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ENGINEERING COST ANALYSIS - AN ADVANCED SPACE PROGRAM TECHNOLOGY COMING OF AGE

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ABSTRACT
Cost analysis can be an engineering tool when the proper data are available. This paper discusses what data are required and shows that the data are available and can be used to make design decisions.

INTRODUCTION
Cost reduction and avoidance activities have long been a part of system development programs through the use of value engineering, operations analysis, producibility and other related groups. While these are important and should not be disparaged, they generally cannot effect the kinds of savings which are potentially available through more and better cost trade-off analysis during earlier (definition) phases of a program.

In addition, congress and the public are no longer sympathetic to pleas of ignorance associated with large cost increases between estimates at the completion of a definition phase and actual development costs. Even without these public pressures, personal pride as managers requires renewed efforts to solve a problem which calls into question our ability to manage and/or our honesty - neither of which creates a desirable image.

Therefore an engineering cost analysis technology serves two functions: (1) provides the means whereby all design trades can be made on the basis of a program cost effect, and (2) holds the promise of a better estimate at the end of the definition phase.

The McDonnell Douglas Corporation (MDC) approach developing this new technology extends back over five years with a concentrated effort starting in mid-1968. It was recognized that the group needed to be composed of engineers who had been trained in cost analysis, and people have therefore been selected accordingly. Furthermore, this technology has been treated like any other in that in addition to a hard core cost analysis group, some short term study assignments have been used to train engineers who have returned to their primary technology, after having been exposed to cost analysis.

TECHNOLOGY DEVELOPMENT
Development of a technology is a slow evolutionary process that requires time for analysis techniques to be derived, applied, tested against the critical measure of history, refined, reapplied, etc.

QUALIFICATION TO TECHNOLOGICALLY "COME OF AGE"

* Subject to analytic investigation
* Proven analytic and empirical techniques
* Accepted as fundamental parameter in making decisions

WEBSTER: TECHNOLOGY - THE SCIENCE OF THE INDUSTRIAL ARTS

These tools are identified in Figure 2 along with some of the specific peculiarities of cost analysis. Experience is the backbone of a technology and the confidence in any analysis
depends in large part on a subjective "feel" based on past experience. To be meaningful however this past experience must be assembled in the form of a data bank, where parameters can be normalized for a true comparison. Cost analysis data banks should be bigger and better than any others but have been restricted because of the proprietary nature of most actual cost data plus differences in accounting procedures between corporations, that make normalization a very difficult task. It should be noted that the Fiscal Department of any company generally does have extensive cost data banks used in preparing formal bids but these are usually somewhat divorced from the needs and objectives of an engineering cost analysis technology. Only in recent years has the need for engineering cost data banks been addressed seriously.

Development of analytic and empirical techniques is directly dependent on the data bank and therefore is usually unique to each company or organization. These will reflect the particular corporation's business practices, subcontracting arrangements, contract peculiarities, etc. The test for the cost analyst comes in retrospect as he examines actual occurrence and tries to empirically adjust his techniques. The standard reporting of cost data is an area which has recently been addressed by NASA for the Shuttle Phase B studies and although this may not help industry in the construction of data banks it should help the government. A standard format for all hardware programs may or may not be feasible because of the unique requirements of each program, but the potential benefit in capability to build a data bank and estimate future programs is obvious.

The cost analysis technology has followed the same steps in development that are part of any new technology (Figure 3). The gross cost analysis was based on only weight and although it may have been a low confidence number, the trends indicated were generally valid and valuable. The gross analysis based on weight is still a necessary and valid approach for many situations. The confidence may be increased by including second order effects that have come from experience, but it has also increased simply with use and understanding of where and how to apply such data.

The hardest work has been in the research necessary to organize and normalize historical data. McDonnell Douglas has spent over 20,000 man-hours in the last few years in this type of research effort, in addition to various government contracts worth more than 20,000 man-hours. Continuous research is required to take advantage of data from new programs and improve the technology.

With the data organized, the cost analyst has a relatively simple task in deriving an analytical expression for predicting behavior, although even here he must examine the data from all sources and decide which are really the cost forcing design parameters. The more difficult task comes in application of the prediction technique because, as mentioned earlier, these techniques have built-in assumptions with respect to a corporations way of doing business, the governments requirements or policies, contractual peculiarities, advances in the state-of-the-art, etc. These are not subject to specific quantization but they are real affects and the confidence in the estimate lies largely in the ability of the analyst to assess the relative requirements between his data base and the program he is estimating.

With this background on the development of cost analysis as a technology, we will examine its specific application to a program. Two kinds of estimates are used: (1) a detailed estimate based on a specific vehicle definition, and (2) simplified estimates based on using trends indicated by a series of detailed estimates.

**DETAILED ESTIMATING TECHNIQUES**

Detailed estimates of manned spacecraft have been generated by McDonnell Douglas over a period of several years. These studies have covered a significant range of performance and design characteristics, all the way from a small ballistic entry vehicle up to complete boost stages with large amounts of entry cross-range maneuver capability. The cost estimates have been refined and extended as the vehicle definitions were refined. The format for the detailed estimate is shown in Figure 4; the estimate is usually made one level lower than that shown.

**FIGURE 3**

**STEPS IN DEVELOPMENT OF A TECHNOLOGY**

<table>
<thead>
<tr>
<th>Step</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gross Analyses - Low Confidence</td>
<td>Research, Test - Development of Historical Data</td>
</tr>
<tr>
<td>Derivation of Analytic Expressions for Predicting Behavior</td>
<td>Application and Refinement of Prediction Techniques</td>
</tr>
<tr>
<td>More Precise Analysis - Increased Confidence</td>
<td></td>
</tr>
</tbody>
</table>

**FIGURE 4**

**DETAILED ESTIMATE**

<table>
<thead>
<tr>
<th>Subsystem</th>
<th>Design</th>
<th>Test</th>
<th>Tooling</th>
<th>Production</th>
<th>Mat &amp; Subc</th>
</tr>
</thead>
<tbody>
<tr>
<td>Airframe Group</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Structure</td>
<td>XX.X</td>
<td>XX.X</td>
<td>XX.X</td>
<td>XX.X</td>
<td>XX.X</td>
</tr>
<tr>
<td>TPS</td>
<td>XX.X</td>
<td>XX.X</td>
<td>XX.X</td>
<td>XX.X</td>
<td>XX.X</td>
</tr>
<tr>
<td>Landing and Recovery</td>
<td>XX.X</td>
<td>XX.X</td>
<td>XX.X</td>
<td>XX.X</td>
<td>XX.X</td>
</tr>
<tr>
<td>Propulsion Group</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Main</td>
<td>XX.X</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ACPS</td>
<td>XX.X</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>OMS</td>
<td>XX.X</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cruise</td>
<td>XX.X</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>APU</td>
<td>XX.X</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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The "detailed" estimate for engineering cost analysis is generally still subject to primarily parametric techniques. This is in contrast to the fiscal estimate which may use some historical and parametric data but would usually also have man-hour and hardware estimates based on detailed task and parts descriptions. The typical cost element shown in Figure 4 is derived from an equation similar to the ones shown in Figure 5 for the structure production cost. This indicates that the production cost of the structure for the crew-section of a manned vehicle is a constant times the weight of the section raised to a power, times some complexity coefficients. A similar equation form is shown for a cargo/propulsion section of a vehicle. The cost for subsystems which would be purchased from vendors is based on parametric trends or vendor quotations, depending on the design depth and data available.

**FIGURE 5**

**TYPICAL COST ESTIMATING EQUATIONS**

**CREW SECTION COST**

\[ \text{Crew Section Cost} = 3950 (W_S) - 0.234 (W_S) (K_MC) + 0.40 \left( \frac{A_HD}{A_T} + 1 \right) \]

**CARGO/PROPULSION SECTION**

\[ \text{Cargo/Propulsion Section} = 2250 (W_S) - 0.234 (W_S) (K_MC) + 0.40 \left( \frac{A_HD}{A_T} + 1 \right) \]

WHERE

- \( W_S \) = WEIGHT OF STRUCTURE
- \( K_MC \) = MATERIAL COMPLEXITY FACTOR
- \( A_HD \) = AREA OF HATCHES, DOORS, AND WINDOWS
- \( A_T \) = TOTAL WETTED AREA

Some indication of the degree of vehicle definition required for the detailed estimate is indicated by Figure 6 which shows the cost spread which results from variations in several design parameters. Obviously a poorly defined vehicle would have a larger confidence band on the cost estimate. Many times in conducting trade studies, however, the detailed estimate has less real value and is more awkward to work with than some simplified estimating techniques and "rules of thumb." These are an important part of any technology and can be applied in cost analysis where very little definition is available and yet retain a high degree of confidence in the relative comparison of systems.

**FIGURE 6**

**THERMO/STRUCTURE COST - DESIGN CORRELATION**

<table>
<thead>
<tr>
<th>DESIGN PARAMETER</th>
<th>DESIGN COST SPREAD (W)</th>
<th>PRODUCTION COST SPREAD (W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>WEIGHT</td>
<td>0.485</td>
<td>0.706</td>
</tr>
<tr>
<td>APPLICATION (ADAPTER-EV)</td>
<td>1-4</td>
<td>1-3</td>
</tr>
<tr>
<td>CONFIGURATION COMPLEXITY</td>
<td>1-3</td>
<td>-</td>
</tr>
<tr>
<td>ENVIRONMENT</td>
<td>1-1.15</td>
<td>1-4.5 STR</td>
</tr>
<tr>
<td>TYPE CONSTRUCTION &amp; MATERIAL</td>
<td>-</td>
<td>1-20 THERMAL</td>
</tr>
<tr>
<td>ACCESS AREA</td>
<td>1-1.7</td>
<td>1-2.4</td>
</tr>
<tr>
<td>DENSITY</td>
<td>0.25</td>
<td>-</td>
</tr>
</tbody>
</table>

Simplified estimating techniques

Analyses over a period of several years indicated that fairly good correlation of total program cost could be achieved with vehicle dry weight as long as the vehicles were in the same "family." The family traits consist of such things as the general configuration characteristics and subsystem characteristics. Therefore detailed estimates were used as a basis to derive simplified equations for estimating cost on the basis of only dry weight. Furthermore, it was found that the adjustment for other "families" of vehicles was generally (although not always) a shift in the level of the cost equation rather than a change in the slope of cost with weight. Figure 7 shows examples of the kinds of correlations which were achieved. These data are for a large reusable spacecraft and cover a range of impulse velocity capabilities and thrust ranges. The largest error shown is less than 0.5% and the average is about 0.1%. Two vehicle "families" are represented by the selection of LH2 or JP-4 for air breathing engine propellant.

**FIGURE 7**

**WEIGHT CER’S**

This capability to estimate costs with a good degree of confidence based on minimal data provided the opportunity to derive the rules of thumb and simple trade factors for comparing design alternatives. McDonnell Douglas has a sizing model which can provide the vehicle characteristics associated with a given set of design and performance requirements. (An earlier version of this was coupled directly to the detailed cost model for complete sizing and costing information; see Reference 1.) These vehicle characteristics are based on scaling relationships which have been derived to approximate the detailed vehicle design characteristics. This sizing model was exercised over a wide range of vehicle characteristics to determine the dry weight and then the costs were determined based on the dry weight. Although many kinds of sensitivities can be-and have been derived, the easiest to apply is the sensitivity of cost to payload because payload is often the design parameter of most interest. An example of this is shown in Figure 8, where it can be seen that for a constant thrust-to-weight ratio at lift-off (T/W) the vehicle has a sensitivity of

12-35
$27,300/lb of payload. Note that a different family of vehicles with a T/M of 1.2 has the same sensitivity but a lower cost for any given payload. Figure 9 shows similar data for variations in staging velocity between the first and second stage.

FIGURE 9
STAGING VELOCITY COST RELATIONSHIP

FIGURE 10
COST GOALS - BOGEYS

The program goals were established by NASA and were $4.5B through the first manned orbital flight and $7.2B for the total program (Figure 10). More than 130 cost trades have been performed with some of the system trades showing cost differences of several hundred million dollars while some of the detailed subsystem trades have been concerned with only $3-$5M. In total, over $2B in cost reductions have been identified.

SYSTEM TRADE-OFFS
The typical system trade-off on the Shuttle Program is characterized by the question of whether or not to include air breathing engines on the orbiter vehicles. The factors which were considered were the vehicle performance characteristics, the design characteristics (weight, payload capability for
various missions, etc.), and the operational characteristics. Figure 11. The biggest effect was the potential reduction in the size of both the orbiter and booster that could be achieved by eliminating the weight of engines and the associated propellants. Since this is weight that goes into orbit it has essentially the same effect on the system as payload and the cost effect of the resizing can be determined by applying the cost sensitivity factor of $27,300/lb. This amounts to $465M as shown in Figure 12.

Cost is only one of several decision criteria for system trades however, and the manager is often still faced with placing a subjective value on things which cannot be quantized (such as no landing go-around). However, he does have an estimate of the cost associated with his decision.

SUBSYSTEM TRADE-OFFS

While not generally reflecting the same potential magnitude of program cost differential, subsystem trade-offs are just as important to a program not only because they do add up, but more because of a philosophy of analysis and approach that can be more significant than individual small savings. The subsystem trade generally is a comparison of two or more alternates, any of which can meet the design, performance, safety, or other requirements, Figure 13. In this case the decision can be strictly on the basis of cost. The type data required for this trade-off consists of (1) the design, development, procurement, and operations cost associated with the particular subsystem alternates, and (2) the impact of the alternate on other parts of the system such as variations in electrical power or propulsion requirements or a resizing to allow for weight changes.

Because of the relatively high dollar value associated with weight reductions, it is easy to equate least weight with least cost. However, this is not always a valid assumption when all factors are taken into consideration. The avionics system for the Shuttle as originally defined by McDonnell Douglas was a sophisticated lightweight system with new and innovative equipment employed to meet the extensive requirements for built-in-test and checkout, the requirements for guidance, communications, flight control, etc. An examination of existing equipment showed that much off-the-shelf hardware was applicable to the Shuttle requirements although there would be potential increases in power requirements, system weight, and environmental control provisions. The design development costs could be determined from descriptions of the systems with the modifications required, and the impact on other parts of the system was derived based on sensitivity data. The incremental cost for additional power and environment control was almost negligible. The additional weight resulted in a resizing cost of about $65M and the saving in the subsystem was over $400M for a net cost reduction of $350M (Figure 14).
ENGINEERING COST ANALYSIS TECHNOLOGY LIMITATIONS

Part of coming of age is a maturity to recognize that, as with any technology, there are some potential pitfalls of which to be aware, and some boundary conditions which must be observed (Figure 15).

FIGURE 15
LIMITATIONS

- REFLECTS CORPORATE PERSONALITY - IGNUHAT DIFFERENT FOR EACH COMPANY
- BUILT IN MANAGEMENT PHILOSOPHY
- NOT FORMAL BID

Unlike weight data where a pound is always a pound, a dollar is not always a dollar, or an engineering hour is not even always an engineering hour. The dollar changes because of inflationary factors and increased costs just to do the same job. The differences in accounting procedures between companies and between programs confuse engineering, testing, tooling, overhead, direct versus indirect, etc. to the point where careful definition is required when making comparisons.

The engineering cost analysis is not intended to supplant the formal bid estimating practices, and it is important that this be recognized by the government (NASA, DOD) or whatever group or agency may be using the information. Although the approach may be similar in many cases, the most value can be gained from the cost technology as a design tool.

CONCLUSIONS

Engineering cost analysis has been developing over a period of years to the point where it can be used as a design tool. All the tools of a technology are available and in use. These have been applied most recently to the Shuttle Program where billions of dollars of cost saving ideas have been examined. Sufficient data are available to apply to both system and subsystem trades. The limitations of the technology are known and if observed, cost can become a basic design parameter in all phases of program development.

REFERENCE

(1) Optimized Cost/Performance Design Methodology, NAS 2-5022, MDC Report E0004, dated 1 September 1969.