

## IMPROVING COST ESTIMATION IN AN ERA OF INNOVATION

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### ABSTRACT

Many innovations are being proposed for spacecraft engineering and there are others that could be proposed. Some that offer opportunities to reduce spacecraft costs are disaggregating spacecraft functions, using commercial buses, relaxing mass limits, standardizing components and interfaces, modularizing systems, and using commercial design principles. Individually and together, they pose a severe challenge to spacecraft cost estimation.

To the extent that these innovations produce significant changes in spacecraft engineering and the cost of spacecraft design and manufacture, they will to the same degree produce discontinuities within the historical data series that drive parametric cost models. Since spacecraft programs currently depend heavily on parametric cost models for the early and middle phases of cost estimation, any significant wave of innovation creates an urgent demand for alternatives to fill the gap. This paper discusses possibilities for improving the scope, accuracy, and precision of each of the three major types of cost estimation: estimation by analogy, parametric estimation, and engineering analysis.

### OVERVIEW OF CURRENT TECHNIQUES AND MODELS

Space systems have been in the forefront of advanced global technology since the 1950's. Innovative development and thinking have driven this industry. Public and private investment has enabled the space industry to thrive and become a critical part of our telecommunications, geospatial, intelligence community, and defense infrastructure worldwide. The space systems developed range in price from thousands of dollars to billions of dollars. They encompass technologies that consist of advanced RF and digital electronics, composite structures, solar cells and substrates, antennas, batteries, ground processing systems, ground terminals to name a few. These technologies are diverse and ever evolving. It is common for a space system at procurement to have achieved as low as technology readiness level 5 or 6.

In this context, spacecraft developers face several challenges in developing accurate, reliable, verifiable cost estimates. Thousands of man years of effort have been spent on accumulating historical cost data and developing models and metrics to estimate the cost of space systems. Government agencies, in particular have deployed teams of subject matter experts to study the challenges faced in developing reliable cost estimating models and methods.

Three major methods are deployed to estimate the cost of future space systems, Parametric, Analogy, and Engineering.

#### ***Parametric Method***

Parametric models are most commonly used for systems that have a significant amount of new design and no one space system has significant similarity. Algorithms and parameters (cost estimating relationships) at the system, subsystem or component level are developed from historical program data that is normalized. These algorithms and parameters are developed through the identification of technical variables that drive cost. The

technical variables include hardware weight, complexity factors, number of units, bandwidth, power, and others. In addition, they sometimes incorporate cost to cost relationships for systems engineering, program management and integration and test type costs. In all instances, these models are dependent on historical cost data. In many cases, the uncertainty around these models is very large, could range from 20% to close to 100%. As these models have evolved over time, the data sets, normalization of data, and generation cost estimating relationships have improved. However, they continue to produce large uncertainty factors due to the constant technology evolution and disruption in this industry.

### ***Analogy Method***

Numerous agencies also estimate the cost of future space systems through analogy. They select one or two similar programs and develop ad hoc models that capture technical, schedule, technical complexity, program complexity, and other adjustments from the historical program to the future program. The fidelity of these models could be more favorable than parametric models if the future systems are closely related to the historical systems. Analogy methods are the least expensive of the cost estimating methods and can be used at the earliest stages of project conception.

### ***Engineering (Bottom-Up) Method***

Engineering or bottom-up cost estimation generally requires extensive detailed definition of system configuration at the lowest possible level. With the existence of the defined baseline and a mechanism to obtain low level cost data, in many cases at the piece part and labor hour level, these estimates can have the highest fidelity. This method is often only available for grass roots estimation, that is, estimation by the people actually doing the work. Customers, whether government agencies or commercial enterprises, frequently lack the detailed design information needed to employ bottom-up methods.

Each method has key features and benefits, and they have been adopted by agencies and contractors based on the data and resources available to generate the estimates. There is one common element that all of these methods possess and that is the dependence on comparison to historical programs. All methods depend on the knowledge obtained through previous program experience. This is not unlike any type of manufacturing industry. The spacecraft industry, however, can experience significant technological advancements that render the dependence on historical programs somewhat useless.

## **THE CHALLENGE OF INNOVATION**

Many innovations are being proposed for spacecraft engineering that could challenge cost estimation by reducing costs so dramatically that historical become much less relevant. Some innovations that offer opportunities to reduce spacecraft costs are:

1. Disaggregation - deploying mission functions in a distributed architecture on many smaller spacecraft (including hosted payloads), rather than deploying fewer multi-function spacecraft
2. Commercial buses and components - using commercial satellite buses or components with high technology readiness, rather than customizing them for each particular mission
3. Standardization and modularization - adopting standardized or modular architectures at the system, subsystem, or component levels
4. Accelerated development schedules - use low-risk methods to enable rapid develop cycles, resulting in design cycles measured in months rather than years
5. Relaxed mass limits - avoiding the costs of meeting tight mass limits by purchasing additional launch capability

6. Commercial design principles - changing the mix of constraints and goals to make performance (function requirements) a constraint and make reliability, manufacturability, and cost reduction the primary goals

None of these innovations are mutually exclusive. Any number of the innovations can be implemented in combination. CubeSat developers, for example, can benefit from all of them at once. Individually and together, they pose a severe challenge to spacecraft cost estimation.

The severity of this challenge is illustrated by the example of the SpaceX Falcon 9 launch vehicle. NASA used the parametric NASA-Air Force Cost Model (NAFCOM) in 2011 to estimate the cost of developing the Falcon 9 using traditional NASA methods and a more commercial method. The NAFCOM estimate for the more commercial approach was about 5 times the actual SpaceX cost, while the estimate for the traditional approach was more than 10 times the actual costs. After revising the NAFCOM inputs to better model SpaceX practices, they were able to produce a fixed-price estimate that was still 30 percent more than the actual costs and a cost plus estimate that was 4 times the actual.

To the extent that design and manufacturing innovations produce significant changes in spacecraft engineering and the cost of spacecraft design and manufacture, they to the same degree produce discontinuities within the historical data series that drive parametric cost models. Since spacecraft programs currently depend heavily on parametric cost models for the early and middle phases of cost estimation, any significant wave of innovation creates an urgent demand for alternatives to fill the gap.

#### **POSSIBILITIES FOR IMPROVING COST ESTIMATION**

There are possibilities for improving the scope, accuracy, or precision of each of the three major types of cost estimation.

##### ***Estimation by Analogy***

The literature on estimation by analogy is not very extensive and the conventional wisdom is that it is too subjective compared with parametric models. With the parametric models handicapped, estimation by analogy deserves a new look.

There are indications that estimation by analogy never had to perform as badly as has been portrayed. Some texts implicitly limit estimation by analogy to 1 cost estimator using only 1 analogy system for each estimate. Significant improvements in estimation by analogy may be achieved by using multiple analogy systems for each estimate or combining estimates from multiple cost estimators. One study in 2004 tested 8 methods for combining analogy estimates from multiple analogy projects. The errors compared to the actual mission costs varied from 1% to 19%, all on the high side, with a Euclidian linear interpolation performing best. This is not bad performance in an industry that has routinely produced 40% cost overruns.

Two other studies in 2003 and 2005 used CERs to adjust the cost of analogy estimates of instrument, sub-system and system costs, producing hybrid estimates that performed as well or better than CERs alone.

Some parametric estimation has been conducted using the Delphi method to combine inputs from multiple cost estimators to help adjust the parameters, but it could be used in analogy estimation as well. The Delphi method allows for either anonymous inputs or consensus building between estimators in communication with each other. Other methods that could be used to combine inputs from multiple estimators include analytic

hierarchy and Bayesian analysis. Bayesian analysis, in particular, offers an ability to estimate variances in addition to point estimates. Bayesian analysis has been used in software cost estimation.

### ***Engineering (Bottom-Up) Analysis***

Many of the innovations cited above involve or enable the use of legacy, standardized, or commercial components and systems. Increased use of pre-existing systems should allow earlier acquisition of vendor price quotations or other equally specific cost estimates, reducing the need for parametric models to bridge the gap between analogy estimation and engineering analysis. This may be a method preferentially employed by space entrepreneurs, who tend to buy as much as possible off-the-shelf and avoid the time, cost, and risk of developing anything really new. Producing a trial design earlier in the design process could also enable earlier use of engineering analysis.

### ***Parametric Estimation***

Cost data on innovative spacecraft will accumulate over time and eventually enable increased use of parametric models. However, if relaxed mass limit engineering becomes common, mass may never again be useful as an independent variable for cost analysis. One alternative would be to develop activity- or function-based parameters instead. Activity based parameters might use numbers of parts, drawings, functions, processes, manufacturing steps, tests, or other countable features as cost drivers. This would be analogous to the function point method of software cost analysis. Combined with materials costs and time estimates, activity based parameters could produce an adequate alternative to mass based estimates.

## **ACTUAL PRACTICE**

The authors interviewed technical representatives familiar with innovative projects conducted by 6 successful aerospace companies, 4 of them relatively young and 2 of them well-established. These companies all use engineering cost estimation analysis as their primary method from the beginning of an innovative project, but some use other methods either before or after the engineering analysis.

Early use of engineering estimates was enabled by the engineering practices adopted by the innovators. All of the innovators used very conservative engineering, preferring to use proven components with quoted prices. The price quotes made up the core of the cost estimates. Specialty parts are avoided. Labor, materials, and launch made up the rest of the cost estimates.

The innovators preferred the highest possible readiness levels in all design choices to reduce both technical risk and costs. Innovation in the designs was used to meet critical requirements while increasing reliability and decreasing costs. Technological innovation was avoided unless it was critical for meeting requirements or reducing costs. For example, research at one company focuses almost exclusively on designing and building components to replace purchased components that are assessed as too costly.

Estimation by analogy was used in at least two cases either by the founders or their investors to justify the initial investments. The founders of one company had built small satellites and other small payloads for NASA and used that experience to create initial analogy cost estimates for their commercial satellites without doing a detailed cost analysis. The investors of another company also used analogy estimation to determine how much money to raise for their initial satellites.

Analogy estimation was also used in at least two cases as a sanity or reality test after the engineering estimates were produced. In one case, both analogy and parametric estimates were used as sanity tests on the engineering estimates. In all instances, the other two methods were subordinate to the engineering estimates.

In the experience of one of the companies, the engineering estimates tended to be lower than the sanity tests. This was expected because the parametric models used for the tests were built upon data from programs that did not take as much advantage of commercial commodity prices in the systems. The sanity tests caused concern only if the cost estimates exceeded the engineering estimates by more than 2 or 3 to 1. In those cases, the company double-checked their engineering analysis to make sure they had captured all the major systems elements and put the appropriate amount of margin on the estimates. For example, if it was a firm fixed price proposal from a supplier, they used a lower cost margin than if it was an analogy cost estimate.

Early use of engineering estimates has also been applied to launch vehicle development. Elon Musk and his team at SpaceX apparently rejected both analogy and parametric methods to estimate the cost of the Falcon launch vehicles. They determined that no prior launch vehicles were sufficiently similar for either method to work. Instead the SpaceX team used a bottom-up approach from the beginning, improving the estimates as engineering data accumulated and became more precise.

#### **CONCLUSION**

Innovative space companies share a common method for becoming commercially viable - using conservative engineering to reduce risks and costs. This method also enables the innovators to use engineering estimates from the beginning or near the beginning of a project. Early use of engineering estimates is also enabled by direct access to the needed cost data. Customers such as the Federal government do not often have the data needed to use the engineering method.

Government agencies are often handicapped in their use of engineering estimates early in the acquisition process both by a frequent intention to develop and use cutting edge technologies and by inadequate access to the needed component-level data. This puts the government in a difficult position as rapid innovation reduces the utility of parametric models. The government needs a third way.

Of the available possibilities, developing improved methods for analogy estimation is both the least expensive and the most promising. Improvement in analogy estimation seems to have been neglected in recent years and may therefore provide opportunities for breakthrough results.

Another possibility is for government agencies to gain access to engineering cost data or estimates based on engineering costs by the simple expedient of paying for them. Vendors could be contracted to produce engineering cost estimates on their own projects in advance of new procurements, while showing their work to the customer. In any case, government agencies will need to be as nimble and innovative as their vendors if they are to keep up with the new pace of development.

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