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STATISTICAL COST ESTIMATING RELATIONSHIPS-SOME BASIC ISSUES (AIRCRAFT EXAMPLES)

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Office of Assistant Secretary of Defense (Systems Analysis)

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Statistical Cost Estimating Relationships
Some Basic Issues (Aircraft Examples)

I. MY PURPOSE.

The plan of my presentation is first to discuss some of the basic issues of Statistical Cost Estimating Relationships (CER's), and then to describe briefly some of our recent studies which have attempted to develop such CER's on aircraft programs. I will conclude by summarizing the major advantages and disadvantages of statistical CER's.

II. THE MAJOR CHARACTERISTICS OF STATISTICAL CER TECHNIQUES.

The major characteristics of the statistical CER technique, as I am using the term, are (as shown in Figure 1):

a) First, is the use of actual, historical, data on the costs of other (both past and current) related programs. Actual data, rather than proposal data, or other estimates, are sought.

b) Secondly, these actual costs are then related to selected cost-influencing program characteristics, particularly the major physical and/or performance characteristics.

c) Finally, statistical procedures are used to develop, test, and to evaluate the cost estimating equations - the CERs. (I am using the term "statistical" rather loosely here. In my view the relation that would result from fitting a line, by eye, to a few data points on a scatter diagram would qualify as a statistical CER.)

FIGURE 1

MAJOR CHARACTERISTICS OF THE STATISTICAL CER TECHNIQUE

1. USE OF ACTUAL, HISTORICAL, COSTS FROM RELATED PROGRAMS
2. COSTS RELATED TO SPECIFIC PROGRAM CHARACTERISTICS
3. USE OF STATISTICAL PROCEDURES IN SELECTING THE SPECIFIC CER's

A major assumption in the use of statistical CER's is that the new programs on which the CER's are to be used, will be affected by the cost influencing variables (i.e. the independent variables) in approximately the same way as they affected the historical programs used to derive the CER's.

III. THE COST ESTIMATING TASK ADDRESSED HERE.

The problem that we are attempting to solve with the help of CER's is that of estimating the costs of future programs. For my purpose here I am excluding the problem of estimating the costs of a follow-on program. That is, we are seeking estimates until the time that the item goes into production and a sufficient body of actual costs on that item begins to be reported.

The use of CER's to compare one contractor cost proposal to another is a more controversial application of CER's.

IV. WHY CER's?

The emphasis on CER's has arisen because of numerous examples of poor estimates in the past on major programs. Estimates in the past have seemed to rely too heavily on contractor proposal estimates, which repeatedly have turned out to be considerably underestimated. The recent efforts in my office can be said to have been given primary impetus by initial estimates on the F-111 program. Numerous other examples of major underestimates such as the B-70, Skybolt, Mk 46 torpedo, SHRIKE missile, etc., can be cited.

This is not to say that we consider the statistical CER as being the last word, or even the only word, in making future program cost estimates. The use of engineering evaluations and the examination of the specific design details, with cost comparisons of individual components, can also provide considerable insight. These other techniques, together with appropriate CER's, should result in considerably improved cost estimates. Where specific equipment designs are not available, recourse to CER's may be the only option. This is often the case, when OSD or the Services are doing advanced Cost-Effectiveness studies.

V. MAJOR PROBLEMS IN THE DEVELOPMENT OF STATISTICAL CER's.

For those who have not been through the experience of developing statistical CER's, I would like to describe briefly some of the major procedural problems typically encountered, using a few aircraft examples. Subsequently, I will describe in more detail the specific aircraft studies sponsored by our office.

These procedural problems can be divided into the categories shown in Figure 2.

A. Choice of the dependent variables.

The choice of the dependent variable involves such problems as:

- whether to estimate cost per pound or to estimate cost per airframe directly
- at what production unit, or units, to make the estimate
- and what cost categories should be covered by each equation.

Figure 2

MAJOR PROBLEMS IN THE DEVELOPMENT OF CER'S

1. CHOICE OF DEPENDENT VARIABLES
2. CHOICE OF INDEPENDENT VARIABLES
3. CHOICE OF FORM OF EQUATIONS
4. HANDLING OF INPUT DATA
5. EVALUATION OF PREDICTION CAPABILITY

Currently, the popular approach for aircraft airframes is to estimate separately manufacturing labor, manufacturing materials, tooling and engineering and usually on a cost per pound basis. Overhead, G&A and profit rates are then applied. The difficulty in separating development from production costs in the data has resulted in these frequently being estimated together in airframe CER's. Total engine and total avionics costs are also each estimated separately. There are also proponents of estimating total cost directly, at least total airframe, if not total flyaway cost. Another aspect of the dependent variable question is the coverage of the equations regarding the end item. For example, aircraft might be subdivided into various aircraft types (such as fighters, bombers, transports, etc.), by weight class, by speed (e.g., subsonic versus supersonic), or by type of propulsion system (e.g., reciprocating versus turbojet).

B. Choice of the Independent Variables.

The choice of the independent variables is the problem of extracting the most important cost influencing characteristics, from the literally hundreds of characteristics associated with any given aircraft program. It is worthwhile to review some of the major types of factors affecting cost. These are listed in Figure 3. It is to be noted, however, that typically, CER's have not directly addressed some of these shown in Figure 3. This serves to indicate how complex the over-all problem of cost estimation is.

1. Physical characteristics such as weight, and size are found in most current CER's. They are used, in a sense, as "proxy" (substitute) variables for .....

FIGURE 3

MAJOR FACTORS AFFECTING COST

1. PHYSICAL CHARACTERISTICS
2. PERFORMANCE CHARACTERISTICS
3. INDIVIDUAL MANUFACTURER DIFFERENCES
4. PRICE LEVEL CHANGES
5. ENGINEERING CHANGES
6. CUMULATIVE QUANTITY AND PRODUCTION RATE
7. OTHER

2. The performance characteristics such as speed, range, payload and reliability. We would in many cases prefer to estimate cost solely as a function of performance. However, typically, CER's include both physical and performance variables since certain physical characteristics such as gross take-off weight are usually available even in the very early stages of program concept formulation. An exception is our experimental model for estimating transport costs which, as will be noted later, aims at relating cost directly to a measure of over-all mission performance.

3. Even with the same physical and performance characteristics, the costs of a given program can vary due to the particular manufacturer -- because of such factors as the quality of the management, the degree of plant modernization, the plant's other workload, and the manufacturer's prior experience on recent, related programs. Most often, DOD CER studies use data samples containing programs from several manufacturers. The resulting CER's therefore represent a "weighted average" of the manufacturers. However, most of the aircraft airframe CER procedures at least do provide provision for applying individual manufacturers' direct labor, overhead, and G&A rates for those programs where specific manufacturers can be identified.

4. The prices of labor and materials can change due to various external influences. Most CER studies adjust historical data using industry price indices and provide CER's that estimate costs in constant dollars. If the cost estimator wishes to estimate a new program in

current dollars, these CER procedures require him to obtain separately price level projections which would then be applied to the CER program estimates.

5. Engineering changes, and changes in the pace of the program, can affect significantly the eventual cost of a program. Their effect upon CER's is a complicated one. This area offers a wide open opportunity for some imaginative and practical research.

6. The quantity problem in CER's is typically handled by adding a cost quantity relation to the basic CER which estimates cost at a specific production quantity. There also are a few studies which use the cumulative production quantity as one of the independent variables in the basic CER.

The production rate problem has frequently not been addressed directly in CER's. Planning Research Corporation in its airframe work for our office, which I will discuss later, has included a production rate variable in some of its equations. However, none of us are yet very happy with our understanding of the effect of production rate upon cost. This is another useful area for future research.

7. Finally, the "Other" category includes such effects as plant fires or labor strikes. If these are truly unique events, it probably is appropriate to adjust the historical data where such events and their costs can be identified. Otherwise, the cost equations will include the effects of such events. The equations should not normally be constructed to predict explicitly these unusual costs.

C. Choice of the Form of the Equations.

The particular form of the equations to be used is seldom completely clear. The variables can be added, multiplied together, given exponents, etc. Figure 4 shows two examples of CER's. PRC has generally used linear combinations of terms (as in the first equation), though each term itself may consist of various forms of the variables. RAND has usually used the multiplicative or exponential form (as shown in the second equation). It is seldom intuitively clear what form is most appropriate.

D. Handling of the Input Data.

Unfortunately, as most of you are probably aware, the basic input data usually has many deficiencies. Appropriate data massaging, such as adjustments for different subcontracting policies or for different accounting definitions, is generally a necessary task. If done improperly, however, it can lead to misleadingly good equation fits to the adjusted sample data. The Cost Information Reporting System being developed for the Department of Defense deals with this vital problem of adequate data, at least as far as major procurement costs are concerned. Incidentally, to add to our woes, our office is beginning to have an uneasy feeling that the physical and performance characteristic data used in CER studies may also be deficient. (We need to review this possibility and correct the problem as needed.)

E. Evaluation of Prediction Capability.

In presenting these major procedural problems in developing CER's, I have said little about solving them. Unfortunately, I can

FIGURE 4

CER EXAMPLES

1. $C_{M,100} = -21 + 1100W^{-0.5} + 11S$

2. $C_E = 14S^{0.54} W^{0.88}$

WHERE. . .

$C_{M,100}$ = Mfg. Materials Cost/lb of Airframe Wt @ Unit 100

C_E = Non-Recurring Airframe Engineering Cost

W = Airframe Weight, pounds

S = Max. Speed, knots

say little of a definitive nature. However, it is probably neither necessary, nor is it desirable, to pre-specify exactly how these should be handled in each case. Essentially, decisions as to the variables and forms of the equations have to be answered for each individual study. Universally applicable solutions are not likely to be found. Initially, on a study, engineering type judgments are used to make preliminary selections. Subsequently, statistical analysis provides the major tools for testing the various alternatives. Even after this however, the analyst may find it desirable to modify the estimation procedure (such as with an adjustment for exotic new airframe materials) in a manner which he feels will help discriminate future program costs.

This leads us to the key problem that no discussion of CER's or of any predictive technique, can ignore. That is the question of just how good is the procedure for predicting. We feel that other techniques for estimating the costs of future programs are by themselves, not good enough. But is the use of statistical CER's any better? Unfortunately, this is as yet a question on which we do not have completely satisfactory evidence though what we do have is encouraging. We currently use the following approaches to attempt to evaluate the capability of statistical CER's:

1) The main approach is to look at the statistical evidence as to how good an equation fits the sample data. We look at such statistics as the correlation coefficient and the standard error of estimate. The presumption is that the better the fits, the more likely are the equations to predict with accuracy.

2) Another approach is to leave out of the sample one or two data points and then to test the derived equation against them. If the equation provides a "reasonably" close estimate, our confidence in the equation's prediction capabilities increases; otherwise, our confidence decreases.

3) A recent proposal is to perform "Historical Simulation" to see how the method for deriving the CER's would have performed in the past. This is an interesting idea and should be explored further. (My office has been looking into this but unfortunately has not been able to spend much time on it.) But, again, historical simulation can provide at best only indirect evidence.

4) The real predictive test of the CER's, or any prediction technique, is of course to see how successful they actually are on real programs after the results are in. Unfortunately, this usually means a long wait. However, we should, at least keep careful histories of our estimates, and the estimating techniques used, to help eventually to evaluate how they performed and for clues as to how they might be improved. The Air Force Systems Command Tracking System recently established is a good step in this direction.

VI. SPECIFIC OSD AIRCRAFT STUDIES.

Now, I would like to describe briefly some of the specific aircraft studies that our office has sponsored.

As noted earlier, the F-111 cost analysis work, which began in our office in 1963, gave impetus to the cost research on aircraft programs.

Since that time our office has sponsored, or engaged in, a number of studies on aircraft costs. Figure 5 lists the five studies that I will describe here.

1) The first study is the work of the Planning Research Corporation. PRC prepared a report issued last February (1965), R547, "Methods of Estimating Fixed-Wing Airframe Costs." It has been given wide distribution throughout DOD.

The PRC study utilized a number of imaginative and provocative approaches. Though the specific procedure suggested by PRC for estimating airframe costs, seems to me, on the whole, to be overly cumbersome and involved, it has served to stimulate much constructive discussion. I will review just a few of the study's characteristics which are of interest here:

a) CER's are provided for each cost element: manufacturing man-hours, and materials, engineering, and tooling costs.

b) About 40 Air Force and Navy aircraft were used in the manufacturing man-hour sample. For the other cost elements, usable data was found for about 25 aircraft. The CER's, with some qualifications, are meant to apply to all types of aircraft, e.g., fighters, bombers, etc., as well as to both subsonic and supersonic aircraft.

c) Numberous data adjustments were made by PRC including the application of "Company Adjustment Factors" for certain companies whose costs in the basic sample appeared to be generally low or high. This "bias" observed by PRC could result from either company accounting practices, from manufacturer efficiency, or both. PRC's description of the

FIGURE 5

OASD (SA) AIRCRAFT COST RESEARCH STUDIES

1. FIXED-WING AIRFRAME COSTS
2. LARGE TRANSPORT STUDY
3. COMMERCIAL SST
4. EXPERIMENTAL CER's FOR TRANSPORTS
5. HELICOPTER PROCUREMENT COSTS

data problems and its various data adjustments make worthwhile reading for those becoming involved with similar problems.

d) PRC utilized a number of variables, other than aircraft physical and performance characteristics, to account for certain of the other factors affecting cost. These included a production rate variable, a "weight growth" (or engineering change) factor variable, and a "time" variable. (The time variable in PRC's analysis showed a significant explanatory ability. Presumably this variable reflects such factors as improved safety, reliability, crew comfort, etc., which are not reflected by the other explanatory variables but which are correlated with time.)

e) The cost-quantity relationship is derived by preparing statistical CER's at each of four cumulative production quantities, 10, 30, 100, and 300. For a given aircraft, a best-fit line connecting these points, would then represent the cost-quantity curve.

A second edition of the PRC report is currently being completed. This will incorporate some additional cost data as well as attempt to improve some of the techniques such as a needed improvement to its "weight growth" procedure and the separation of recurring from nonrecurring tooling and engineering costs.

2) As an outgrowth of the C-5 analyses and the desire of our office to have an independent cost estimate on this major program, we jointly undertook with PRC a study to develop CER's for large transport aircraft. The PRC portion of this work is presently being finalized. It will be distributed when available. This report will cover only the airframe.

Engine and avionics estimates, however, were made in-house using rougher tools. PRC for the study drew heavily from its work in R547. However, in this study, PRC found that the best statistical results were achieved by utilizing a sample consisting only of transports and bombers. The explanatory variables chosen, such as payload weight, appear more appropriate to the estimation of large transport aircraft. Also, a somewhat different "weight growth" approach was included in the final equations.

3) In 1964 our office monitored and directed for the Department of Commerce a cost analysis study for the Commercial Supersonic Transport program. Two contractors, Operations Research Inc. and PRC, undertook parallel studies to develop cost estimating relations for all phases -- Development, Investment, and Operating -- of the SST. Unfortunately, at this time, this material has not been released for general usage. However, organizations able to provide sufficient justification would be able to review the material. The samples used consisted primarily of DOD aircraft. PRC's procedures were again similar to those used in its R547 report. ORI, however, developed equations separately for subsonic and supersonic aircraft. It also applied an "empirically" developed titanium cost factor to adjust for expected increases in airframe labor, materials, and tooling costs due to the substantial use of titanium in the airframe. Both contractors prepared statistical CER's for engine costs as well as airframe costs. The primary explanatory variables used in the engine equations were: thrust, weight, speed, and turbine inlet temperature. The sample sizes for the engine analyses were quite small, from 5 to 14 engines.

The operating cost equations derived for the study reflect commercial practices, and though of some interest, are not fully useful for DOD purposes.

4. Internally, our office, as part of our technique research program, has experimented on transport aircraft CER's. This study currently is attempting to relate cost primarily to an over-all mission performance level, in this case ton-miles per hour .... and to estimate total aircraft flyaway cost directly rather than estimating the individual components, such as labor, materials, engineering and tooling or the individual subsystems such as airframe, engines, and avionics.

5. We currently are also undertaking internally a program to develop CER's on helicopter airframe procurement costs. These CER's will cover helicopters of all three services. The sample presently consists of approximately 13-17 helicopters. It will, of course, attempt to take into account the work on airframe man-hours already performed by the Army.

6. In discussing these five projects, I have made little mention of avionics procurement costs or of aircraft operating costs. Both these areas have so far seemed to have had little attention paid to them as far as the development of CER's is concerned. My office did sponsor an abortive avionics study last spring. The recent work by Mr. Teng of RAND (RM 4851-PR dated February 1966) which provides CER's for aggregative avionics systems for fighter and interceptor aircraft, is the only presently available significant study that I am aware of. Aircraft avionics

is becoming an increasingly important element of cost and merits greater research efforts.

On operating costs, the SST work as indicated earlier, though interesting, was primarily commercially oriented. My office has recently been trying to get into this area. Thus far, our efforts have been directed primarily at the data problems.

However, PRC has performed for us with some success a test study on fuel CER's for Air Force aircraft using cost data currently available in the Air Force Planning Factors Manual. The sample contained 16 aircraft of various types. An interesting feature of this study is its presentation of two equations, one for use early in the planning stages when only such characteristics as speed and weight are available. The other equation is for use in later stages when an estimate of such characteristics as engine specific fuel consumption is also available. This report will be distributed shortly.

Both the avionics and operating cost fields are clearly wide open for CER work. Data problems, as usual, have probably been the chief stumbling block. We will be most interested in seeing results from the Air Forces' current CER program on O&M costs.

VII. SUMMARY OF ADVANTAGES AND DISADVANTAGES OF STATISTICAL CER's.

Finally, I would like to list what I believe to be the major advantages and disadvantages, of statistical CER's.

A. Advantages (Figure 6)

1) First they permit relatively rapid cost estimation. A quick reaction time is possible after the appropriate CER's are available. (The development of the CER's themselves, of course, is a more lengthy process.)

2) Second, only a relatively small amount of manpower is required to make the estimate with CER's. (Note, however, that making an estimate for a new program is not a trivial exercise. Considerable judgment is required in determining the extent of applicability of the CER to the new program and in making adjustments, if any are required, to the CER estimating procedure.)

3) Third, the procedures for developing statistical CER's, and for the subsequent use of them, is a relatively objective process.

4) Fourth, the procedure is a systematic one which will provide consistent estimates and ones which can be reproduced. This permits considerable visibility so that other persons can relatively easily evaluate them.

5) And most importantly, the use of actual historical data, in a systematic manner, seems to lead to potential accuracy advantages as compared to other current techniques for estimating costs of new systems.

B. Disadvantages (Figure 7)

1) First, past practices and occurrences implied in the historical cost data will be reflected in the derived cost equations and

FIGURE 6

ADVANTAGES OF STATISTICAL CER'S

1. RAPID COST ESTIMATION
2. LESS MANHOURS REQUIRED TO PREPARE THE ESTIMATES
3. RELATIVELY OBJECTIVE
4. PROVIDE CONSISTENT AND REPRODUCIBLE ESTIMATES
5. POTENTIAL PREDICTIVE ACCURACY IMPROVEMENTS

FIGURE 7

DISADVANTAGES OF STATISTICAL CER'S

1. PAST PRACTICES ARE REFLECTED IN THE EQUATIONS
2. TENDENCY TO OVER-SIMPLIFY
3. TOO MUCH VISIBILITY OF ESTIMATION METHOD
4. DOES NOT ELIMINATE PREDICTION UNCERTAINTY
5. STATISTICS QUESTIONABLE WHEN EXTRAPOLATING

therefore in the estimates for the new system. To the extent that future practices will differ, estimation errors are likely to occur. Should, for example, the Value Engineering program or incentives from greater use of incentive contracting, significantly improve manufacturers' efficiencies in future programs, CER's based upon past practices would tend to give overestimates. (Note, however, that provision for such occurrences, at least currently, may be more realistic, and it is this which helps to avoid cost over-optimism.)

2) Second, there is a tendency to over-simplify the many factors which do affect cost. CER's must as a practical matter be restricted to a relatively few explanatory variables. With a new program, there may be introduced a characteristic of major cost importance (such as an unusually stringent reliability requirement) but with respect to which the equations do not discriminate because the characteristic was not of importance in explaining cost in the data sample. Human judgment is necessary with CER's to consider such possibilities and to make any necessary modifications to the CER procedures.

3) Third, a possible disadvantage is that since the CER's can be expected to become common knowledge in the defense community, there is some danger that manufacturers might use them in such a way as to affect their own cost proposals in an undesirable fashion. However, we have not yet thought through the possible consequences. If more often than not, this leads to more realistic cost proposals, the Defense Department will probably be ahead.

4) Fourth, the use of CER's does not, by any means, eliminate uncertainty. As with any cost estimating procedure, considerable uncertainty will inevitably be present on estimates of future systems. However, use of a statistical approach does permit the computation of certain measures of uncertainty - the confidence or prediction intervals. Nevertheless I have not listed this as a major advantage for statistical CER's since:

a) I am not, myself, certain that these predictions, though useful, have the meaning they purport to have. The applicability of the computed statistical probability statements to the aircraft program being costed is not clear.

b) With any estimation technique, some quantitative measure of uncertainty can, and should, be provided even if subjectively arrived at.

A major omission to the program of this symposium is the absence of a paper devoted solely to the subject of providing quantitative information on the magnitude of the uncertainty of particular cost estimates.

5) Finally, it is often necessary to provide estimates of programs whose characteristics are outside the range of the sample data used to derive the CER's. Statistical theory has little to say as to whether the same trends reflected in the sample data will also hold beyond the range of the data. However, this again is a problem common to all present cost estimation techniques. At least with the statistical CER, past trends are identified. Nevertheless, the cost estimator should of course always be very cautious when using CER's to extrapolate far beyond the range of the sample data.

In balance, it is the position of my office that the proper use of CER's offers a significant opportunity for the improvement of the quality of cost estimates on new systems. Further, as the data base improves, further estimation improvements can be expected.