	1.00			
C&DH	5.73	3.47	5.45	8.68	2.04	4.65	5.64	1.33	1.00		
S/C Software	-0.02	0.99	0.58	1.63	3.17	2.38	2.40	1.27	1.40	1.00	
Testbeds	5.09	0.63	8.69	7.62	3.20	3.91	6.00	2.89	6.70	1.42	1.00

* Shaded cells indicate t values above the required critical values for significance (1.99 per Table 4)

VII. DATA APPENDIX 7: PEARSON'S R CORRELATIONS FOR HISTORICAL SPACECRAFT SUBSYSTEMS

COST Correlation	Project Management	Project Sys. Engineering	Mission Assurance	Science	Instrument	Spacecraft	ATLO	Mission Operations	Launch Vehicle
Proj. Management	1.00								
Proj. Sys. Engineering	0.70	1.00							
Mission Assurance	0.65	0.57	1.00						
Science	0 55	0 09	0.56	1.00					
Instrument	0.25	0.14	0.40	0.56	1.00				
Spacecraft	0.86	0.80	0.78	0.35	0.17	1.00			
ATLO	0.74	0.59	0.60	0.31	0.16	0.82	1.00		
Mission Operations	0.74	0.68	0.64	0.48	0.24	0.64	0.44	1.00	
Launch Vehicle	0.63	0.71	0.58	0.18	0.05	0.74	0.53	0.51	1.00

VIII. DATA APPENDIX 8: CRITICAL VALUE, NULL HYPOTHESIS TEST FOR HISTORICAL SPACECRAFT SUBSYSTEM

COST Null Test	Project Management*	Project Sys. Engineering*	Mission Assurance*	Science*	Instrument*	Spacecraft*	ATLO*	Mission Operations*	Launch Vehicle
Proj. Management	1.00								
Proj. Sys. Engineering	10.89	1.00							
Mission Assurance	9.07	6.77	1.00						
Science	6.40	0.76	6.47	1.00					
Instrument	2.14	1.13	3.83	6.56	1.00				
Spacecraft	27.43	18.03	15.98	3.24	1.42	1.00			
ATLO	12.86	7.28	7.60	2.75	1.32	20.35	1.00		
Mission Operations	13.17	9.93	8.81	5.04	1.99	8.73	4.39	1.00	

* Shaded cells indicate t values above the required critical values for significance (1.99 per Table 4)

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