PARAMETRIC COST ANALYSIS: A DESIGN FUNCTION

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Parametric cost analysis uses equations to map measurable system attributes into cost. The measures of the system attributes are called metrics. The equations are called cost estimating relationships (CER's), and are obtained by the analysis of cost and technical metric data of products analogous to those to be estimated. Examples of system metrics include mass, power, failure_rate, mean_time_to_repair, energy _consumed, payload_to_orbit, pointing_accuracy, manufacturing_complexity, number_of_fasteners, and percent_of_electronics_weight.

The basic assumption is that a measurable relationship exists between system attributes and the cost of the system. If a function exists, the attributes are cost drivers. Candidates for metrics include system requirement metrics and engineering process metrics. Requirements are constraints on the engineering process. From optimization theory we know that any active constraint generates cost by not permitting full optimization of the objective. Thus, requirements are cost drivers. Engineering processes reflect a projection of the requirements onto the corporate culture, engineering technology, and system technology. Engineering processes are an indirect measure of the requirements and, hence, are cost drivers.

Many metrics are obvious. Mass and lines_of_code are measures of unit production effort. Number_of_production_units and number_of_prototypes are measures of program size. Technology is a function of time, so its effects may be measured through changes with time. For expendable launch vehicles the mass of the tankage is proportional to the tank volume. Thus tank _volume, energy_consumed, and fuel_energy _density are functionally related to mass, a measure of production effort. Other metrics are not so obvious.

Parametric analysis normalizes for the effect of metrics x_k.

$$c = e^{a_0} \prod_{i=1}^{r} e^{a_i x_i} \prod_{j=r+1}^{s} x_j^{a_j}$$

is a commonly used CER with associated linear form

$$\ln(c) = a_0 + \sum_{i=1}^{r} a_i \, x_i + \sum_{j=r+1}^{s} a_j \, \ln(x_j)$$

used with least squares to obtain the coefficients a_k.

   The exponential factors do an excellent job of normalizing cost for temporal effects such as inflation, technology escalation, and for binary categories and other abstract metrics. The power law factors do an excellent job of normalizing cost for economic quantities such as number_of_ production_units, lines_of_code, number_of _prototypes, kilograms_per_production_unit, and so on. The hybrid combination of these factors usually improves accuracy over the use of either separately. If we pre-normalize the data for inflation using an inflation table and define

$$q = a_0 + \sum_{i=1}^{r} a_i \, x_i \, ,$$

then

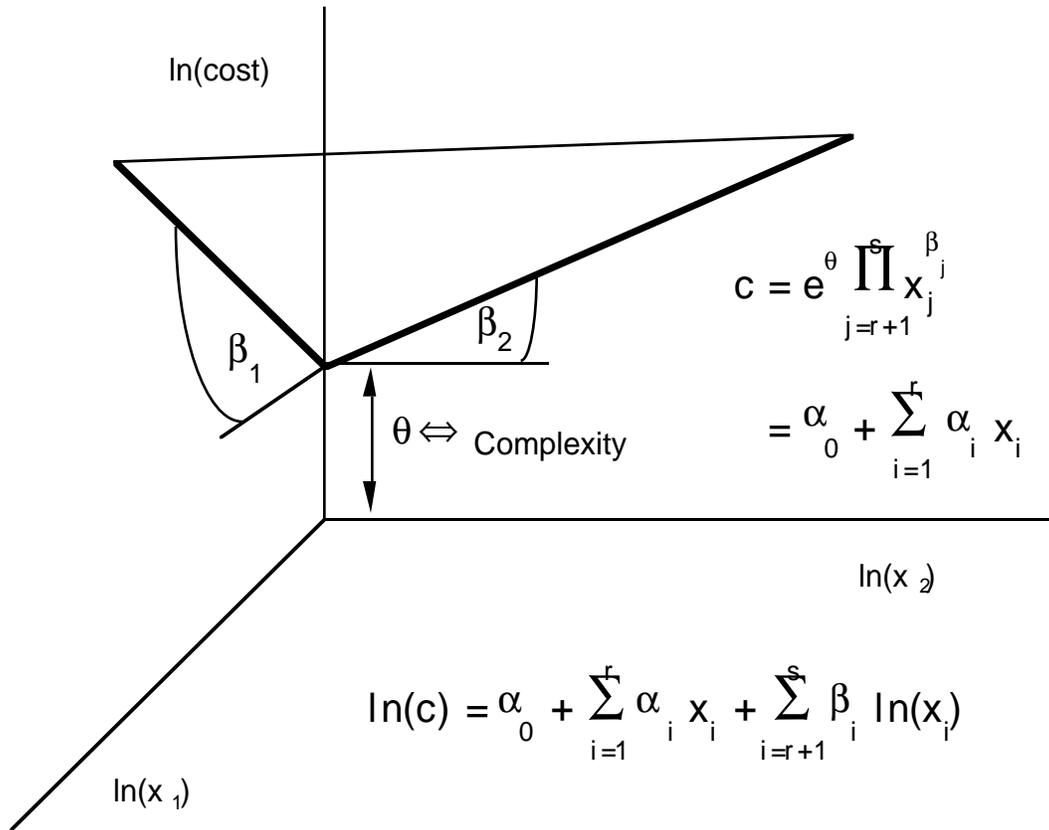$$\ln(c) = q + \sum_{j=r+1}^{s} a_j \, \ln(x_j),$$

or

$$c = e^q \prod_{j=r+1}^{s} x_j^{a_j}$$

expresses cost in a form in which technology escalation and the more abstract quantities adjust the unit economic quantity case up and down to establish the origin for the unnormalized economic quantities as in Figure 1. If x_1 = time then q is a measure of system complexity which includes the additive temporal effect of technology measured by $a_1 \, x_1$.

   This definition of system complexity is convenient since it is linear in its components. The component a_0 represents complexity arising from as yet undetermined complexity drivers. With a_1 measuring technology escalation, the remaining components could be chosen to represent binary characteristics of the system, such as whether the unit was to be used in a manned or unmanned spacecraft or whether recent software engineering techniques were used to develop the software.

FIGURE 1: COMPLEXITY AND ECONOMY OF SCALE

ln(cost)

$$c = e^{\theta} \prod_{j=r+1}^{s} x_j^{\beta_j}$$

$$= \alpha_0 + \sum_{i=1}^{r} \alpha_i\, x_i$$

$\theta \Leftrightarrow$ Complexity

β_1 β_2

$\ln(x_2)$

$$\ln(c) = \alpha_0 + \sum_{i=1}^{r} \alpha_i\, x_i + \sum_{i=r+1}^{s} \beta_i\, \ln(x_i)$$

$\ln(x_1)$

   This form also permits a simple relative analysis of cost for specific cost drivers. Suppose two systems had identical metric values except for MTBF = mean_time_between_failure. All other metrics being equal, either

$$r_m = e^{a_m}(MTBF_1 - MTBF_2)$$

or

$$r_m = \left(\frac{MTBF_1}{MTBF_2}\right)^{a_m},$$

whichever provides the least root_mean_square
_error over the data base, measures the relative cost factor due to reliability as measured by MTBF.

The property of normalization, in effect, increases the data base of the parametric analyst. When unofficially first asked how much the National Aerospace Plane would cost, I used this process to qualify a B1B bomber for the manned space environment and project it's technology to the initiation of operational capability. Within a half hour I had an unofficial estimate. I recently saw an estimate for a Mars rover vehicle which manned space qualified an army vehicle and projected its technology to the Mars landing date.

RISK ANALYSIS

When asked some years ago by a project manager to provide the exact cost of a project just beginning the conceptual design phase, I replied that I would do so if the project manager would first supply me an exact labor, material, and rate scenario over time which represented the final product configuration. The fact is, there is no single cost for a system until after completion. In all cases prior to completion, a range and distribution of final cost exists which corresponds to the many possible projects resulting from future decisions.

Dean, et al, 1986, developed a simple procedure for analyzing cost risk which is used extensively at the NASA Langley Research Center (LaRC). The premise is that the distribution of possible costs is defined by future project decisions. Although these decisions are not yet known, they are represented by best case, perceived case, and worst case parametric engineering process and configuration assumptions. For each work breakdown structure (WBS) element, the costs are derived by parametric analysis from the assumptions for that case. A program receives as inputs the three case costs from the output of three independent parametric cost estimates. Each of several hundred passes through this data provides a possible cost consisting of the sum of the possible costs for each element. The cost for each element is selected randomly from one of the three case costs for that element. The result is an approximation of the distribution of possible costs covering the cost range from very best case to very worst case.

Results are presented to management in the form of this distribution of possible costs with an expected value. The typical skew of this distribution toward the worst case cost provides an expected value which is usually considerably higher than the perceived cost. This phenomenon has also been observed by Mazzini, R.A., 1986. The expected value represents the net risk considering that some tasks will cost less than perceived and some more than perceived. The typically observed ratio of the expected cost to perceived cost for a project is about the same ratio as the average NASA cost overrun based on actuals.

THE COST ESTIMATING PROCESS

There is a fundamental process which underlies any cost estimate to provide the basis for credibility.

First, the estimator must understand the system to be estimated. What functions must the system perform? What are the operations and support requirements? What are the environmental requirements of the system? What are the major subsystems? What technologies are employed by each subsystem and assembly? What are the system and subsystem reliability, maintainability, availability, and safety requirements?

Next, the estimator must understand the programmatics of the system to be estimated. When is development supposed to begin? When is the first production article to be completed? How many prototypes, test articles, production items, and spares will there

be? When is the envisioned initial operating capability? What and when are the system review points?

Next, the estimator must establish the system estimating work breakdown structure (WBS). What are the system deliverables? At what level of the WBS are items found for which comparable cost data are available?

Next, the estimator must obtain comparable or analogous cost data for each WBS element at which cost is estimated and normalize for known differences such as material, quantity, quality, operational environment, or performance.

Next, the estimator must interview project personnel to obtain system parameters and risk factors. How much design has already been accomplished? What are the materials and their relative percentages? What is the percentage of electronics by weight? How much is each subsystem pushing the state-of-the-art? What could possibly go wrong in design, test and evaluation, production, operations, and support?

Next, the estimator must perform a technology projection. What will the technology candidates be for each subsystem at design freeze? What technology is most likely to be used? What are the potential cost effects of each of the candidate technologies? If technology candidates are unspecified, what is the rate of cost escalation for comparable past technologies?

Next, the estimator must obtain feedback from project personnel on the validity of system parameters used to build the cost model. Did I understand correctly that you said ...? Is ... technology really a candidate for the ... subsystem? Is ... really a safety risk?

Next, the estimator must iteratively generate cost estimates from system parameters until all input parameters are representative of the project as perceived by the project and estimating personnel.

Next, the estimator must perform a risk analysis which should indicate a measure of cost risk based upon the degree of engineering definition available. What are the relatively high risk subsystems? What are the reasons for that risk?

Next, the estimator must undergo a systematic peer review. Does the model and its inputs properly describe the system? Have the model results been properly reported?

Next, the estimator must document the cost estimate, the cost model, the cost model inputs, the cost model outputs, and the supporting analysis. What is the distribution of possible project costs? What models and modeling techniques were used? What are the project assumptions for the best, perceived, and worst cases for the risk analysis?

Finally, the results must be presented to the proper authorities and *successfully defended* .

THE ESTIMATING ENVIRONMENT

At NASA LaRC, the Vehicle Analysis Branch (VAB) has the responsibility for analyzing future space transportation systems. The Cost Estimating Office (CEO), among other duties, estimates the cost of each VAB configuration. One or more members of the CEO is a member of each conceptual design team. The VAB team members generate the configuration and, in interview with the CEO, provide the technical system metrics required

by the CEO. The CEO generates the cost estimate and, in interview with the VAB, provides an expected cost, an optimum schedule, a cost risk distribution, and an analysis of the cost drivers. A very important feedback loop between cost and configuration now exists which permits the VAB to alter configurations based upon an analysis of cost and schedule.

An early realization that the cost estimating tools and techniques were inadequate to provide requested information led to a very important quest for understanding. As is always true for large budget products, it is very important to have a credible project cost estimate. However, with the cost/configuration loop, it became equally important to have a credible understanding of <u>why</u> the project costs that much and <u>how</u> it might be reconfigured to save cost. That was the information being requested! A large mental, cost technology, and technical leap was required between estimating "the cost" and participating as an integral member of a highly qualified advanced space transportation system design team.

NASA has developed a scale of technology readiness which is defined as follows:

Level 0:   Basic principles not yet observed or reported.

Level 1:   Basic principles observed and reported.

Level 2:   Conceptual design formulated.

Level 3:   Conceptual design tested analytically or experimentally.

Level 4:   Critical function/characteristic demonstration.

Level 5:   Component/breadboard tested in relevant environment.

Level 6:   Prototype/engineering model tested in relevant environment.

Level 7:   Engineering model tested in space.

Level 8:   Full operational capability.

Because it is closely related to engineering difficulty, it is exceptionally useful for discussing and quantifying technology readiness.

Since the proposed initial_operating_capability _date for NASA systems being studied at LaRC ranges from as early as 1995 to beyond 2030, the proposed configurations contain much technology that is highly immature. Some structural technology borders on being made with "unobtainium," a level 0 material, with an occasional level 8 Shuttle type construction. The control technology ranges between levels 2 and 4. The propulsion is between levels 2 and 8. The software ranges between levels 1 and 4. The system health monitoring ranges between levels 1 and 4. The operations and support range between levels 1 and 8. Naturally, the further out the projected initial_operating_capability_date, the lower the technology level index.

The wide range of technology choices yet to be made is <u>the</u> major cost risk driver in all of these studies. This often results in a wide range of technical metric values between the best and worst cases. The cost uncertainty index

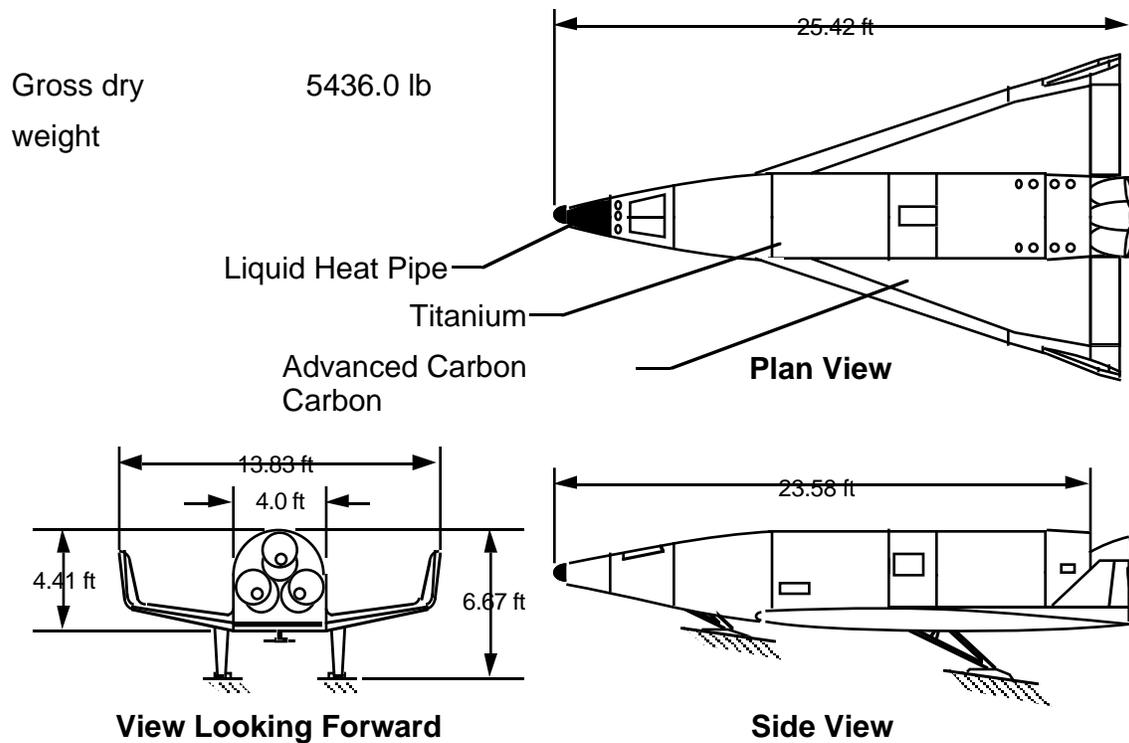$$u = \frac{worst\_case\_cost}{best\_case\_cost}$$

is an indicator of engineering definition maturity. The second major cost risk driver is the uncertainty associated with the calibration data.

For the projects discussed in this paper the primary hardware development and production estimating model was PRICE H (Anon., 1988a). The primary software estimating model was PRICE S (Anon., 1988b). The life cycle and risk analysis models were developed by the CEO. Various NASA and Air Force models were used for calibration.

ENTRY RESEARCH VEHICLE

The Entry Research Vehicle (ERV), shown in Figure 2, was proposed as an experiment to be carried into space in the Shuttle payload bay, released in orbit, deorbited, and reenter the atmosphere. Virtually each component of the spacecraft was an experiment to test some new material or concept. The nosecap was a liquid heat pipe which, because of its conical shape, was deemed by some to be impossible to develop, i.e., level 0 technology. With the exception of a level 8 propulsion system adopted from Shuttle, most other technologies were between levels 1 and 4.

FIGURE 2: THE ENTRY RESEARCH VEHICLE

Gross dry weight   5436.0 lb

Liquid Heat Pipe

Titanium

Advanced Carbon Carbon

Plan View

13.83 ft
4.0 ft
4.41 ft
6.67 ft

View Looking Forward

25.42 ft

23.58 ft

Side View

Because it was the first major estimate for the estimator who had no previous aerospace background, a considerable amount of time was spent in understanding the system and

learning the tools and techniques required to perform this estimate. The VAB arranged special meetings with the primary purpose of educating CEO personnel. Additional time was spent developing and fine tuning the LaRC estimating process. This estimate, see Moore, A.M., Bogart, E.H., and Dean, E.B., 1987, produced two major outputs: a credible cost estimate for ERV and, even more important, a credible estimating process for LaRC.

The cost estimate, including cost risk, was successfully presented to NASA Headquarters by the estimator.

CREW EMERGENCY RETURN VEHICLE

The Crew Emergency Return Vehicle (CERV) is shown in Figure 3. CERV is a space vehicle which remains attached to the space station Freedom to provide emergency return of astronauts to Earth. Three configurations have been in competition, a ballistic capsule sponsored by the Johnson Space Center (JSC), an Apollo-like capsule sponsored by JSC, and a lifting body sponsored by LaRC.

The CERV Project Office at JSC requested a workshop to compare the three vehicles from both a technical and cost viewpoint. Nine different requirements were established and each vehicle was designed to meet those requirements. Requirements one through three were combined to generate another configuration for comparison. A water landing version called the Assured Crew Return Craft (ACRC) was also established to make a direct comparison between lifting body and non-lifting body technologies by removing the runway landing variable associated with the lifting body.

FIGURE 3: THE CREW EMERGENCY RETURN VEHICLE
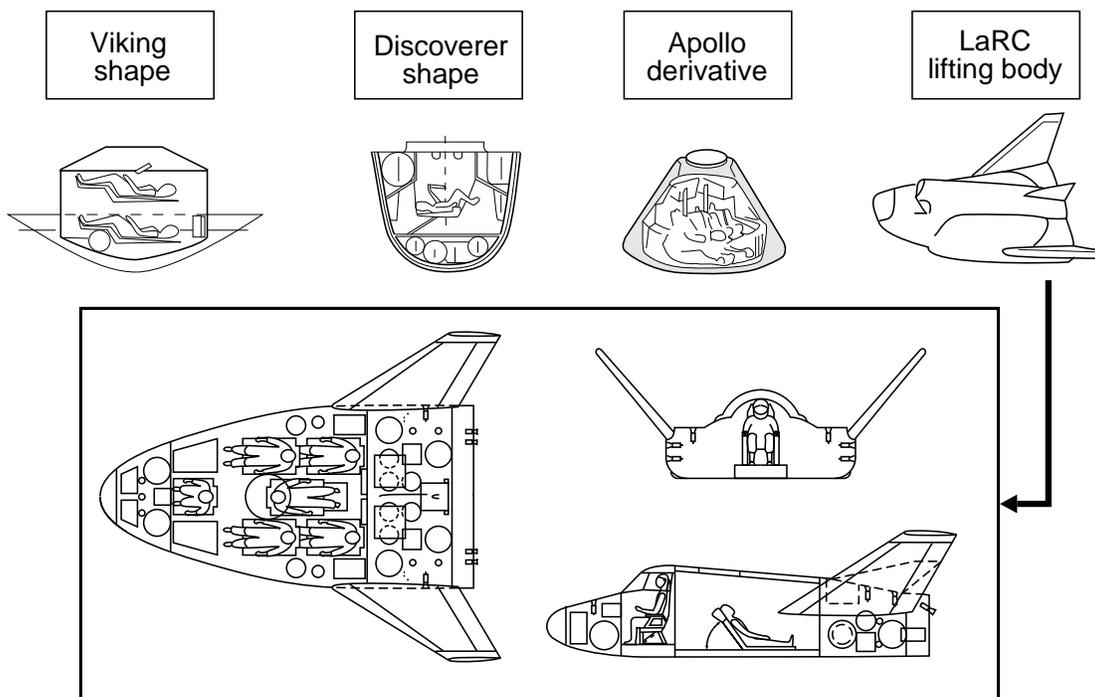
Over a two month period, each configuration was designed and costed. The cost risk distributions were overlaid as in Figure 4. Clearly, the risk of the project itself was dominant over the risk inherent in any single configuration. With the exception of two configurations, the configuration choice should be made on requirements, not cost.
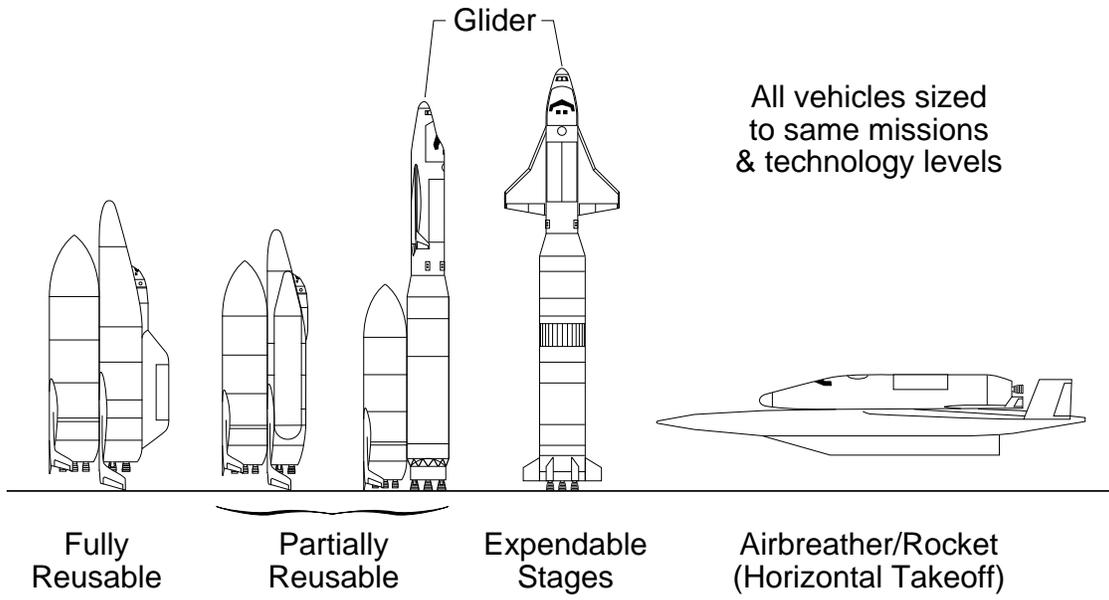
FIGURE 4: CERV COST RISK FAMILY
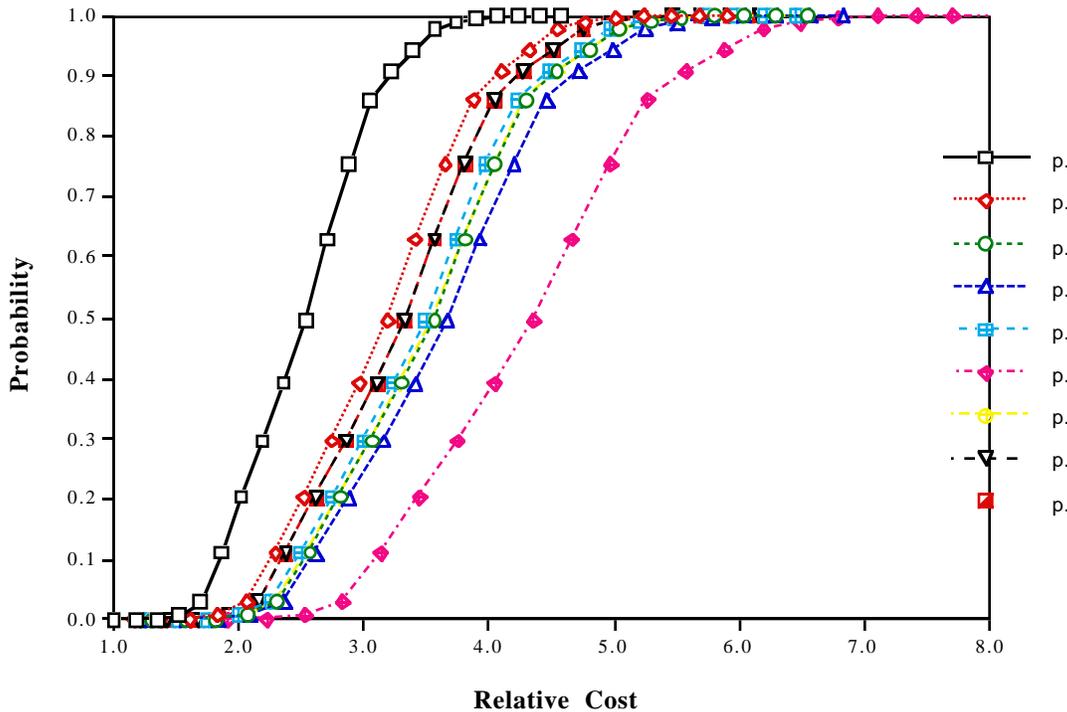
The workshop at JSC consisted of sessions to reconcile technical and cost assumptions. From the cost viewpoint, it was recognized early that the LaRC and JSC cost estimating methodologies were extremely different and most of the workshop was spent reconciling those differences. Since JSC did not perform a risk analysis, considerable time was spent removing risk to provide a single point perceived estimate for comparison. At the conclusion, all agreed that the lifting body was only slightly more costly than the other versions. However, since one of the parties had not performed a risk analysis, that decision was made without the extra perception provided by risk.

After the workshop the resolution of the tradeoffs was left to CERV and NASA management. Whatever the final decision, cost has played an important role in the design and decision process.

ADVANCED MANNED LAUNCH SYSTEM

Recent configurations of the Advanced Manned Launch System (AMLS) are shown in Figure 5. The AMLS is a high priority manned vehicle for satellite servicing and up-payload/down-payload to and from space station Freedom. At the NASA steering committee kickoff meeting a viewgraph stated that "Cost is a key design parameter." The Chair's prompt restatement was that "Cost is the key design parameter."

FIGURE 5: THE ADVANCED MANNED LAUNCH SYSTEM

Glider

All vehicles sized
to same missions
& technology levels

Fully
Reusable

Partially
Reusable

Expendable
Stages

Airbreather/Rocket
(Horizontal Takeoff)

technology for technology's sake. Examine the economic effects of each major design issue. Increase tolerances as much as possible. Reduce the number of pieces. Do not trade structure for relatively expensive electronics. For low production items, do not trade the economy of scale of hardware for the dis-economy of scale of software. Buy spares, don't cannibalize. Relax performance requirements. Do whatever is necessary to economically increase system reliability and quality. In general, avoid complexity.

After a number of tradeoffs of different vehicles to place the same payload in orbit over time, it became evident that the cost did not seem to vary greatly even though substantially different technologies were used. A graph demonstrated that for each technology there was a minimum vehicle dry mass required to place a zero payload in orbit. This graph also demonstrated that the vehicle dry mass was a linear function of payload mass. Repeated observations led to the hypothesis that the energy required to obtain orbit was the primary cost driver. Also the architecture of the system, i.e., how the overall system is structured, is a large but secondary cost driver. The technology differences fine-tuned the energy dominated complexity. The very humbling current hypothesis is that the energy demands to accomplish the task fix the technology levels and the system structure so that we have some, but only slight, capability to adjust and still meet requirements.

The more leisurely period of assessing progress has come and gone again with the renewed analysis of additional configurations. The design team recently designed, sized, and estimated the cost of an expendable rocket launch vehicle with a return glider, a partially reusable rocket powered vehicle with an expendable core and a reusable propulsion/avionics module, and a fully reusable two stage rocket powered vehicle; each at four different payloads. The cost estimates and subsequent analysis provided surprising and sometimes counterintuitive results.

The lessons learned on the last round of configurations are currently being applied by the design team to a number of new configurations. The design and sizing of the new configurations is in process. The search has been renewed for cost and related technical data for more specific system functions, hopefully, to provide a better cost estimate and analysis for the new configurations. The design process continues for both the technical and cost members of the design team.

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