Exploring the Limits of "Faster, Better, Cheaper" With Mission Cost Risk Assessment

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Introduction

In May 2000, David Bearden of the Aerospace Corporation Presented "A Complexity-Based Risk Assessment of Low-Cost Planetary Missions: When is a Mission Too Fast and Too Cheap?" At the fourth IAA International Conference on Low-cost Planetary Missions, JHU/APL.

- Pioneering effort to establish risk, cost, and schedule tradeoffs
- Highly critical of "faster, better, cheaper" policy
- Featured in Aviation Week and Space Technology article

The May 2000 Aerospace Study and GSFC's Experience

- The Aerospace study's conclusions were different from Goddard space flight center's experience with "faster, better, cheaper"
  - e.g., the small explorer (SMEX) program

- In July 2000, we examined the aerospace study and tried to reproduce the results using Goddard data

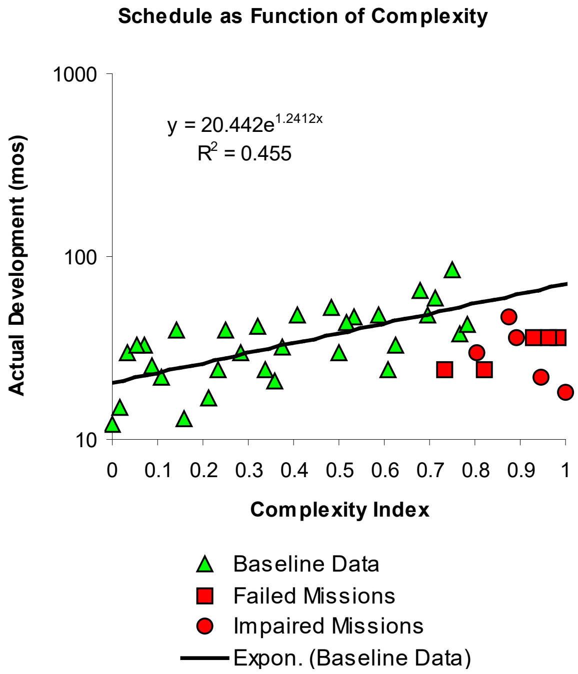
May 2000 Aerospace Corp. Study

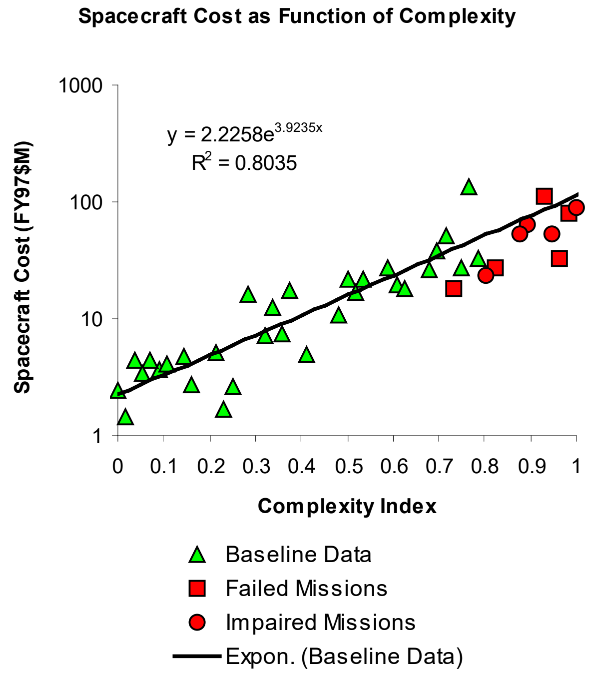
- Over 40 missions launched between 1990-1999 were studied
  - Includes earth-orbiting and planetary
  - Does not include non-U.S. missions
  - Includes both NASA and non-NASA missions
- Introduces "spacecraft complexity" metric
  - Arithmetic mean of the "complexity" levels of 21 technical and programmatic parameters for the spacecraft (e.g., mass, power, data rate)
  - Complexity levels for each parameter computed as a percentile rank
  - Spacecraft complexity ranges from 0 (least complex) to 1 (most complex)

May 2000 Aerospace Corp. Study (Cont'd.)

- Mission classification
  - Successful
  - Failed
  - Impaired
- Relates Spacecraft Complexity to Cost and Schedule
  - Cost strongly correlated
  - Schedule correlation is weaker but significant

May 2000 Aerospace Corp. Study (Cont'd.)





Aerospace Study Conclusions:

- More complex missions more likely to fail
- Regression curves can be used as parametric indicators

Task: Determine whether or not Goddard experience is consistent with the May 2000 Aerospace study

- In July 2000, we attempted to reproduce Aerospace Study using Goddard data

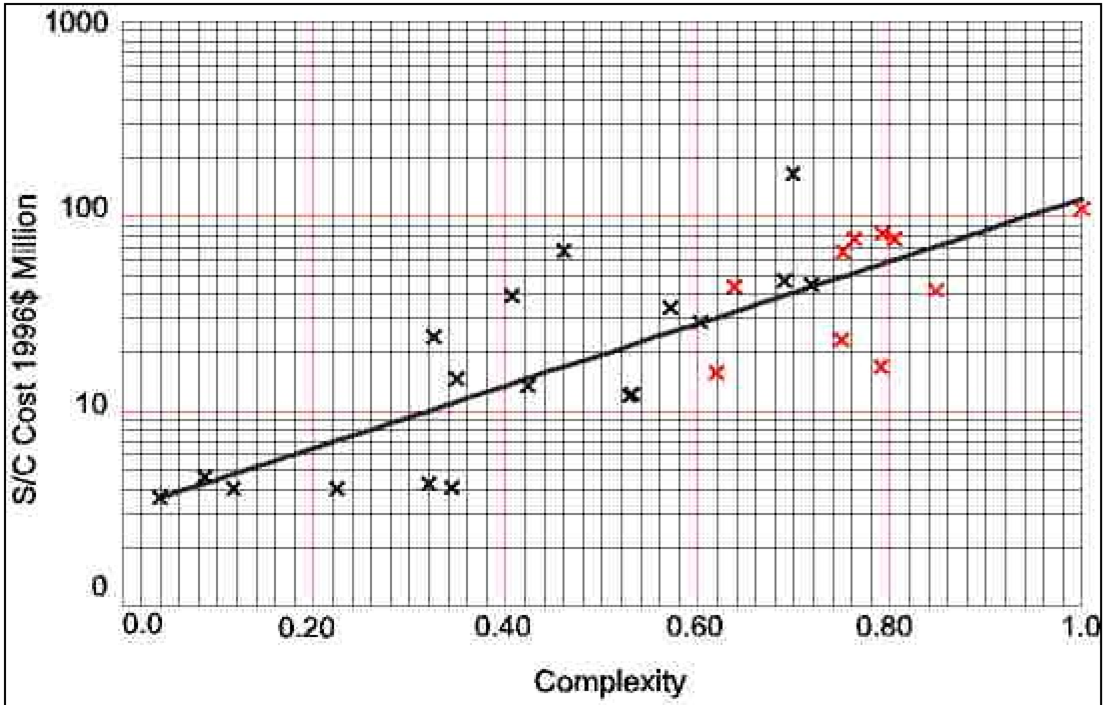
Task: Determine Whether or Not Goddard Experience Is Consistent With the May 2000 Aerospace Study

- Different results
  - Weaker, but still strong relationship between cost and complexity ($R^2 = 0.658$)
  - No relationship between schedule and complexity ($R^2 = 0.070$)
- Reasons for differences
  - Slightly different database (we did not have data for two non-NASA missions and thus could not include them in our study)
  - Used 14 parameters to calculate spacecraft complexity (several parameters used in Aerospace study are highly correlated – e.g., BOL Max power and EOL max power, which can give too much weight to certain subsystems, and skew the results)

Task: Determine Whether or Not Goddard Experience Is Consistent With the May 2000 Aerospace Study (Cont'd.)

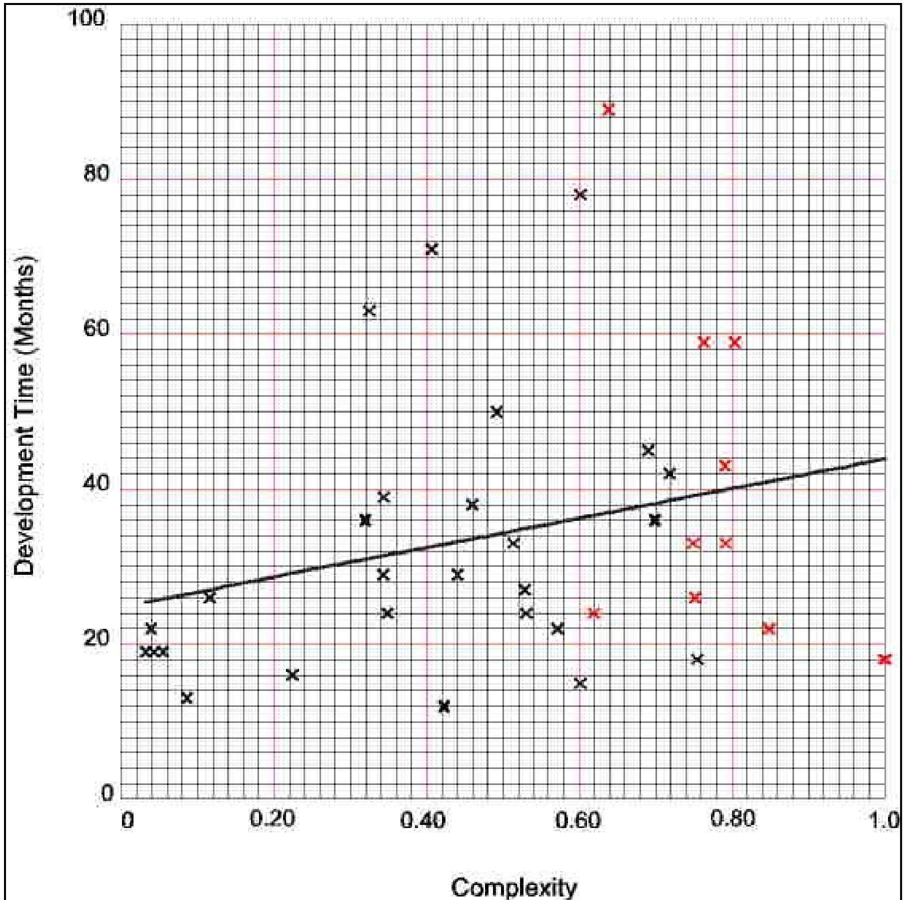
- Small changes in assumptions and data result in large changes in results (see charts that follow)
  - Only half the failed missions have cost or schedule below average for a given level of complexity
  - Model results seem sensitive to small changes in data

RAO Analysis Results
Cost Vs. Spacecraft Complexity



N1: S/C Cost = 3.094 * 39.841^ Complexity
N = 28
CC = 0.811
SEA = 0.677
RSQ = 0.658
CV = 0.216

RAO Analysis Results
Schedule Vs. Spacecraft Complexity



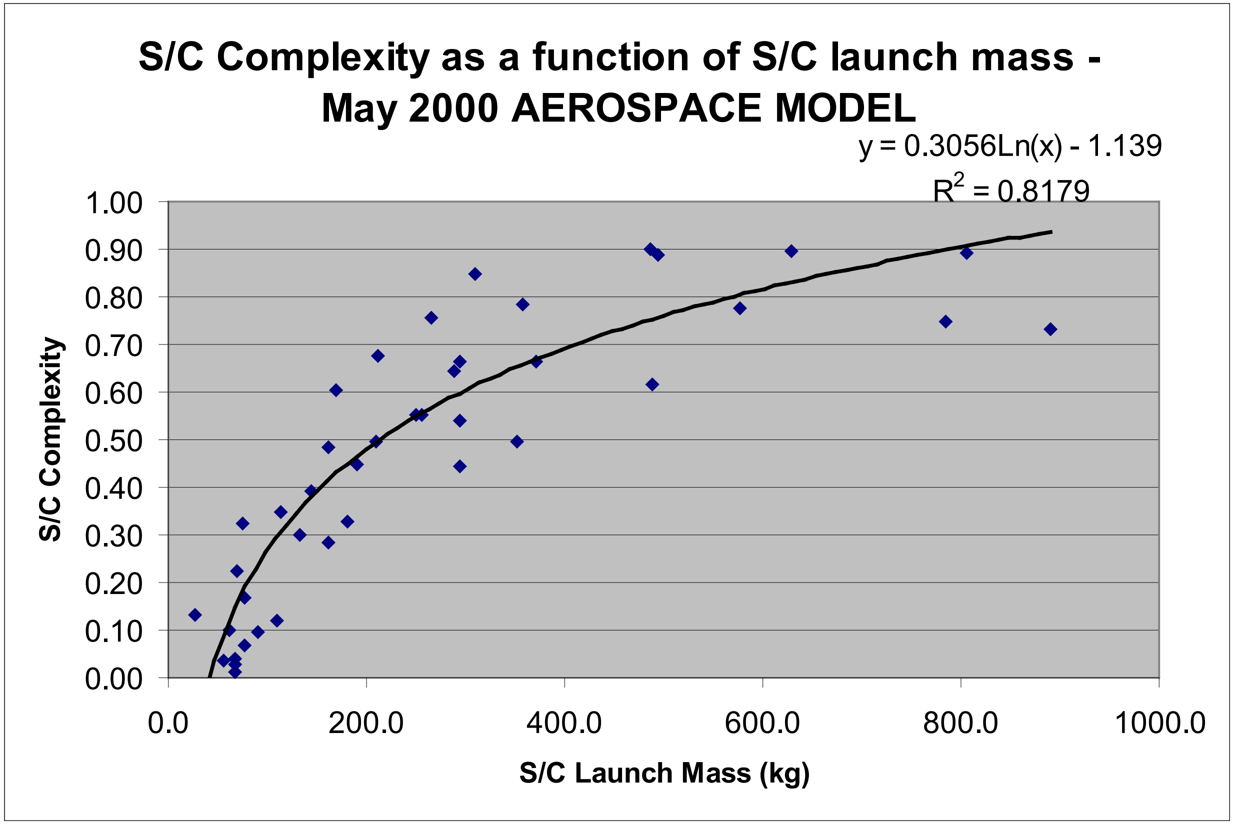
N1: Development Time = 24.854 +19.031 * Complexity
N = 37
CC = 0.265
SEA = 18.403
RSQ = 0.070
CV = 0.536

Preliminary Observations on the May 2000 Aerospace Model

- Data discrepancies, as discussed above
  - Half of missions in dataset are non-NASA
  - Database includes several small satellites with design lives of only a few hours or days
- Risk NOT measured directly
- Treats cost and schedule as independent from each other
- Complexity seems to be driven by spacecraft mass

Complexity and Mass

There is extremely high correlation between launch mass and Aerospace spacecraft complexity parameter.



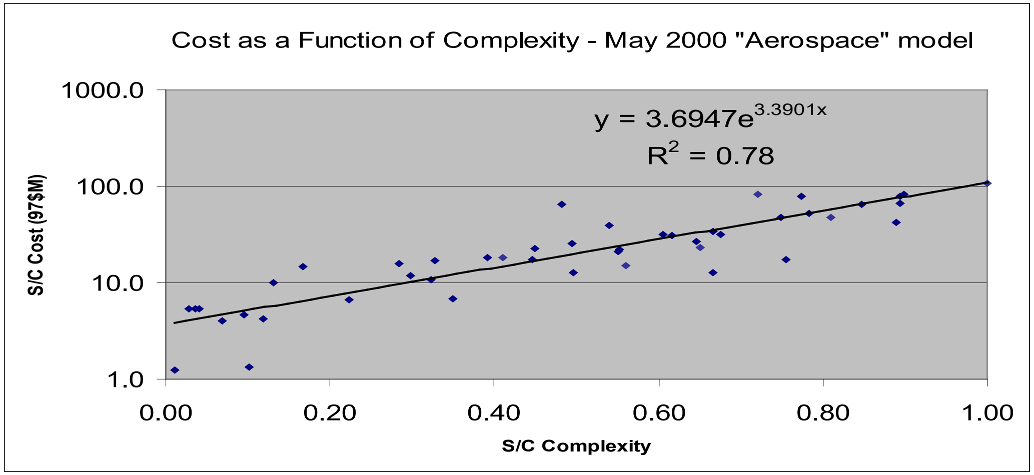
Complexity and Mass (Cont'd.)

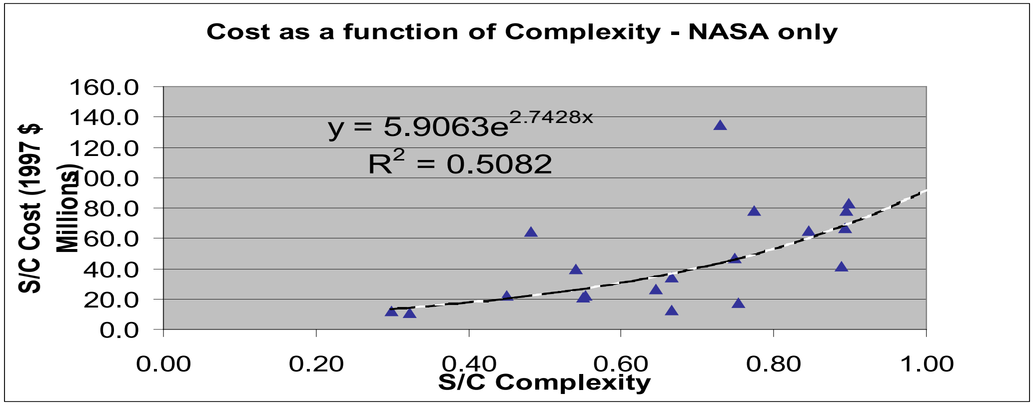
- High correlation between weight and complexity caused in part by considering non-NASA microsatellites
  - Weight seems to drive the complexity

Inclusion of Non-NASA Missions

- Including non-NASA missions seems to affect the results
  - Possibly overstates the goodness-of-fit of the model
- The impact of removing these missions
  - Approximated the May 2000 Aerospace model by using the graphs from the Aviation Week article ($R^2 = 0.78$ vs. $R^2 = 0.80$ for weight/complexity equation), then removed the non-NASA missions
  - R^2 dropped to 0.51

Inclusion of Non-NASA Missions



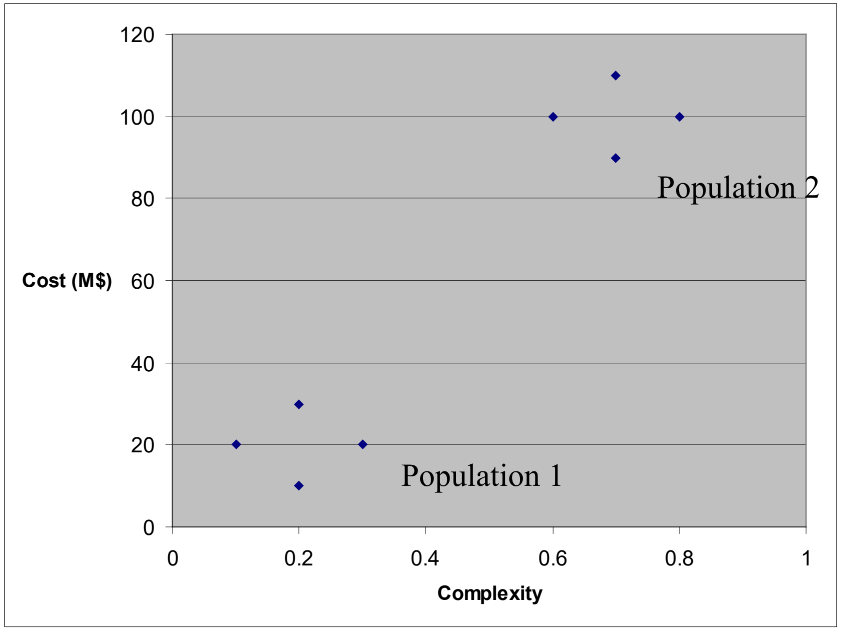


Remarks on Non-NASA Missions

- Non-NASA missions included in study:
  - represent a different culture
  - smaller than the average NASA mission
  - less complex than the average NASA mission
  - shorter in duration than the average NASA mission
- Consequence: including the non-NASA missions seems to overstate goodness of fit due to pseudo-correlation
- Conclusion: the non-NASA missions represent a different population and should not be included in the study of science-related missions

Pseudo-correlation: An Example

Comparing two distinct populations can introduce pseudo-correlation



Correlation within each population is zero, but considered as one population, correlation is 95%!

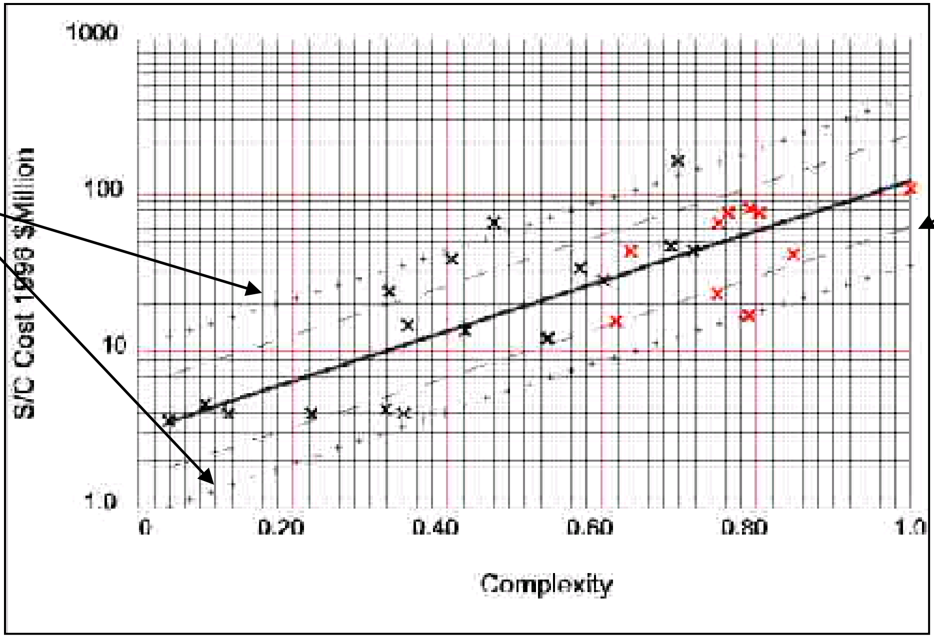
Regression Models

- Regression lines represent an average. An average is not sufficient information for parametric indicators.
- Must consider uncertainty – e.g., standard deviations, confidence limits
- Missions below the *average minus two standard deviations* could be considered to be too risky (for example)
- Another possibility: treat failure as a dummy variable – minimum distance between lines needed for significant difference

Regression Models (Cont'd.)

In the graph below, we have added error bands (average +/- 2 standard deviations), and 95% confidence limits

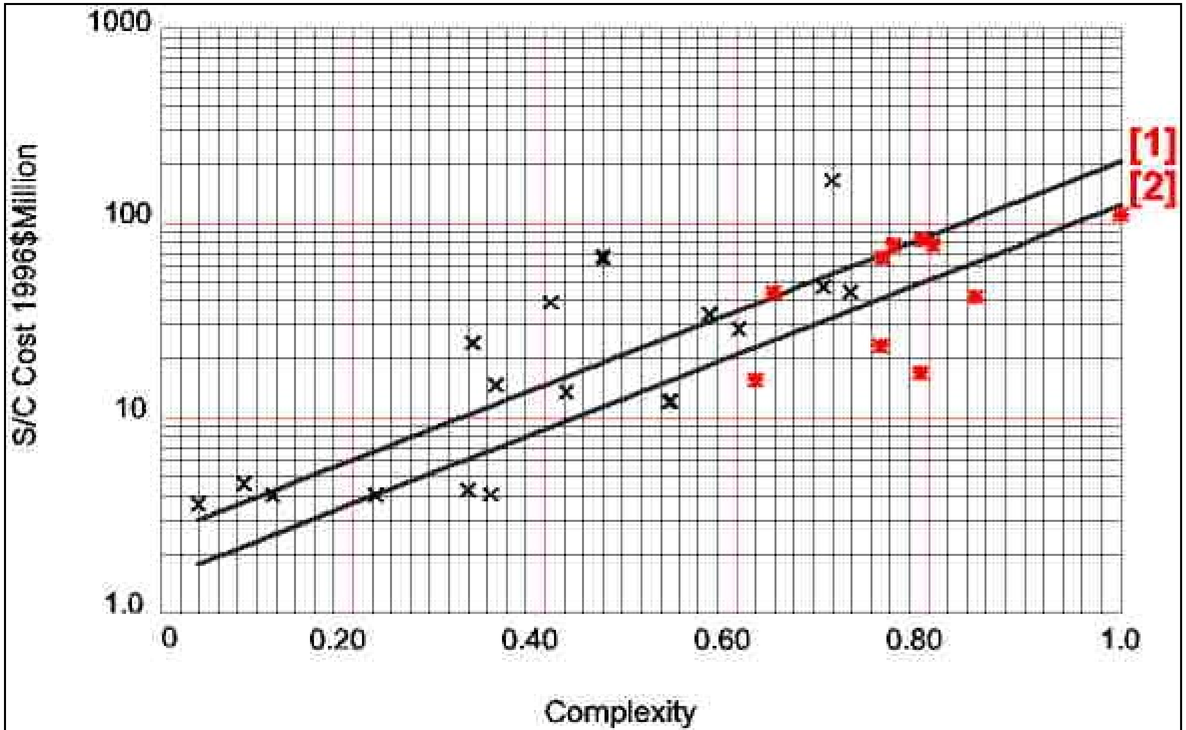
95% confidence limits



Error bands

Regression Models (Cont'd.)

Failure treated as a dummy variable



[1] REGULAR (x)

$S = 2.523 * (81.645)^{C}$

[2] FAILED (*)

$S = 1.502 * (81.645)^{C}$

CC = 0.826
SEA = 0.665
RSQ = 0.682
N = 28

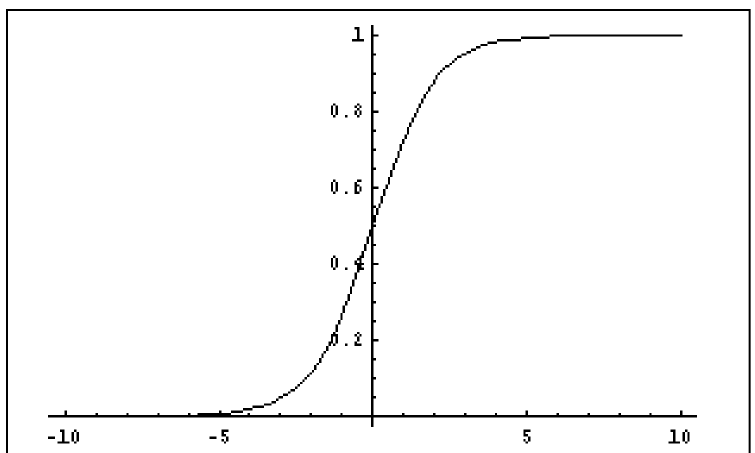
Lessons Learned

- May 2000 Aerospace model is a pioneering effort and a terrific first step, but there is room for improvement
- Consideration of non-NASA missions questionable
- Discrepancies in data
- Results sensitive to small changes in data
- Complexity metric needs more study – driven by weight?
- Model not directly related to risk
- Simple regression line not sufficient for parametric indicators
- Interdependency between cost and schedule not considered

Goddard Improvements

- Risk should be modeled directly
  - We have completed some **preliminary** work in this direction
  - Used over 50 NASA missions to directly predict risk, using logistic regression

For one independent variable, the model has the form:



Goddard Improvements (Cont'd.)

- Logistic regression
  - Algebraically, the logistic regression model has the form:

$$\pi(x) = \frac{e^{g(x)}}{1 + e^{g(x)}}$$

where $g(x) = \beta_0 + \beta_1 * x$

- Logistic regression arose in epidemiological research, and is now commonly employed in business and finance, ecology, engineering, health policy, and linguistics

Goddard Improvements (Cont'd.)

- Directly measured the impact of cost, schedule, and spacecraft and payload complexity, reliability, and new technology advances
  - Based on our findings, these predictors better predict risk than spacecraft complexity alone
- Our model takes into account the relationship between cost and schedule (treated as independent in the May 2000 Aerospace model)

Goddard Improvements (Cont'd.)

- Predicts the probability of the return of scientific data - "mission success"
- A NASA metric, the level of technology maturation, is a better predictor of success/failure than "spacecraft complexity"
  - *Findings indicate that "spacecraft complexity" has little correlation with risk of mission failure*
- Model was tested and validated with Authority to Proceed (ATP) data

Goddard Improvements (Cont'd.)

Model Performance

Mission Result	Mission Success Level
Successful	99%
Successful	99%
Successful	99%
Successful	99%
Successful	99%
Successful	99%
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Successful	97%

Mission Result	Mission Success Level
Successful	96%
Successful	95%
Successful	95%
Successful	93%
Successful	93%
Successful	92%
Successful	92%
Successful	92%
Successful	91%
Successful	91%
Successful	91%
Successful	91%
Failure	**88%**
Successful	84%
Successful	79%
Successful	70%
Successful	67%
Failure	**65%**
Successful	61%
Successful	58%
Failure	**55%**
Successful	50%
Failure	**45%**
Failure	**41%**
Successful	34%
Successful	28%
Failure	**16%**

80% and above	"Fly" zone
51 -79%	"Caution" zone
50% and below	"No-fly" zone

Goddard Improvements (Cont'd.)

Model Performance

- The statistic $G = -2\ln[\frac{\text{likelihood without the variables}}{\text{likelihood with the variable}}]$ plays a central role in assessing goodness-of-fit for logistic regression. For our model, G = 15.615. G is X^2-distributed with six degrees of freedom. $Pr(X^2(6)>15.615)=0.015977$, which means the model is statistically significant up to the 97.5% confidence level.
- R^2 is not a very meaningful statistic for a logistic regression model, which is not exactly a regression model. Significant logistic regression models with good fits often have very low R^2 values, in the range of 0.1 - 0.2. For our model, $R^2 = 0.294$, which is quite good for a logistic regression model.
- The area under the ROC(Receiver Operating Characteristic) curve is 93%, which means the model has outstanding discrimination ability. Also, according to a ROC analysis, the optimum mission success level to distinguish between success and failure is 80%, the threshold for our "fly" zone.
- The Hosmer-Lemeshow statistic, C, has a p-value equal to 99.4%, which indicates an excellent fit.

Goddard Improvements (Cont'd.) Model Validation

- Mission success levels calculated at both ATP and at Completion:

ATP	Completion
99%	97%
99%	99%
99%	99%
96%	99%
96%	97%
91%	99%
90%	95%
90%	91%
87%	91%
82%	97%
42%	61%
41%	58%
17%	N/A

Summary and Conclusions

- Replicated May 2000 Aerospace Study with Goddard data
  - Obtained different results
    - Schedule has little relationship with spacecraft complexity
    - Cost has a positive correlation with spacecraft complexity, but only about half of the failed missions have a lower than average cost for a given complexity level
  - Our results are consistent with Goddard's experience, and do not invalidate "faster, better, cheaper"

Summary and Conclusions (Cont'd.)

- Developed a tool with Goddard data that is used for decision-making within Goddard
  - Model is used by the RAO to independently assess mission risk with respect to cost,and schedule
  - RAO employs the model in developing independent assessments as part of the mission confirmation process
    - Mission confirmation is the most important review during a mission's development
      - Point at which Goddard commits to cost and schedule