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AN INTEGRATED APPROACH TO THE STRUCTURING OF A COST MODEL

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Design decisions commonly are made today without consideration of their total economic implications. Resource requirements covering the entire life cycle of a system -- that is, from development through manufacture and operations -- frequently are treated on a fragmentary basis. Total systems costing techniques are applied too late to be included in the optimization of engineering design.

Construction of a systems cost model can provide critically important data for the engineering development effort and, furthermore, serve as the framework for coordination of the entire study. A procedural approach for construction of an integrated model is outlined in this presentation. Emphasis is on an integrated approach rather than on full details of the methodology.

The method of presentation is a case example, viz., the use of airships for the transportation of outsize commodities. The requirement which gave rise to the need for development of a cost model is reviewed at the outset.

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STATEMENT OF THE REQUIREMENT

A requirement for a method of transporting outsize objects, free from the constraints imposed by road limitations and the necessity for locating facilities on bodies of water, exists in both the Department of Defense and in NASA (Chart I). The airship offers certain characteristics which promise to fulfill these requirements.

Chart I

THE PROBLEM

- o Need for a method of transporting outsize objects, free from constraints imposed by bridges, tunnels, and underpasses in Department of Defense and NASA.
- o Potential of rigid airship in fulfilling this need.

NASA, for example, presently utilizes barges for the shipment of large launch vehicles by water. However, many facilities, such as the government test site at Jackass Flats (Nevada), are inaccessible by water. Even an attempt to locate all manufacturing facilities and launching pads adjacent to seaways would not totally solve the problem. Any gap, whether it be three miles or 3000 miles, portends an impasse.

Some other possible American applications for a means of transporting outsize items may be usefully noted. Examples of heavy industrial, construction, and military equipment and facilities which could be moved include fabricated building sections, pre-assembled bridge and tower sections, earth-moving machinery, industrial generators and transformers, storage tanks, radomes, and field hospitals, to name but a few possibilities. The airship could also serve as a recovery vehicle for Gemini and Apollo capsules. Many types of machinery and structural elements might be better supplied in an assembled state if an economical means of transport were available, since transportation expenses currently often approach or exceed manufacturing and assembly costs.

It is possible that the airship can uniquely fulfill the need for transport of outsize cargo, since its load-carrying potential, in both weight and dimensions, exceeds any other kind of transportation with the exception of ocean-going vessels. Airships capable of carrying 60 tons of cargo were being built as far back as the 1930's.

In Russia, an Izvestia news report in 1962 emphasized the advantages of the great lifting capacity and radius of action of the airship. Considered equally important by a Soviet study group is its economy of operation. An example identified was the possible movement of 50-ton turbines from factories in European Russia to hydro-electric remote sites in Siberia.

The Soviet report further stated:

> If we take as unity the cost of transporting one ton over one kilometer by airplane, then the figure for its transport by helicopter is 5.65, but its transport by airship is only 0.33. And this is without allowing for the fact that an airship does not require an aerodrome and can be kept almost continuously in service, because its maintenance and running repairs can be carried out while it is flying.*

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*See L. S. Hill, American and Soviet Interest in Airships, RM-3698-PR, The RAND Corporation, June 27, 1963.

OBJECTIVES OF STUDY

Because of a continuing concern with economy in national defense, it is important that consideration be given to the possible use of airships as an economical means for performing certain defense missions. This presentation is a description of a cost model which can be developed to aid in an analysis of potential defense and space applications of such a vehicle for this specific application. Detail of the model has been significantly condensed (Chart II).

Chart II

OBJECTIVES OF STUDY

- To collect and synthesize economic data for rigid airships.
- To develop a cost model, based on design criteria, for computation of initial and annual operating costs.

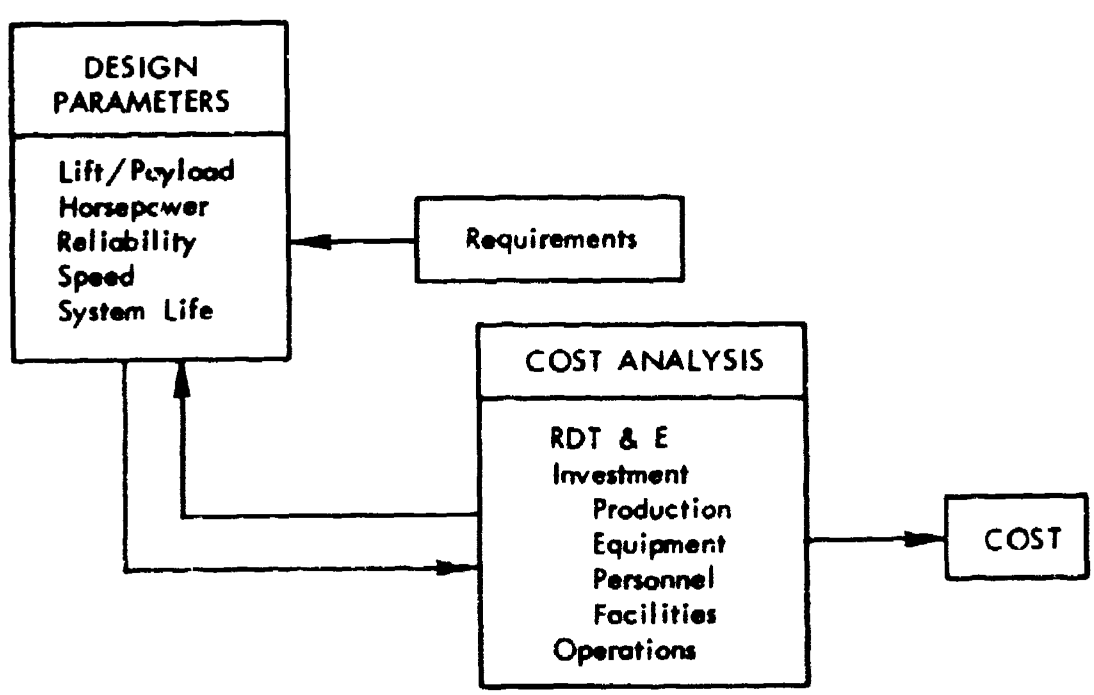
There are two types of airships: those with a rigid structure, the dirigible, and those with a non-rigid structure, commonly referred to as blimps. No comprehensive body of cost data on the construction and operation of a fleet of modern rigid airships is directly available, because operational use of the dirigible was discontinued about 25 years ago.

The cost study of the type described here has as its initial requirement the compilation of whatever cost data are available on rigid airships, and the translation of the data through appropriate analysis into a form usable for computation of development, investment, and operating costs for a fleet of modern airships. Necessary updating would be dependent on translation of the effects of new materials, propulsion techniques, and logistics concepts on costs and on adjustment of the dollar data to current price levels. In many instances, cost estimates would have to be computed through the use of relationships derived and adapted from non-rigid airship operations which were continued until recently.

Chart III is a considerably abbreviated flow chart of the procedural approach to be utilized in the study. This illustration reveals the relationships between the basic design performance variables and cost considerations.

Chart III

ABRIDGED OPERATION FLOW CHART



DEVELOPMENT, USES, AND LIMITATIONS OF THE MODEL

Appropriate preliminary design parameters, for airships with varied transport missions, would be derived from aerodynamic formulae. Chart IV presents certain summary equations for use in determination of preliminary sizing and performance estimates. In designing a rigid airship, a concept of airship capacity for carrying a specified load is a prerequisite. This necessitates a series of preliminary calculations as to required speed, horsepower, endurance, and size.

For example, Equation (1) may be used to compute the displacement of an airship for a given payload. The first order estimate might very well be based on known data from a past airship -- perhaps the Graf Zeppelin. For example, the ratio of structural weight to displacement, "S," for that airship may be available from historical records. Incorporating any necessary scaling adjustments and a weight reduction factor for use of modern materials, this ratio may be estimated as, say, 0.25 in Equation (1). The estimated ratio of crew, ballast, and stores, "C," may also preliminarily be predicated on historical data for an analogous use of an airship. Air and gas weights would be obtained from tables and the data used to estimate "G" in the equation.

The displacement, "D," having been estimated, the attendant horsepower and speed may be ascertained through Equations (2) and (3). In addition to the types of equations shown in Chart IV, the engineering designer, of course, must also take into account numerous other considerations, for example, structural integrity and gust load factors. The complexity in design is due in part to the fact that all these considerations are highly interrelated.

Chart IV

DESIGN CONSIDERATIONS

Displacement

Functional Form

$D = f\ (P, S, C, G)$

Structural Form

$$D = \frac{P}{1 - (S + C + G)} \qquad (1)$$

Where

D = sea level standard air displacement (in lb),

P = weight of payload and power group (in lb),

S = ratio of structural weight to displacement,

C = ratio of crew, ballast, and stores to displacement,

G = ratio of air + helium to displacement.

Horsepower and Speed

Functional Forms

$HP = f\ (D, \rho, Q, K)$

$Q = f\ (HP, K, \rho, V)$

Structural Forms

$$HP = \frac{D^{2/3}\ \rho\, Q^3}{99\ K} \qquad Q = \left[\frac{(HP)\ (550)\ (K)}{\rho\, V^{2/3}}\right]^{1/3} \qquad (2), (3)$$

Where

HP = horsepower,

Q = speed (ft/sec),

V = air volume of airship (cu ft),

D = sea level standard air displacement (lb),

ρ = density of air (slugs per cu ft),

K = non-dimensional coefficient combining propeller efficiency and airship configuration.

Source: C. P. Burgess, Airship Design, The Ronald Press Company, 1927.

The cost analyst must have a comprehensive knowledge of vehicle characteristics and system requirements as developed by the designers; and it is equally important that the designers be apprised of the system cost implications of their technical decisions. Suppose that different structural weight or crew size estimates were assumed by the designers and cost analysts. The implications of differences in such assumptions could be highly significant. Differing structural or crew weights would affect the displacement of the airship which in turn might influence horsepower requirements. The chain reaction could continue, since fuel requirements and endurance might be affected, and so on. Thus, close coordination must exist between the preliminary designers and the cost analysts. The example given above is not meant to imply that a design is necessarily highly sensitive to all cost assumptions. However, it is important to test for such sensitivity.*

A cost model serves as a framework for the cost information available on the system. It should be recognized, though, that actual costs of an advanced system seldom coincide precisely with estimates because of uncertainties which are prevalent in most long-range planning problems. It should be remembered that the model is composed of elements each of which represents further detail with its associated uncertainties. The model is predicated on assumptions which should be made explicit, and it must be tractable enough to allow for changes in such assumptions. The model is a method of developing a meaningful set of relationships among the variables. It should be a workable tool for substituting alternate estimates at any stage in the process.

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*See, for example, F. S. Pardee, Weapon System Cost Sensitivity Analysis as an Aid in Determining Economic Resource Impact, P-2021, The RAND Corporation, June 15, 1960.

Chart V presents an aggregated cost model for the airship study. This model takes into account all elements of cost during the life cycle of a given system, that is, research and development, initial investment, and annual operating, shown in Equations (5), (6), and (7), respectively.

Research costs, "R," are most difficult to estimate today, because a detailed base of historical data seldom exists. Hopefully, as more data are obtained through improved cost accounting procedures -- for example, PERT Cost and related techniques -- a more substantial statistical foundation may be available for development of cost estimating relationships covering the research and development area.

Initial investment costs, "I," detailed in Equation (6), may be defined as those one-time outlays required to introduce a new system into the operational inventory after the required equipment has been developed and tested to an acceptable level of reliability. The cost of each airship depends to a considerable extent upon the number of units produced. Consequently, cost-quantity relationships must be taken into account in computing the cost of this equipment.

In the aggregated model, procurement costs of the airships have been defined to include initial spares and spare parts. In order to estimate the costs of such spares, the cost analyst must know the projected annual utilization rate of such equipment and its system design life.

Specialized equipment, "E," in Equation (6) includes masts, ground handling equipment, helium purifiers, and "high-rangers," that is, mobile extension ladders. Specialized equipment varies considerably

Chart V

AGGREGATED COST MODEL

$$C = R + I + nU \qquad (4)$$

Where

C = total program cost,

R = research, development, and test and evaluation cost,

I = initial investment costs,

n = number of operational years,

U = annual operating costs.

$$R = D + T + T_S + \epsilon_1 \qquad (5)$$

Where

D = cost of design and development,

T = cost of test vehicles and testing operations,

T_S = cost of test support equipment,

ϵ_1 = miscellaneous RDT&E costs not included in above.

$$I = A + E + F + V + T + \epsilon_2 \qquad (6)$$

Where

A = cost of airships,*

E = cost of specialized equipment,*

F = cost of facilities,*

V = cost of personnel travel,

T = cost of personnel training,

ϵ_2 = other initial investment costs not included above.

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*The principle of declining costs per unit associated with increased production should be considered in finding total vehicle cost. For a detailed discussion of cost-quantity relationships, see J.W. Noah, and R.W. Smith, Cost Quantity Calculator, RM-2786-PR, The RAND Corporation, January, 1962. The same principle applies in computing the cost of specialized equipment, "E," and to some degree, facilities, "F." For purposes of aggregation, spares have been included above in the costs of the airships, specialized equipment, and facilities.

Chart V (Cont'd)

$$U = A_2 + E_2 + F_2 + V_2 + P + T_2 + L + M_A + M_E + M_F + \epsilon_3 \qquad (7)$$

Where

A_2 = cost of replacement airships,*

E_2 = cost for replacement of specialized equipment,*

F_2 = cost of replacement facilities,*

V_2 = cost of annual personnel travel,

P = cost of annual pay and allowances,

T_2 = cost of replacement training,

L = cost of fuel, lubricants, and helium,

M_A, M_E, M_F = cost for maintenance of airships, specialized equipment, and facilities, respectively,

ϵ_3 = other operating expenses not included in above.

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*Ibid.

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from system to system. Estimation of cost for specialized equipment can be most troublesome in advanced systems, particularly if the designers do not offer some rather specific technical detail covering its major characteristics.

Operating costs, "U," in Equation (7) are those expenses incurred in maintaining and operating a system after it has been initiated into service. It is often a difficult task to calculate operating costs for existing systems. For advanced systems, the computation and allocation of these costs becomes even more complex. At the same time, however, the prediction of operating cost is of paramount importance in the selection of alternatives.

Cost of replacement airships, "A_2," is dependent on attrition of primary mission equipment. Since very little applicable historical data is available on airship attrition rates, such a factor should be predicated on design estimates.

Likewise, the replacement cost of specialized equipment, "E_2," often is computed by taking a percentage of the investment in specialized equipment. Preferably these factors again should be derived from analyses of historical attrition data for various analogous types of specialized equipment.

One of the key inputs to systems costing is manpower requirements. Estimates must be prepared of all necessary personnel involved in the life cycle of a system by skill levels or grades. Training costs, "T," must be estimated both for the initial complement of personnel and for replacement personnel during the operational life of the system. The annual pay and allowance category, "P," includes basic pay, and, where applicable, subsistence allowances, quarter allowances, dislocation allowances, and so on. The cost of pay and allowances is determined by applying appropriate factors by personnel types in a system. Other personnel-related cost elements usually comprise a significant part of total systems costs.

In order to measure only the incremental costs to the Department of Defense or NASA for operation of a fleet of modern airships, every effort should be made to avoid the inclusion of "inherited" assets, that is, assets for which expenditures have already been made. Thus, for example, the cost model should not include the total expense of constructing depots for maintenance of the airships, since many of these already exist throughout the country. Perhaps a logical assumption would be that these huge hangars cannot be put to good alternative use. Consequently some arrangement might be made with the Navy, the present custodian, either to lease or transfer these structures to the using agencies. In such an instance, the outlay would be much less than for new construction.

The interdependency of cost estimating and design data is inherent in the development of estimating relationships.* In the field of cost analysis, some of the most important estimates are predicated on physical relationships, that is, the relationship of resource requirements to physical and performance considerations. Chart VI shows, as a hypothetical example, the cost of depot maintenance in dollars per flying hour as a function of horsepower requirements. If such a relationship could be derived from analyses of parallel data, it could be applied either to forecast the cost of such maintenance for preliminary designs or to corroborate some other method of estimating. Obviously, it is necessary that a large body of such estimating relationships be developed to support a comprehensive model of total systems cost.

OUTPUTS

Economic considerations have become so complex in recent years that decisions about the cost elements *per se* cannot be made solely, as in simpler times, by a specialist working in one area. Moreover, the final choices may involve an intricate interrelationship among technical, economic, and policy considerations.

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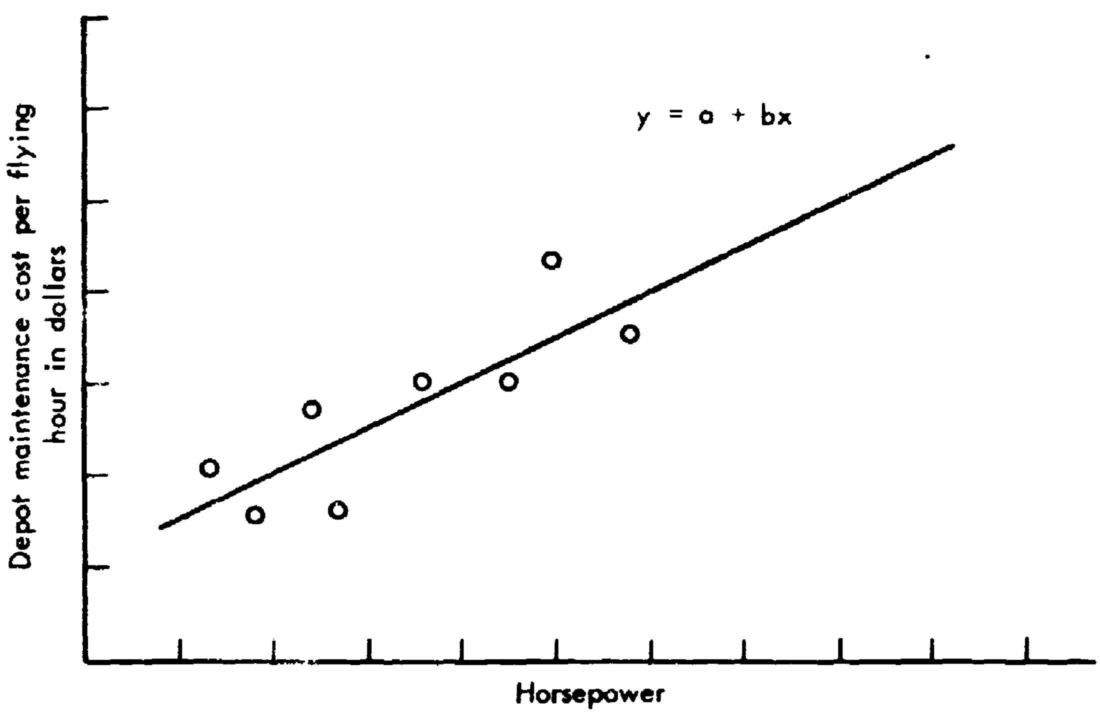
*See G. H. Fisher, *Derivation of Estimating Relationships: An Illustrative Example*, RM-3366-PR, The RAND Corporation, November, 1962.

Chart VI

COST ESTIMATING RELATIONSHIP



A coordinated effort of both designer and cost analyst does not represent a total interdisciplinary approach. The same relationship should exist among the economic analyst, market researcher, political scientist, or others who may be involved in the design phase. In support of this complex evaluative process, the cost analyst is responsible for rendering as explicit as possible the assumptions upon which his estimates are predicated.

In this connection, a tree diagram may prove useful in conjunction with the cost model in order to display the range of alternative estimates which have been developed. Such a device is shown in Chart VII. The diagram shows the number of possible cost estimates when three levels of costs are considered for the three major phases in the life cycle of a weapon system. Three estimates are shown for each of the cost sub-divisions as an attempt to deal with the design and costing uncertainties involved.

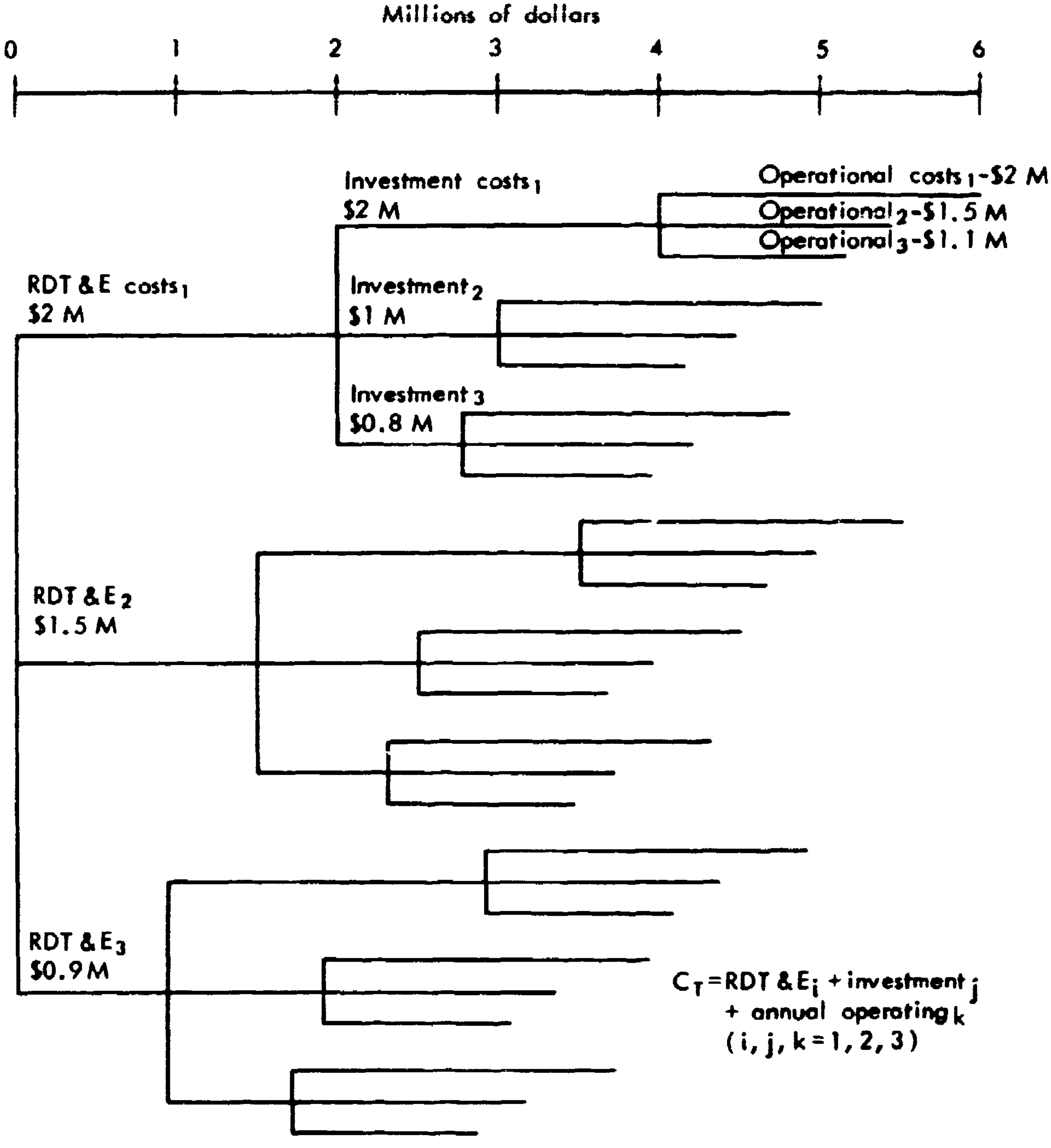
In the chart, the cost estimates have been drawn to scale. A tree diagram, of course, may be used similarly to display the range of alternative estimates at any level, with as many different possibilities per element as desired.

The cost-tree with suitable labeling may prove useful as a working means for presentation, discussion, and classification of interim results before final cost computations are undertaken. At the same time the diagram would graphically reveal the results of taking a certain path of assumptions.

For example, the handling of uncertainty as to whether depots for airship maintenance would be leased or received as a free asset could

Chart VII

TREE-DIAGRAM FOR RDT&E, INVESTMENT, AND OPERATING COSTS WITH PROPORTIONATE COST ELEMENTS



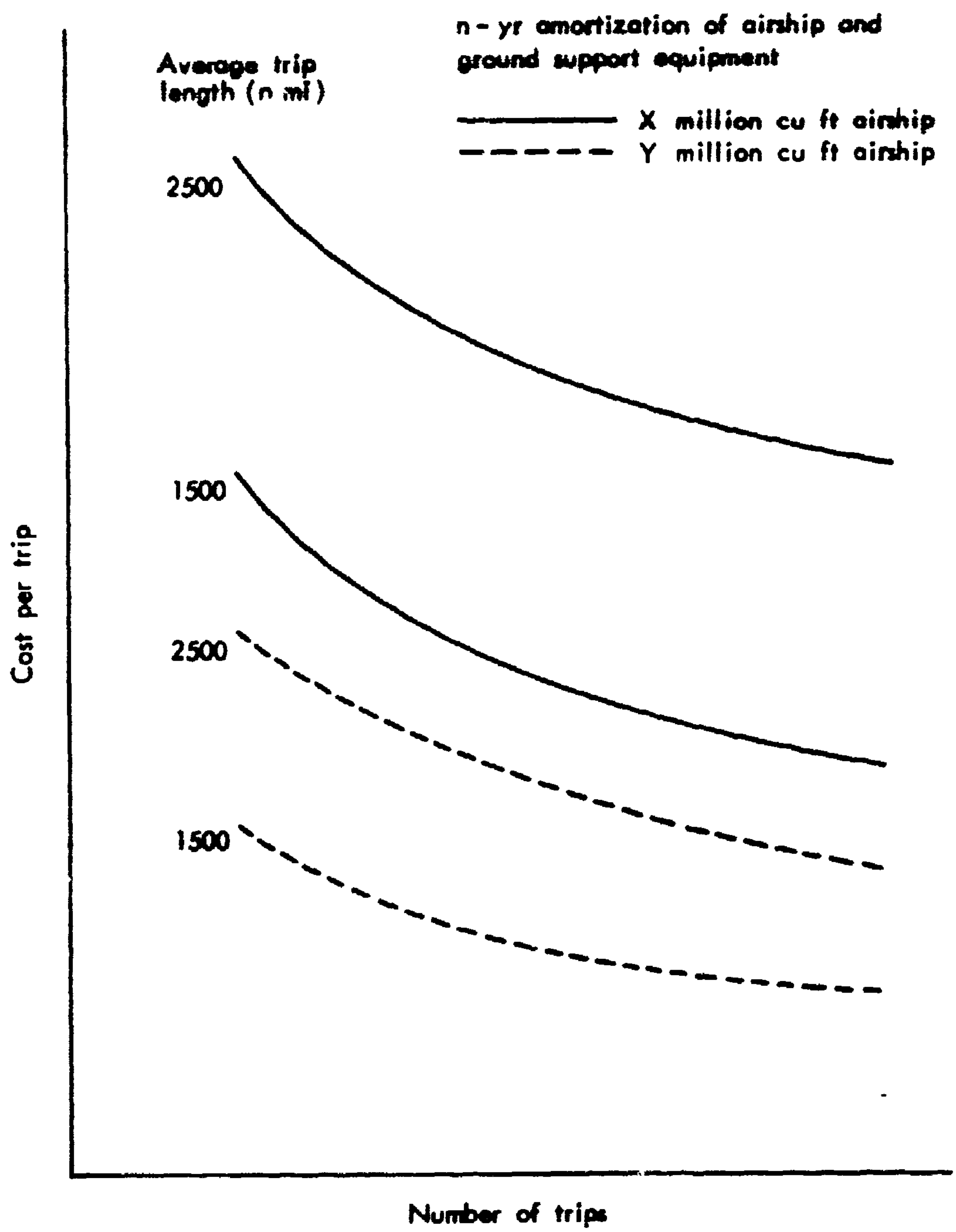
be readily incorporated into the diagram. At the time the decision became known, the path based on the false assumption would be eliminated.

Normally, the responsibility for planning in different areas -- operations, manning, supply, and so on -- is delegated to specialists in those areas who then develop their plans in relative isolation from plans being developed in other areas. It is obvious that these various policies and plans influence one another in a significant way. Limitations on communications result in the development of a series of independent plans which are later fitted together, and still later, retrofitted as necessary. This is true, for example, both within a firm and among the firm, its subcontractors, and customers. In this context, the cost-tree, with suitable labeling and notes, could be used as a vehicle to aid in the needed cost integration. The simplicity and flexibility of the device readily lends itself to such a use.

Chart VIII indicates the type of parametric cost data which might be developed during the study. These curves would enable the designer to select economically efficient designs based on vehicles of various sizes, trip lengths, and numbers of trips. These factors are, of course, not necessarily mutually exclusive. A family of charts displaying the resource implications of each of the possible major design and operational parameters should be a primary output of the cost modeling process.

Chart VIII

AIRSHIP TRIP COST (DESIGN PAYLOAD)



CONCLUDING REMARKS

To date, the application of systems costing in preliminary design has been limited, even in defense industries where reference to cost-effectiveness studies is becoming commonplace. Obviously, the principles are applicable to the design of a great variety of man-machine systems in both defense and civilian fields. The integrated approach described here applies in differing degrees to the production of equipment ranging from space capsules to tractors. In current practice, cost optimization studies frequently are conducted in a fragmentary fashion and are performed too late in the design process to ensure the achievement of effective use of economic analysis.

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