Appendixes

Appendix A
Cost-Estimating Relationships

This appendix contains a brief summary of current cost estimation methods to illustrate the uncertainty and subjectivity involved. Methods used in the Space Transportation Architecture Study (STAS) are typical and are used as examples for the general discussion. The second half of this appendix presents three examples from STAS. One illustrates the derivation of a cost-estimating relationship for vehicle structures; l the other two illustrate estimated labor cost savings achievable by developing and applying automation technology.

A Summary of Cost Estimating Relationships Used in STAS

Ground Rules and Assumptions

A cost estimation effort such as undertaken in STAS must begin by making basic assumptions; those made by the sponsor of the analysis are included in stated ground rules, which also specify what the system must do. For example, STAS specified a matrix of possible mission models and required: 1) design and cost estimates of a minimum of two independent vehicles, with no major subsystems in common, including launch, orbital transfer, and return of specific high-priority payloads "to provide assured access"; and 2) design of facilities and equipment allowing a surge factor of 40 percent over the nominal launch rate.

Parametric Cost Estimation: When, as in STAS, systems are to be designed for economy, designers do not know optimal values of system parameters such as size and weight at the outset. The costs of vehicles or vehicle subsystems are therefore estimated parametrically; in other words, they are expressed as formulas called cost-estimating relationships, or CERS, which may be used to calculate estimated cost in terms of parameters such as weight.

A CER for a vehicle may be derived in a "bottom-up" manner by designing several launch vehicles that are similar except in size, and, for each vehicle, adding up the estimated costs of the subsystems and labor required. The costs of the subsystems maybe estimated in a similar manner by designing them and adding up the estimated costs of the parts and labor required to build them, etc. This approach is labor-intensive, because it requires preliminary design of a vehicle.

Alternatively, a CER may be derived by fitting a curve to a "scatter plot" of the weights and inflation-adjusted costs of similar vehicles that have actually been built.[2] The most common procedure is a combination of these approaches: designers develop a preliminary design for a vehicle in only enough detail to estimate the weights of its major subsystems in terms of the vehicle weight or its payload capacity. CERS for the subsystems are then derived by extrapolation and interpolation from historic data, if they are available.

Individual CERS are derived for development costs and for the cost of producing the first unit. Incremental costs of additional units are assumed to be lower than the cost of producing the first unit by a factor that depends upon the number of units produced (learning effect) and the production rate (rate effect). CERS for labor costs of ground operations are derived in a similar manner.

Manifesting and Optimization

After CERS for vehicles, facilities, and operations have been developed, manifesting and optimization programs are employed to determine the most economical types and sizes of vehicles for the mission model. First, a trial mix of vehicles is assumed. A size is assumed for each vehicle, and its cost is estimated from the CERS. Then a manifesting program is run to determine the least costly way of combining (co-manifesting) payloads on vehicles so they reach their operational orbits in the specified year, taking into account any restrictions on co-manifesting for security and safety. The launch rates in the resulting manifest determine the operations costs, and the maximum launch rate, inflated by 40 percent to provide a surge capability, determines the number of facilities required for processing and launch. Costs of development, facilities, vehicle production, and operations are discounted and totalled to obtain a projected present value of life-cycle cost. The process is repeated assuming different vehicle mixes, sizes, and technologies, and different ground operations and mission control technologies, to determine the most economic architecture and technology content.

[1] In STAS, costs of expendable hardware and spare reusable hardware are included in operations costs.

[2] For a comprehensive published description of this approach, see D.E. Koelle, "Cost Model for Space Transportation Systems Development, Fabrication and Operations" (Ottobrunn, FRG: Messerschmitt-Boelkow-Blohm GmbH, Bericht Nr. TN-RX1-328 B, 1983).

Estimation of Risk of Greater-Than-Expected Cost

STAS contractors estimated cost risk subjectively at the level of the vehicle systems mix, not in a bottom-up manner. The estimated risk, expressed as a cost, was given as percent weight in the overall score used to screen system mixes, as specified by stud~ ground rules. Those who estimated the risk may halve been unfamiliar with cost risks apparent to subsystem experts. Moreover, cost risk was estimated *assuming* ground rules were met; risk that ground rules will not be met increases cost risk.

Cost Estimation Examples

Example 1: Parametric Estimation of Vehicle Structure Cost

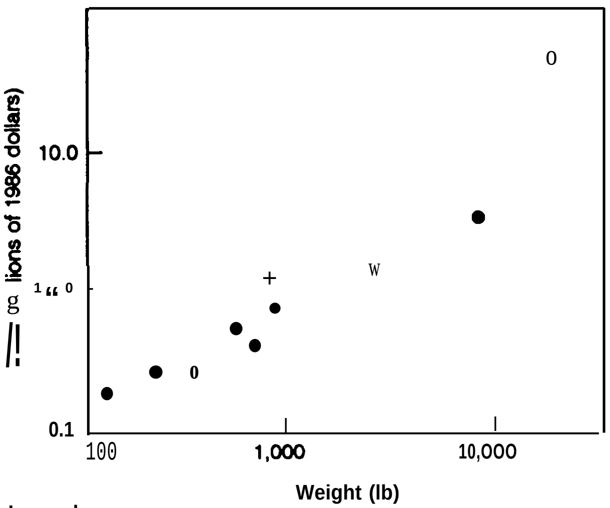
To derive a CER for the cost of vehicle structures (e.g., inter-stage adapters), one contractor began by plotting the weights and inflation-adjusted costs of vehicle structures it had built previously.[3] The resulting scatter plot is shown in figure A-1.

[3] Such data are often proprietary, which makes valid comparisons with CER's derived by other manufacturers very difficult.

The contractor observed that the costs of the structures rated for human use-especially the reusable one, were significantly higher in proportion to their weights than were the costs of the expendable structures not rated for humans. It therefore decided to derive a basic CER for unpiloted expendable structures and*assume* that the greater costs of crew-rating and reusability could be represented by "complexity factors" by which the basic cost should be multiplied. The basic CER is represented by a straight solid line in figure A-1, and complexity factors for crew-rating and reusability y are represented by arrows from this line up to the data points for the crew-rated systems. Figure A-2 was derived from three assumptions: 1) that design for reusability increases cost by a factor independent of structure weight, or 2) rating for human use, and 3) that the complexity factor for rating for human use is independent of structure weight.

Critique: The contractor could verify assumption (3) by comparison with a commercially available CER, presumably derived from different data and independent assumptions; the contractor found good agreement, but this does not imply that the assumption would be correct in all cases. Assumptions 1 and 2 were neither supported nor contradicted by the limited data available to the contractor; they are educated guesses—the best the contractor could do under the circumstances. Although they are not clearly incorrect, their accuracy is unknownj and the contractor pre-

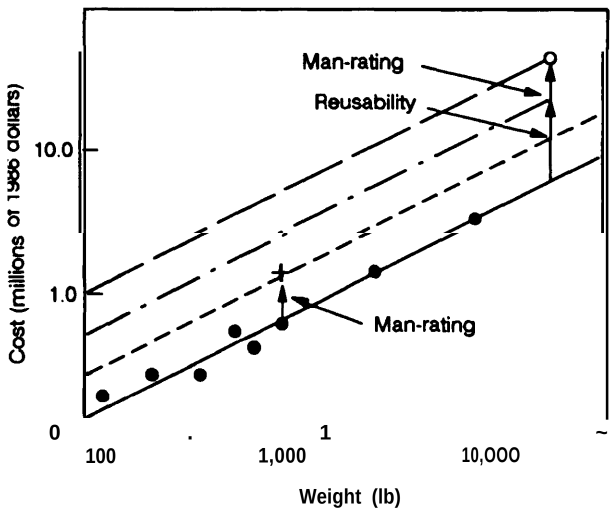
Figure A-l. - Historical Costs and Weights of Vehicle St-n=



Legend:
● non-man-rated expendable
+ mm-rated expendable
O man-rated reusable

SOURCE: Office of Techno@y Assesament, 19W

Figure A-2.-Coat-Estimating Relationships (CERS) for Vehicie Structures (first-unit production costs)



Legend:
— non-man-rated expendable

SOURCE: Office of Technology Assessment, 1988 sented no estimates of uncertainty in the complexity factors. If the contractor or a Government agency had access to proprietary data of other contractors on expendable structures rated for humans, there might be enough data points to test assumptions 1 and 2, although the variety of vehicles built to date maybe inadequate to accept or reject the assumptions with high confidence.

Example 2: Savings From Automating Ground Operations

This example and example 3 summarize the procedures a different STAS contractor employed to estimate potential savings from automating ground operations and mission control functions.

To estimate savings from automating ground operations, the contractor first calculated the labor required to perform functions such as refurbishing avionics using current methods based on estimates of labor required to perform similar functions on existing vehicles, and adjusted to reflect the fact that a new vehicle would have different needs. For example, a flyback booster would require a more robust thermal protection system than the Shuttle orbiter and would not require refurbishment. A percentage reduction in labor for each such function was then estimated for each new technology proposed (e.g., automated test & inspection). This reduction was assumed to be achieved by decreasing the crew size and the number of shifts by equal percentages; the reduction in processing time (number of shifts) allowed the required number of vehicles per year to be processed with fewer facilities, thus saving costs and lead time as well as direct labor costs for new facilities. From these savings was subtracted the costs of developing the new technology required and applying it; these costs "were estimated based on the costs associated with similar programs, including the costs of developing the STS Launch Processing System."

Critique: The relevance of such costs as a basis for extrapolation could be questioned, because comparable automation was not developed for the STS Launch Processing System.

Example 3: Savings From Automating Mission Control

To estimate savings from automating mission control, the contractor first estimated the recurring and non-recurring costs of performing five mission control functions (flight planning, simulation and training, payload integration, data load preparation, and flight control) using current technology. The costs of performing these functions in 1995, using 1990 technology, and in 2000, using 1995 technology, were also estimated; in general, the recurring costs were lower while the non-recurring costs were higher. At the high launch rates assumed, the life-cycle costs were lowered by assuming use of the new technology, when available. The fractions of net savings (cost reduction minus cost of technology development) for each function attributable to each new technology and to improved management were then allocated according to a formula, e.g., 40 percent of net savings on flight planning was attributed to use of expert systems. Technology development funding requirements were listed by year, although the contractor's reports do not make clear the basis for their derivation.

Critique: The costs of developing "ordinary" software have proven difficult to estimate accurately, even a posteriori, when the size of the program (on which some estimates are based) is known.[4] The accuracy with which existing methods can estimate costs of developing software such as expert systems is not known.

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[4]Chris F. Kemerer, "An Empirical Validation of Software Cost Estimation Models," *Communications of the Association for Computing Machinery*, vol. 30, No. 5, May 1987, pp. 416-429.