A Survey of Weapon System Cost Effectiveness Methodologies

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A SURVEY OF WEAPON SYSTEM COST EFFECTIVENESS METHODOLOGIES

BY

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B.A.E., Georgia Institute of Technology, 1973

RESEARCH REPORT

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Orlando, Florida
1976
ABSTRACT

A survey of cost effectiveness methodologies used in the defense industry is presented and an application of cost effectiveness is developed. A breakdown in the level of the decisionmaking is made and follows the example of the Weapon System Effectiveness Industry Advisory Committee. Examples of cost effectiveness methodologies at each decision-making level are shown.
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I. Introduction

Through the years several methods of decision making employing some sort of relative indexing have been developed. One of these methods is cost effectiveness, which has found application in the design, development, procurement, and deployment of military weapon systems. Broadly defined then, cost effectiveness analysis is an analytical study designed to relate a system's cost performance, and "to assist a decision-maker identify a preferred choice from among several possible alternatives" (Quade 1965, p. 1). It must be recognized that a true cost effectiveness index can only be established after a system has been retired. For decisionmaking however, this index must be projected and requires a carefully constructed model. Moreover, it is necessary to continually update the cost effectiveness model throughout the life of the system.

Generally, estimates of cost effectiveness are used to:

* Provide a timely and objective management decision criterion for the selection of the preferred system,
* Highlight technical and cost weaknesses
of the system or potential problem areas requiring resolution during later phases,
* Justify proceeding with the Contract Definition Phase and subsequent Engineering Development,
* Provide the initial traceability of critical system performance parameters to preliminary design requirements (Lockheed 1970).

The purpose of this paper is to present several examples of cost effectiveness methodologies that have been recently documented in the defense industry and to make comparisons as to their usefulness, practicality, adaptability, applicability, and efficiency. Methodologies will be subdivided into three levels of analysis and examples of each presented. In addition, an example of the application of cost effectiveness analysis will be demonstrated.

Each of the three levels of analysis, 1) overall defense goals, 2) system competition, and 3) component selection, will be discussed and several models of cost effectiveness evaluation will be presented with emphasis on their advantages and disadvantages. Using the problem of the procurement of a military helicopter training system, an application of the methodologies will then be developed.
The breakdown of the levels of analysis was accomplished by following the example of the Weapon System Effectiveness Industry Advisory Committee (1965). Using this approach cost effectiveness methodologies can be grouped by their particular application. To demonstrate this, several examples of cost effectiveness analysis were chosen, without regard to their merits or disadvantages, and placed in their respective analysis level. After a brief examination of each model and the methodologies that were presented, a problem from the literature was chosen and an application of the methodologies was made. It was found that the problem required a second level analysis with the objective to minimize the cost at a fixed level of effectiveness. It was necessary to make several assumptions, because of lack of data, to simplify the model, and it is recognized that with more specific data a more complex and more accurate model could be developed.
II. Comparison of Methodologies

Decisionmaking Levels

As in all forms of analysis, one of the first steps that must be taken is to structure the level of effort of the decisionmaking. In effectiveness analysis of a military weapon system this breakdown serves to define the scope of the system in question. Using the approach set forth by the Weapon System Effectiveness Industry Advisory Committee (1965), effectiveness analysis is divided into three decision-making levels. The relationship of each specific level to the others is shown in Figure 1 (WSEIAC 1965, fig. 3). Generally, the levels to which the analysis is structured roughly correspond to the phases during the system development.

The first of these levels is concerned with the overall defense goals of the nation. It is the broadest of all the levels and its application is usually found in the Department of Defense, with political, economic and technological factors considered to the extent of making decisions on offensive and defensive allocations of missiles, naval fleets, air forces and ground forces and their targets. The second of these levels
Figure 1. Relationship of Cost Effectiveness Analysis Levels
will be referred to as the "system competition" level and as the name implies will be concerned with trade off and performance studies on systems which may already exist in a hardware prototype stage or merely on paper. The primary responsibility of this level lies with the military procurement agencies. An example of this level might be seen in the recent Air Force fly-offs between the A-9 and A-10 attack aircraft and also between the F-16 and F-17 light weight fighter aircraft. An additional example would be the case of the NASA space shuttle configuration studies, where only one configuration will be built, but several designs have been studied to determine the most economical (Gregory 1973). The third and last level is the "component selection" level and is the responsibility of the system developers. Parameters to be investigated here are for example weights, dimensions, reliabilities, and other performance variables. The decisions to be made involve the choice of one "off-the-shelf" component over another or over any newly designed equivalent. Also involved is the optimization of the levels of redundancy in the component selected, that is the cost model should included losses due to system down time as a factor influenced by reliability and maintainability (von Alven 1964).
First Level Models

The most notable of the effectiveness models applicable to the first level of overall defense goals are those considering the missile allocation problem (MAP). These are not cost effectiveness models per se, but recent publications in this area have included costing submodels and budgeting constraints as part of the total model. Offensive strategies are considered in the model of Arms et al. (1975), while defensive missile allocations are the concern of both the models of Soland (1973) and of Brodheim et al. (1967). Although optimal defense strategies are the primary concern of Owen (1969), his game model considers offensive and defensive tactics.

Table 1 presents the four models mentioned above and outlines some of their highlights. The Arms et al. model is the most recent of these and it incorporates several refinements over previous models. Important to this discussion is the cost optimization model designed to choose a strategic arsenal at minimum cost to achieve a specific objective. Essentially this model sets a required system effectiveness level and tries to maximize its cost effectiveness by minimizing the cost. The missile allocation model of Miercort and Soland (1971) is used as a submodel in this model and it determines whether the arsenal
<table>
<thead>
<tr>
<th>Model Name</th>
<th>Model Type</th>
<th>Algorithm</th>
<th>Description/Advantages/Disadvantages</th>
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| Arms et al.         | Min Cost at Fixed Effectiveness | Non-linear Programming | 1) Allocation model of Miercort and Soland  
2) Two-strike war assumed  
3) Linear build-up and phase-out of weapons assumed  
4) Only immediate effects are considered  
5) Cost is the sum of each area defended and terminal weapon type  
6) Opposing side is fixed  
7) Provides information on sensitivity of strategic force levels to changes in national goals  
8) Determines minimum cost from arms agreements  
9) Obtains best balance between offensive and defensive allocations  
10) Large computer run time for large number of variables |
| Soland              | Min total damage at fixed cost | 0-1 Branch and Bound | 1) Chooses discrete ABM levels  
2) Assumes optimal attack  
3) Cost function need not be continuous or separable  
4) Assumes attacker has knowledge of defense levels  
5) Defender moves first; then attacker allocates optimum offense |
| Brodheim et al. | Max offensive costs at fixed defensive cost | Stochastic Dynamic Programming | 1) Aircraft and missile problems are considered  
2) Kill probabilities are considered  
3) Portrays multiple stochastic and deterministic interactions between offense and defense  
4) Flexibility in absorbing a number of parameters  
5) Computationally efficient  
6) Limited choice of offensive weapons  
7) Must have a separable objective function for solution |
|---|---|---|---|
| Owen | Min damage at fixed cost | Game Theory | 1) Attacker constrained by number of missiles available  
2) Considers passive defense  
3) Gives continuous, simple solution |
meets the required objectives, by maximizing the difference in damage by the opposing sides.

The defensive missile allocation model of Soland also uses as a submodel, the model of Miercort and Soland. The objective in Soland's model is to maximize defensive effectiveness given a fixed budget. It assumes an optimum offensive allocation (provided by the Miercort and Soland model). The problem is formulated as a min-max problem, designed to minimize the maximum damage done by the enemy, and then is reduced to a 0-1 implicit enumeration problem to which a branch and bound technique is applied.

The Brodheim model is similar to Soland's in that costs are considered in the form of budget constraints. It also is a defensive allocation problem but the objective of its optimization is the maximization offensive side's costs. Again, the missile allocation model is used as a submodel to the cost effectiveness model. Postulating the problem in this manner is equivalent to formulating the cost effectiveness model as a sub-optimization problem.

Owen also limits his defender's budget in his two-sided war game model, while he tries to minimize fatalities incurred. Like in the Soland model, Owen employs a min-max optimization algorithm which is reformulated into a pure minimization problem.
As mentioned previously, the cost effectiveness models presented here are outgrowths of a larger class of problems - the missile allocation problem. These models are too numerous to discuss in detail, however it is fair to say that with the addition of costing sub-models and/or budget constraints, conversion to cost effectiveness models can be accomplished. Table 2 presents some of the more important missile allocation models and their characteristics (Matlin 1970).

Second and Third Level Models

The second and third levels of analysis are very similar in their approach, since the performance parameters of entire systems and individual components are very much alike. The basic objective is to meet some previously described specification at a minimum expenditure of resources. Each system or component is evaluated on one or more parameter defined by its mission objectives. An optimization objective function is formulated, and depending upon its formulation it is minimized or maximized, subject to a set of given constraints.

The final report of the Weapon System Effectiveness Industry Advisory Committee seems to have the most influence on recent cost effectiveness models found in the literature. Both the models of Lockheed and ARINC (1969) use the WSEIAC approach, but ARINC employs
<table>
<thead>
<tr>
<th>Name</th>
<th>Algorithm</th>
<th>Model Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kooharian, Saber, and Young</td>
<td>Max-min</td>
<td>Max total damage</td>
</tr>
<tr>
<td>Miercort and Soland</td>
<td>Integer non-linear programming, branch and bound</td>
<td>Max total damage</td>
</tr>
<tr>
<td>Bracken and McGill</td>
<td>Non-linear programming</td>
<td>Max expected damage</td>
</tr>
<tr>
<td>Pugh</td>
<td>Lagrangian Dynamic Programming</td>
<td>Min combat losses</td>
</tr>
<tr>
<td>Bradford</td>
<td>Dynamic Programming</td>
<td>Max expected value of targets destroyed</td>
</tr>
<tr>
<td>denBroder, Ellison and Emerling</td>
<td>Linear Programming</td>
<td>Max expected value of targets destroyed</td>
</tr>
<tr>
<td>Furman</td>
<td>Lagrange Multipliers</td>
<td>Max expected target damage</td>
</tr>
<tr>
<td>Jacobson and Crabtree</td>
<td>Dynamic Programming</td>
<td>Max value destroyed</td>
</tr>
<tr>
<td>MacLaren and Walkup</td>
<td>Monte Carlo</td>
<td>Max target damage, Min target damage</td>
</tr>
<tr>
<td>MITER</td>
<td>Search</td>
<td>Max total target value destroyed</td>
</tr>
<tr>
<td>Morgan and Flemming</td>
<td>Linear Programming</td>
<td>Min total number of boosters to meet demand</td>
</tr>
</tbody>
</table>
a costing submodel developed by the RAND Corporation. Dynamic programming techniques are applied to several of the models developed on this level. Although many techniques are described in the WSEIAC report, both the Lockheed and ARINC models use a form of dynamic programming. Sacco and Schlegel (1965) use a dynamic programming approach to cost effectiveness, while Rush et al. (1967) is similar to the missile allocation problems in the use of non-linear programming. The use of cost effectiveness indices, like those of WSEIAC is used by Meissner and Biagioli (1967).

The models mentioned above are but a selected few of quite an expansive list, and no attempt has been made to rank one model above another. Table 3 shows some of the highlights of these models, and the discussion that follows is an attempt to describe in more detail some of their features.

A closer look at the WSEIAC model is appropriate, before discussing the Lockheed and ARINC models. WSEIAC considers three basic models with variations on each: 1) profit, 2) cost effectiveness (level) ratio, and 3) cost effectiveness (long term) ratio. The profit model is simply the application of the concept of return on investment, either absolute return or rate of return. The ratio models compare cost and effectiveness in natural terms with the long range model considering
<table>
<thead>
<tr>
<th>Model Name</th>
<th>Model Type</th>
<th>Algorithm</th>
<th>Description/Advantages/Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>WSEIAC</td>
<td>1) Profit</td>
<td>(various)</td>
<td>1) Ratio model measures value in natural terms</td>
</tr>
<tr>
<td></td>
<td>2) Ratio-level</td>
<td></td>
<td>2) Long range model considers time in effectiveness and cost models</td>
</tr>
<tr>
<td></td>
<td>3) Ratio-long term</td>
<td></td>
<td>3) Difficult to find common units for profit model</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>4) Ratio models can not evaluate &quot;no system&quot; candidate because value becomes meaningless</td>
</tr>
<tr>
<td>ARINC</td>
<td>Max effectiveness at fixed cost</td>
<td>Dynamic Programming</td>
<td>1) Minimum operation time constraint</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>2) Neglects small cost terms</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>3) Uses marginal costing</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>4) Uses effectiveness model of WSEIAC</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>5) Uses costing model of the RAND Corp.</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>6) Reduces n-dimensional problem to one dimension</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>7) Must have separable objective function</td>
</tr>
<tr>
<td>Lockheed</td>
<td>Max effectiveness at fixed cost</td>
<td>1) Enumeration</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>2) Dynamic Programming</td>
<td>1) Models are broken down for different missions</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>2) Reduces n-dimensional problem to one dimension</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>3) Must have separable objective function</td>
</tr>
</tbody>
</table>
|                | Max performance at fixed cost | Dynamic Programming | 1) Maximum cost constraint  
2) Reduces n-dimensional problem to one dimension  
3) Must have separable objective function |
|----------------|--------------------------------|---------------------|-----------------------------------------------------------------|
| Sacco and Schlegel |                                |                     | 1) Constraints represent "state of the art" limitations  
2) Includes trend analysis for future costing  
3) Use of learning curve in cost analysis  
4) Examines marginal costs  
5) Allows bending of mission to fit design  
6) Use of trend analysis introduces more uncertainty in cost model |
| Meissner and Biagioli | Max ratio                    | Enumeration         | 1) Constraints are physical interrelations, and desired achievements  
2) Variables are airframe weight, total inert weight, mass fraction, thrust, propellant weight, length, etc.  
3) Large cost savings over previous use of no optimization  
4) Provides sensitivity information  
5) Basic assumptions must be made: number of stages, number of engines per stage, type of propellant, total number to be built  
6) Must use several starting values to assure finding global minimum |
| Rush et al. | Min total cost at fixed effectiveness | Non-linear Programming (SUMP) |  |
effectiveness over a finite period of time. WSEIAC suggests employing a Lagrangian multiplier technique. Such a problem might be stated as:

Maximize Effectiveness subject to:
  cost constraints
time constraints
other constraints

or as:

Minimize Cost subject to:
  effectiveness constraints
time constraints
other constraints

The ARINC model uses the effectiveness model of WSEIAC as a submodel. It adds a cost submodel by the RAND Corporation in computing its cost effectiveness curves, which are then used in intra-system trade offs to optimize the system with respect to performance, cost, schedule and manpower. The three major components of its effectiveness model are availability, capability, and dependability. These components are defined as follows:

Availability is a measure of the system condition at the start of the mission. It is a function of the relationships among hardware, personnel and procedures.
Dependability is a measure of the system condition at one or more points during the mission, given the system condition at the start of the mission.

Capability is a measure of the system's ability to achieve the mission objectives, given the system condition during the mission. Capability specifically accounts for the performance spectrum of the system (ARINC 1969, pp. 2.21-23).

The model considers the availability and capability of a system in a number of different states and the probabilities of transition from one state to another. The effectiveness is then the product of an availability vector, a dependability matrix, and a capability vector. The elements of system effectiveness discussed by ARINC are outlined in Figure 2 (1969, fig. 2-6A).

The Lockheed model uses an identical approach to the effectiveness evaluation, considering the three main parameters to be availability, dependability, and capability. Figure 3 (Lockheed 1970, fig. 3-7) shows a graphic representation of the system transition from state to state during the time periods of a mission for a simplified two-state analysis. Effectiveness is defined differently for each type of mission being analyzed. Simple and complex missions of both discrete and continuous natures are considered and summarized in Table 4 (Lockheed 1970, table 3-6). Table 5 presents examples of cost effectiveness models listed in the Lockheed report (1970, table 3-7). One of the optimization techniques suggested in this report is that
Figure 2. Elements of Effectiveness

- AVAILABILITY
  - Scheduled Maintenance
  - Checkout
  - Trouble Shoot
  - Repair Time
  - Spares Doctrine
  - Manpower
  - Mean Time Between Maintenance Actions

- DEPENDABILITY
  - Reliability
  - Operational Environment
  - Failure Rate
  - Degrade Modes
  - Back-up Modes

- CAPABILITY
  - Range
  - Circular Error Probability (CEP)
  - Hours of Operation
  - Channel of Information
  - Power Output
  - Single Shot Kill Probability
<table>
<thead>
<tr>
<th>State 1</th>
<th>State 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fully operable</td>
<td>Inoperable</td>
</tr>
</tbody>
</table>

Parameter = X, Y

**Initial States**
- Availability Vector
- Dependability Matrix

**Dependability States**
- Capability Vector

**Performance Parameter**
- Effectiveness Evaluation

**Figure of Merit**

![Flow Graph](image)

**System effectiveness two-state flow graph**

- System condition at end of mission
- Evaluated by summation of all paths
### TABLE 4
#### EXAMPLES OF SYSTEM EFFECTIVENESS MODELS

<table>
<thead>
<tr>
<th>Type Mission</th>
<th>Characteristic</th>
<th>Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>* Discrete (with respect to mission time)</td>
<td>Mission is short in duration, and system expended after one mission assignment</td>
<td>ADC(^+) product or average or minimum capability</td>
</tr>
<tr>
<td>Recurring</td>
<td>System is reusable and is operationally employed on many assignments to accomplish the same set of mission objectives</td>
<td>Average or minimum capability</td>
</tr>
<tr>
<td>* Continuous (with respect to mission time)</td>
<td>System is operationally employed over an extended period of time</td>
<td>Integral over time of ADC product, with D and C potentially changing with time, or a value of the ADC product</td>
</tr>
</tbody>
</table>

+ A-Availability  
+ D-Dependability  
+ C-Capability
TABLE 4 - Continued

Complex Discrete and Continuous Missions

<table>
<thead>
<tr>
<th>Type Mission</th>
<th>Characteristic</th>
<th>Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>* Multiple levels of threats</td>
<td>System is operationally employed in the face of all threat levels</td>
<td>Most probable effectiveness for each threat level</td>
</tr>
<tr>
<td>* Multiple missions for discrete and continuous missions</td>
<td>System is operationally employed for a variety of missions</td>
<td>Most probable effectiveness for each set of mission objectives</td>
</tr>
<tr>
<td>* Multiple missions and threats</td>
<td>System is operationally employed in the face of all threat levels and for a variety of missions</td>
<td>Most probable effectiveness for each set of mission objectives and threat levels</td>
</tr>
</tbody>
</table>
TABLE 5
EXAMPLES OF COST EFFECTIVENESS MODELS

* Maximum system effectiveness for a fixed cost
* Minimum cost for a fixed level of system effectiveness
* Maximum system effectiveness per cost, or minimum cost per system effectiveness (Ratio model)

* Net value received for cost expended - (Net Value Received Model). Can be expressed as:

Net Value Received = \( VE - C \)

= gross value received minus cost

= value per increment of effectiveness times planned level of effectiveness minus cost

* Net rate of return per unit cost - (Rate of Return Model). Can be expressed as:

Net Rate of Return = \( \frac{VE - C}{C} \)

= Net value received per cost

* Gross value received, averaged over entire life of system, per cost - (Long Term Model). Can be expressed as:

\[
\frac{1}{C(t_0 - t_d)} \cdot \int_{t_d}^{t_0} V(t) \cdot E(t) \, dt
\]

where \((t_0 - t_d)\) is remaining useful life
of total enumeration, however it can easily be seen that a dynamic programming approach to this model and to that of ARINC would be applicable in these state variable problems.

The cost effectiveness model of Sacco and Schlegel also employs a dynamic programming approach. The objective in this model is to maximize the effectiveness of a system of components subject to a cost constraint. This method is geared toward a third level analysis as for each component there exists several alternative choices, each with an associated cost. Under this formulation the objective function is a separable function and is equal to the product of the effectiveness of each component.

The model developed by Rush, Bracken, and McCormick was done for the specific application of minimizing the cost of launch vehicles, using a non-linear programming technique. This problem is solved using the sequential unconstrained minimization technique (SUMT) also employed in the allocation model of Miercort and Soland discussed earlier. The motivation for this model was to use cost estimating relationships to influence the design. Again, this model is geared toward component selection or design, on the third analysis level. The major problem with this model is uncertainty in the results due to the non-linear nature of the
problem and the fact that it does not assure convergence on a global minimum.

Methodology outlined by Meissner and Biagioli can be applied to both level two and level three analysis. Analysis is performed on both complete competing systems and on competing components. A cost effectiveness index for the Utility Tactical Transport Aircraft System (UTTAS) is presented by a Boeing-Vertol assessment and is defined as a function of a work ratio, time ratio and a cost ratio as follows:

\[
C.E.I. = \frac{(W.R.)(T.R.)}{C.R.}
\]

where \( W.R. \) = Work Ratio = \( \frac{\text{number of aircraft #1 required}}{\text{number of aircraft #2 required}} \) for a specific mission at some set of standard conditions

and \( T.R. \) = Time Ratio = \( \frac{\text{(time for standard distance + down time) for aircraft #1}}{\text{(time for standard distance + down time) for aircraft #2}} \)

and finally:

\[
C.R. = \text{Cost Ratio} = \frac{\text{cost of aircraft #1}}{\text{cost of aircraft #2}}
\]

The final measure of cost effectiveness used in the UTTAS presentation is:

\[
\text{Cost/Man Delivered} = \frac{\text{Cost/Sortie}}{\text{Number of Men/Sortie}}
\]

The proposed system is then arrayed against the system currently in use or against the current favored proposal.
III. Application of Cost Effectiveness Methodology

Reynolds, Wirth, and Mathews (1975) have discussed the cost effective use of flight simulation without directly assigning an index of cost effectiveness. This section will discuss one approach which may be taken in the procurement of a military flight training system. The system in question is a flight simulator for the United States Coast Guard HH-52A helicopter. Planning for this particular problem involves the choice of simulator type and "the time in each simulator based on producing the desired data or level of training with the needed degree of reliability for minimum cost" (Reynolds et al. 1975, p. 1). Cost and effectiveness data from the Reynolds paper will be used whenever possible, however several assumptions will be made to facilitate the solution.

First, it should be recognized that the application would be categorized as a second level analysis. At this level six basic methodologies have been discussed in the previous section. Those are:

* Maximize effectiveness at a fixed cost
* Minimize cost at a fixed effectiveness
* Cost effectiveness ratios
* Net value (profit)
* Rate of return
* Gross value

Reynolds et al. states that "the best combinations of simulators for training are the ones producing the most transfer of training for the lowest overall cost" (1975, p. 2). Here the measure of effectiveness is in transfer of training or translated to physical terms, the number of training hours required in the aircraft. The objective then is choose the simulator system which reduces the number of aircraft training hours and therefore reduces the total cost of training. Stated another way, we want to minimize the cost of the training system while maintaining a fixed level of effectiveness. Mathematically this is:

$$\min_{j} C_j, \text{ where } j = 1, 2, \ldots, n, \text{ is an index for each alternative system.}$$

The cost, $C_j$, can be broken into the cost coefficients for both the aircraft and the simulator, and the actual costs will be defined as the product of these coefficients and the time spent in the aircraft or simulator. That is:

$$C_j = c_{1j}t_{1j} + c_{2j}t_{2j}$$
where $c_{1j}$ and $c_{2j}$ are the cost coefficients for the aircraft and the simulator, respectively, and $t_{1j}$ and $t_{2j}$ are the times required for the aircraft and the simulator, respectively. Complete costing data is not available and therefore for the sake of simplicity all costs will be assumed to be based upon a unit time spent in the aircraft of simulator. All operating and maintenance costs will be considered in the cost coefficients and will not be broken out separately. Given this, the coefficients can be defined as the slopes of the curves in Figures 4 and 5. In general it can be assumed that these curves are approximately linear. At this point it should be recognized that a Life Cycle Cost model would be the most accurate way to represent the costs of the system.

Effectiveness required will be defined in terms of time required for qualification in the aircraft. From available data it can be shown that time spent in an actual aircraft can be reduced by prior training in a visual simulator. For example, in a United States Army Rotary Wing Instrument Training Study instrument training concluded in 6.5 flight hours after utilizing subsystem Device 2B24 of the Army's Synthetic Flight Training System (SFTS), as opposed to 60 flight hours for students in the existing
Figure 4. Aircraft Cost

Figure 5. Simulator Cost

Figure 6. Required Effectiveness
program (Reynolds et al. 1975, p. 6). In addition, U.S. Air Force utilization of a single TV-camera, rigid model visual system, has reduced required air plane hours for training by 4.6 hours in the C-5 program and 2.0 hours in the C-141 program (Reynolds et al. 1975, p. 8). Similar results have been noted in the commercial field. Federal Air Regulations were amended to allow recurrent training to be conducted in approved visual simulators resulting in the data gathered by American Airlines and presented in Table 6 (Reynolds et al. 1975, p. 5).

The level of effectiveness required will then define a third relationship, that of average aircraft time required, as a function of the amount of time spent in the simulator (Figure 6). This function can be determined by knowledge of historical data on the particular system in question or knowledge of results of other similar systems already in operation. At worst it can be assumed that there is a one-to one correspondence between the time spent in a simulator and the time required to be spent in the aircraft. This function will generally vary from one simulator to another. Constraints for this problem would possibly include a minimum time for both the aircraft and the simulator.
TABLE 6

TOTAL ACTUAL AIRPLANE TIME FOR TYPE RATING
AT AMERICAN AIRLINES

<table>
<thead>
<tr>
<th>AIRCRAFT</th>
<th>AVERAGE AIRCRAFT TIME (HRS)</th>
<th>1971</th>
<th>AFTER REG. AMEND.</th>
</tr>
</thead>
<tbody>
<tr>
<td>747</td>
<td></td>
<td>5.3</td>
<td>1.9</td>
</tr>
<tr>
<td>DC-10</td>
<td></td>
<td>2.1</td>
<td>1.7</td>
</tr>
<tr>
<td>707</td>
<td></td>
<td>3.1</td>
<td>1.3</td>
</tr>
<tr>
<td>727</td>
<td></td>
<td>3.5</td>
<td>1.3</td>
</tr>
</tbody>
</table>

In the problem of Reynolds et al., two simple alternatives are proposed, the first being no simulator and the second with a simulator system. Training hours and cost data for the three courses (proficiency, transition, and qualification) are summarized in Tables 7 and 8. These courses represent different levels of training in the Coast Guard program. For example, the transition course is provided for those with previous pilot experience in other types of aircraft. It can be seen that it is
more cost effective to use the simulation based system; however for illustrative purposes we shall pursue this further.

Again, because of lack of available data, the aircraft time required function will be assumed to be linear as shown for each of the three courses in Figure 7. Aircraft cost data provided is converted into cost per student trained for compatibility and is presented in Table 9 and Figure 8. Also shown here are the cost coefficients computed using the aircraft hours. Similarly, the simulator cost coefficients are found using the 1974 cost data less the aircraft costs, which are based on the relationships defined in Figure 8. Simulator costs are summarized in Table 10. Now, applying the coefficients to the cost equation derived earlier results in the cost figures shown in Table 11 for each of the candidate systems. Again it is readily seen that the simulator system is the more cost effective choice.

At this point other alternative simulator candidates should be evaluated using this same methodology. With very little trouble this model could be made more complex if more detailed data were available. Also with other simulator candidates available for analysis a cost effectiveness index methodology (ratio model) could be employed, such as:
### TABLE 7
SUMMARY OF U.S. COAST GUARD HH-52A TRAINING PROGRAM: 1974

<table>
<thead>
<tr>
<th>Course Title</th>
<th>Annual No. of Students</th>
<th>Ave. Training Hours</th>
<th>Simulator</th>
<th>Aircraft</th>
</tr>
</thead>
<tbody>
<tr>
<td>Proficiency</td>
<td>300</td>
<td>6</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Transition</td>
<td>30</td>
<td>8.5</td>
<td>26</td>
<td></td>
</tr>
<tr>
<td>Qualification</td>
<td>18</td>
<td>11.5</td>
<td>39</td>
<td></td>
</tr>
</tbody>
</table>

### TABLE 8

<table>
<thead>
<tr>
<th>Course Title</th>
<th>1969</th>
<th>1974</th>
<th>Benefit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Proficiency</td>
<td>-</td>
<td>-</td>
<td>$400K</td>
</tr>
<tr>
<td>Transition</td>
<td>$469K</td>
<td>$408K</td>
<td>61K</td>
</tr>
<tr>
<td>Qualification</td>
<td>708K</td>
<td>366K</td>
<td>342K</td>
</tr>
</tbody>
</table>
Figure 7. Required Effectiveness Function for HH-52A
### TABLE 9
**AIRCRAFT COSTS: 1969**

<table>
<thead>
<tr>
<th>Course Title</th>
<th>Time</th>
<th>Cost</th>
<th>Cost/Hour</th>
</tr>
</thead>
<tbody>
<tr>
<td>Proficiency</td>
<td>6</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Transition</td>
<td>34.5</td>
<td>$16K</td>
<td>$453</td>
</tr>
<tr>
<td>Qualification</td>
<td>50.5</td>
<td>39K</td>
<td>778</td>
</tr>
</tbody>
</table>

### TABLE 10
**AIRCRAFT AND SIMULATOR COSTS: 1974**

<table>
<thead>
<tr>
<th>Course Title</th>
<th>Aircraft Time</th>
<th>Aircraft Cost</th>
<th>Aircraft Cost/Hour</th>
<th>Simulator Cost/Hour</th>
</tr>
</thead>
<tbody>
<tr>
<td>Proficiency</td>
<td>0</td>
<td>0</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Transition</td>
<td>26</td>
<td>$14K - $14K</td>
<td>$453</td>
<td>$215</td>
</tr>
<tr>
<td>Qualification</td>
<td>39</td>
<td>20K - $19K</td>
<td>778</td>
<td>990</td>
</tr>
</tbody>
</table>
Figure 8. Training Costs

Cost of Training - (Dollars)

Qualification

Transition

Hours in Aircraft
## TABLE 11
COST EFFECTIVENESS RESULTS

<table>
<thead>
<tr>
<th>Course Title</th>
<th>Cost</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>No Simulation</td>
<td>With Simulation</td>
</tr>
<tr>
<td>Transition</td>
<td>$16K</td>
<td>$14K</td>
</tr>
<tr>
<td>Qualification</td>
<td>39K</td>
<td>20K</td>
</tr>
<tr>
<td>Total</td>
<td>55K</td>
<td>34K</td>
</tr>
</tbody>
</table>
$C.E.I. = \frac{T.R.}{C.R.}$

where $T.R. =$ Time Ratio $= \frac{\text{Training time of candidate } #1}{\text{Training time of candidate } #2}$

and $C.R. =$ Cost Ratio $= \frac{\text{Cost of candidate } #1}{\text{Cost of candidate } #2}$

This approach would be impractical where one candidate was no simulation, since the index would be meaningless where the time required for simulator training is zero.

An additional approach that may be considered is that of the classical cost benefit analysis using incremental costs of the different simulator candidates. Here effectiveness would have to be measured in terms of benefit dollars gained by use of the particular simulator candidates.
IV. Conclusions

The models that have been discussed in the previous sections are just a few of the many cost effectiveness methodologies used in recent years. The main problem with cost effectiveness modeling as with any type of modeling, is the degree of complexity to which the model must be built. The problem becomes a trade off between simplicity, which requires a minimum of input and whose solutions are easily obtained at the price of less accuracy and more uncertainty, and complexity, which generally produces results with a higher accuracy and lower uncertainty at the expense of a more costly solution and lengthy solution time, requiring more specific data input. However the benefits of cost effectiveness analysis far outweigh the disadvantages. One of the major benefits of an analysis is that it can generate new alternatives -- some of which may be combinations or modifications of existing ones -- as the analysis progresses. "When properly employed, effectiveness analysis can be used to provide the optimum test plan for system verification which will reduce testing costs and minimize schedule impacts" (Pringle}
The cost effectiveness model developed for this paper was very simple in nature, mainly due to the lack of available data on the particular problem. In most of the models discussed, the analysis was broken down into modeling the cost and effectiveness separately. Here the cost had already been determined, since the system was already in use. Since techniques in cost estimating were not included in the scope of this paper, no specific costing model was found necessary other than the breakdown of the costs into coefficient form. The problem then became the modeling of system effectiveness in some physical form. This was done by relating simulator time to required aircraft time to achieve a set level of effectiveness. The choice of the cost effectiveness model followed from this -- to minimize the cost at a given level of effectiveness. The need for more specific data on costing and effectiveness is evident. Application of a Life Cycle Cost model would serve to identify and utilize cost estimates for each phase of the system's life which must be considered. In the simple case of evaluating one simulator the values produced by the model are relative but not absolute. The assumption of linear data, that was necessary, leads to more uncertainty in the results.
The results of the model developed shows a savings per student of $2000 in the transition course and $19,000 in the qualification course. This compares with the data given by Reynolds et al. of $2033 and $19,000 per student for the transition and qualification courses, respectively. Overall a more complex model with more specific data would be needed if more than one simulator candidate were available.

Given enough data to build a more complex model, it would be recommended that the approach of minimizing the cost at a fixed level of effectiveness be taken. The ratio model is not recommended because it tends to break down under certain conditions described earlier. The cost benefit approach has problems in the modeling of effectiveness in natural terms, and it therefore is not recommended.
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LIST OF REFERENCES


