Cost Analysis as an Aid to Aircraft Design

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A statistical approach to aircraft cost estimating, with costs presented in functional form, has been developed. This approach relates cost to various aircraft physical and performance characteristics so that the optimization technique can be applied to identify preferred combinations of variables for specific levels of capability. This enables analytical treatment of many of the decisions associated with system design and cost. The general cost categories usually associated with aircraft, including airframe, propulsion, and other government-furnished aeronautical equipment (GFAE) are discussed. The airframe portion is examined in detail, treating individually the costs for direct labor, materials, overhead, engineering and tooling, general and administrative expense, engineering changes, and profit. The propulsion and other GFAE portions are considered in the aggregate. Aircraft estimates are derived by estimating costs at unit 1000 and then by using generalized "typical" slopes to extrapolate the curves back to unit 1. A generalized estimating equation for a complete aircraft system is presented and represents a type that may be useful in a system selection study.

Nomenclature

a = coefficient for learning curve $C = aN^b$
b = exponent for learning curve
C_e = cumulative average cost of "other GFAE," thousand dollars
C_j = cumulative average cost of turbojet engines at unit 10,000, thousand dollars
C_m/lb_{1000} = unit cost of airframe materials/lb at unit 1000, dollars
C_p = cost of material plus labor plus overhead
C_s = cumulative average cost of turboprop or turboshaft engines at unit 10,000, thousand dollars
C_t = cumulative average cost of complete airframe
ECP = cost of engineering change proposals
ET/lb = cumulative average cost of engineering and tooling/lb of airframe, dollars
F = significance test parameter $[R^2/(1 - R^2)]\cdot[(m - n)/n - 1)]$
F_j = specific fuel consumption, turbojet engine, lb/lb-hr
F_t = specific fuel consumption, turboprop/shaft engine, lb/hp-hr
GA = general and administrative costs
m = number of observations used in regression analysis
MH/lb_1 = man-hours/lb of airframe at unit 1
MH/lb_{1000} = man-hours/lb of airframe at unit 1000
M_j = design Mach number limit of engine, normal operating conditions
n = number of dependent and independent variables in estimating equation
N = cumulative production quantity
P = profit
P' = number of engines per aircraft
P_t = horsepower, military rating [equivalent shaft horsepower (eshp) for turboprop, shaft horsepower (shp) for turboshaft engines]
R^2 = coefficient of multiple determination
R_j = thrust-to-weight ratio, lb/lb ($= T_j/W$)
R_t = power-to-weight ratio, hp/lb ($= P_t/W$)
S = maximum speed at operational altitude, knots
TC = total cost, thousand dollars
T_j = thrust, military rating, less afterburner, lb
W = engine dry weight, less prop (or less afterburner), lb
W_a = airframe (AMPR)† weight, thousands of lb
W_e = aircraft empty weight, thousands of lb
σ = standard error of estimate

Presented as Preprint 64-178 at the AIAA Aviation Design and Operations Meeting, Wichita, Kansas, May 25–27, 1964; revision received December 15, 1964.
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† AMPR is an acronym for Aeronautical Manufacturer's Planning Reports. The AMPR weight is an authoritative specific definition of what is included in airframe weight.

I. Introduction

THIS paper presents a statistical approach to aircraft cost estimating. This approach relates cost to various aircraft physical and performance characteristics so that the "optimization technique" can be applied to identify preferred combinations of variables for specific effectiveness levels. It also enables cost estimates to be made with fair accuracy based solely on the major aircraft characteristics before the detailed design is actually completed.

This statistical approach involves the development of empirically derived cost functions; e.g., an equation relating cost to speed and weight. This type of estimating equations is often referred to as cost estimating relationships (CER's). Briefly described, a CER is how one or more variables affect cost. The objective is to make use of historical data obtained from existing or past systems for purposes of estimating costs of future systems of a similar nature.

The alternative estimating method to the forementioned approach is what might be called the direct detailed approach. It consists of determining the price and quantity of each type of material and each type of labor required for fabrication of the system under consideration. The individually determined costs are then summed. This is possibly a more accurate method if all information is available. In essence, this means a detailed component parts list is necessary, and unfortunately this is often not available until after production is underway.

Emphasis in this paper is on the functional relationships that can be developed, and not the over-all task of systems

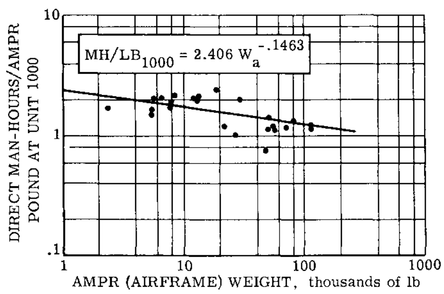

Fig. 1 Direct man-hours per AMPR found at unit 1000 for selected aircraft vs AMPR weight.

Table 1 Equations for estimating man-hours per pound of airframe at unit 1000

Equation	R^2	F test	σ	m
$MH/\text{lb}_{1000} = 0.3031\ W_a^{-0.1181}\ S^{0.3205}$	0.55[a]	$12.81 > F^{0.001}$	0.093[a]	24
$MH/\text{lb}_{1000} = 2.406\ W_a^{-0.1463}$	0.28[a]	$8.56 > F^{0.01}$	0.114[a]	24
$MH/\text{lb}_{1000} = 1.438 - 0.004861\ W_a + 0.0006115S$	0.39	$6.71 > F^{0.01}$	0.366	24
$MH/\text{lb}_{1000} = 1.824 - 61.71\ W_a$	0.21	$5.85 > F^{0.025}$	0.409	24

[a] Of logarithm.

analysis of aircraft. The data on which this analysis is based consisted of historical costs for 24 airframes, 34 turbojet and turboprop/shaft engines, and "other GFAE" for 47 aircraft. The general cost categories usually associated with aircraft are discussed in Sec. II. A generalized estimating equation for a complete aircraft system is presented in Sec. III. Specific aircraft characteristics have been excluded from this paper because of their classified nature.‡

II. Elements of Aircraft Cost

The general cost categories usually associated with aircraft are airframe, propulsion, and other GFAE. The airframe portion is estimated by examining in detail the costs for direct labor, materials, overhead, engineering and tooling, general and administrative expense, engineering changes, and profit. A thorough discussion of airframe costs is contained in Ref. 2. The propulsion and other GFAE portions are considered in the aggregate. If detailed data were available, the labor, materials, etc., could be considered separately for these cost categories too.

In this approach, aircraft estimates are derived by estimating costs at unit 1000 and then by using generalized "typical" slopes to extrapolate the curves back to unit 1. If at least the first lot of aircraft has been produced, the progress curve is then "fitted" between the accumulated cost of the first lot and the estimate at unit 1000. Production unit 1000 is regarded as the "leveling-off" cost and historically has proven more reliable than estimates made at unit 1, where production mistakes have a chance to occur. If and specifically where this cost "leveling-off" occurs is a controversial question.

When specific information is known about any one cost element, it should be used in lieu of the general estimating equations. The price index for all of the derived equations is on a base of 1959 = 100. A conversion factor is given in Sec. III to allow the total generalized estimating equation to be adjusted to 1963 dollars.

Table 2 Aircraft manufacturing cost indices (1959 = 100)

Year	Labor hour wage, dollars[a]	Labor index	Materials index[b]	Aircraft manufacturing cost index, (col 2 + col 3)/2
1959	2.60	100.0	100.0	100.0
1958	2.51	96.5	98.2	97.4
1957	2.36	90.8	98.8	94.8
1956	2.28	87.7	97.3	92.6
1955	2.17	83.5	89.0	86.3
1954	2.08	80.0	84.0	82.0
1953	2.00	76.9	83.0	80.0
1952	1.90	73.1	79.5	76.4
1951	1.79	68.8	79.0	73.9
1950	1.64	63.1	71.3	67.3
1949	1.57	60.4	68.7	64.6

[a] Aerospace Industries Association (AIA) aircraft and parts average hourly earnings.
[b] 1949–1956: AIA price indices for metals and hardware commonly used in constructing airframes. 1957–1959: Monthly labor review index of wholesale prices for metals and metal products.

Airframe

Direct labor

Airframe costs are estimated on a per-pound basis at quantity 1000. Direct labor man-hours are estimated by examining empirical data[3] of similar aircraft, or by using the following estimating equation:

$$MH/\text{lb}_{1000} = 0.3031\ W_a^{-0.1181}\ S^{0.3205}$$

The statistical significance of this equation is shown in Table 1, along with three other regression equations.§ Of somewhat less significance is the second equation in Table 1. This is plotted in Fig. 1 and can be used when an expedient estimate is needed or when the speed variable is not applicable (e.g., for helicopters). A bothersome restriction in the statistical evaluation of this function, as well as all others throughout the report, is that an assumption was made about the form of the distribution function (normality in these cases). Unfortunately, the distribution was not always known.

Estimated man-hours per pound of airframe at quantity 1000 are then multiplied by the current aircraft labor hour wage in order to determine the labor cost per pound of airframe. Wage rates through 1959 and other useful aircraft indices are shown in Table 2. From Table 2, the 1959 hourly wage rate of \$2.60 is used as a multiplier to find the labor cost per pound of airframe.

Another technique is to estimate the man-hours effort at unit 1 rather than unit 1000. One company has found a general relationship between direct man-hours at unit 1 and total airframe (AMPR) weight. This is shown in Fig. 2 along with another company's man-hours curve. The resulting equation is shown in Table 3.

Using man-hours per pound is only a "means to an end" of arriving at total cost. It is recognized that other activities probably should not be based on direct labor man-hours because of the way individual manufacturers define direct labor. (For example, inspection manpower is alternatively classified as direct labor or overhead.)

Materials

Material costs at unit 1000 are estimated by examining the regression line derived from available data on post World War II fighters and bombers (see Fig. 3) or by using the equation for the regression line:

$$C_m/\text{lb}_{1000} = 0.002692S^{1.2415}$$

‡ Specific aircraft characteristics and costs are contained in Ref. 1.

§ Regression equations make possible estimates of the dependent variable from the independent variable or variables. These equations are the result of correlation analysis. Correlation analysis also provides a measure of the accuracy of such estimates (e.g., the standard error of estimate, σ) and the degree of correlation (e.g., the coefficient of correlation, R^2). A test can also be made of the significance of the estimating equations (e.g., the F test).

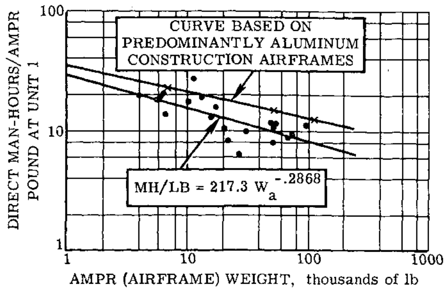

Fig. 2 Direct man-hours per AMPR pound at unit 1 for selected aircraft.

The significance of the estimating equation is shown in Table 4 with results of separate regressions of fighters and bombers. Caution should be used in extrapolating beyond the limits shown by the regression line.

Overhead

An appropriate overhead factor (sometimes referred to as the factory burden rate) is applied to the labor cost per pound of airframe. An aircraft industry average overhead rate of 150% can be used. It is recognized that overhead rates fluctuate widely (generally from 125% to 185%) and are also dependent upon a specific company's organizational structure.

Application of the learning curve

After the material, labor, and overhead costs for unit 1000 are determined, the learning curve principle is applied. In the absence of specific data about an individual manufacturer's experience or a particular type of aircraft, or where time is not sufficient to determine the individual labor and materials learning curves, the slope of the individual curves can be estimated from generalized industry curves. Such curves for labor and materials (with the slopes noted) are shown in Figs. 4 and 5. Both curves are based on earlier work completed at the Rand Corporation, and the labor curve is substantiated by the data shown in Table 5. These curves are used to extrapolate the values learned at unit 1000 back to unit 1.

The complete airframe can be estimated on a "per pound" basis. However, it may be useful to examine the total production cost curve of the airframe. Therefore, the cumulative average curves are calculated for the labor plus overhead and material unit curves and then summed. There are many methods of determining the cumulative average curve from the unit curve. The method used by the author was one previously developed at General Electric Technical Military Planning Operation.[4]

Table 3 Equation for estimating man-hours per pound of airframe at unit 1

Equation	R^2	F test	σ	m
$MH/\mathrm{lb}_1 = 217.3\, W_a^{-0.2868}$	0.49^a	$17.28 > F^{0.001}$	0.12^a	20

^{a} Of logarithm.

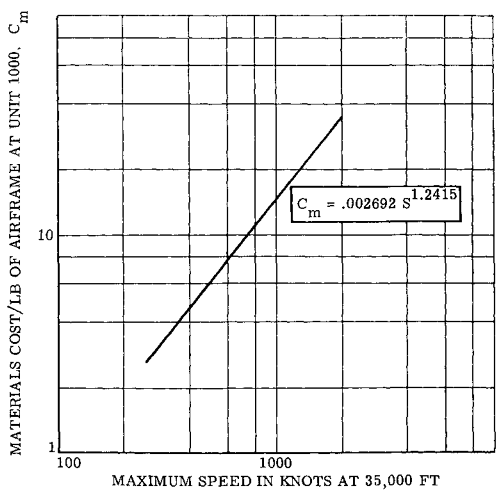

Fig. 3 Estimated minimum materials cost at unit 1000 for selected post World War II fighter and bomber aircraft (1959 = 100).

Engineering and tooling

The cumulative average engineering and tooling cost per pound of airframe is shown in Fig. 6. The curve is based on a group of post World War II fighters, bombers, and transports. Tooling cost per pound of a single airframe is related to the total number of units planned for production. Hence, the cumulative average tooling cost for unit 100, if 1000 units were planned, would be different from the cost for unit 100 if 5000 units were planned. This means that Fig. 6 reflects the cumulative average tooling cost for specific planned quantities. When this is added to the cumulative average airframe production cost curve, the total reflects the cost for the same specific planned quantities.

The following equation approximates the engineering and tooling curve for production units between 10 and 4000:

$$ET/\mathrm{lb} = (200/N) + 7.5\, N^{-0.15}$$

where

N = number of units planned for production,

where $10 \leq N \leq 4000$

After the costs are converted from a per-pound basis to a total airframe basis, the engineering and tooling (ET) cost function is thus determined.

GA, ECP, and profit

The remaining cost elements of general and administrative expenses (GA), engineering change proposals (ECP), and profit (P) are combined in equation form. The following percentage factors are commonly used in the aircraft industry:

$GA = 0.1\,(C_p)$ where C_p = material + labor + overhead

$ECP = 0.1\,(C_p + ET + GA)$

$P = 0.1\,(C_p + ET + GA + ECP)$

Table 4 Equations for estimating materials cost per pound of airframe at unit 1000

Type aircraft	Equation	R^2	F test	σ	m
Fighters and bombers	$C_m/\mathrm{lb}_{1000} = 0.002692S^{1.2415}$	0.82^a	$34.487 > F^{0.001}$	0.09^a	10
Fighters	$C_m/\mathrm{lb}_{1000} = 0.004045S^{1.1818}$	0.61^a	$4.68 > F^{0.10}$	0.13^a	5
Bombers	$C_m/\mathrm{lb}_{1000} = 0.004278S^{1.1634}$	0.75^a	$9.00 > F^{0.10}$	0.07^a	5

^{a} Of logarithm.

Table 5 Industry average learning curves by type of airframe, 1954–1957

Type of air frame	"a" value[a]	Unit curve slope, %[b]	Value limit of "N," unit number
1957			
Bomber	15.66	77.5	500
Fighter	25.34	76.7	500
Transport	16.73	74.5	1000
1956			
Bomber	14.97	78.0	500
Fighter	22.26	77.6	1000
Transport	17.07	74.6	500
1955			
Bomber	14.60	77.8	500
Fighter	21.89	77.6	1000
Transport	9.82	78.5	500
1954			
Bomber	16.59	76.3	500
Fighter	19.78	78.3	1000
Transport	10.07	78.7	500

[a] Where $C = aN^b$.
[b] Cost of $2n$th unit as percent of cost of nth unit. Note: The transports for 1957 and 1956 are "new transports" and for 1955 and 1954 are "follow-on transports."[5]

Since

$$GA = 0.1\ C_p$$

$$ECP = 0.1\ C_p + 0.1\ ET + 0.01\ C_p$$

$$P = 0.1\ C_p + 0.1\ ET + 0.01\ C_p + 0.01\ C_p + 0.01\ ET + 0.001\ C_p$$

then C_t, the cumulative average total airframe cost, is

$$C_t = 1.331\ C_p + 1.21\ ET$$

The (C_t) equation is applied to appropriate production units along the C_p and ET curves, and the result is a cumulative average total airframe cost curve.

Several additional points are necessary to clarify the cost estimating technique.

1) Most of the data available on aircraft costs are based on predominantly aluminum construction aircraft. Complexity factors are available and should be used to adjust costs for other types of materials (e.g., titanium or stainless steel).

Table 6 Estimating equations for aircraft engines

Equation	R^2	F test	σ	m
Turboprop/shaft				
$C_s = 17.36 + 0.02016\ P_t - 3.317\ R_t - 8.824\ F_t$	0.98	$98.0 > F^{0.001}$	7.7	10
$C_s = 9.686 + 0.02053\ P_t - 2.829\ R_t$	0.98	$114.2 > F^{0.001}$	7.2	10
$C_s = 1.719 + 0.02072\ P_t$	0.97	$86.0 > F^{0.001}$	7.1	10
Turbojet				
$C_j = -56.58 + 0.01174\ T_j + 6.622\ R_j + 27.99\ M_j - 7.695\ F_j$	0.89	$38.43 > F^{0.001}$	32.5	24
$C_j = -62.99 + 0.01186\ T_j + 5.896\ R_j + 27.95\ M_j$	0.89	$53.96 > F^{0.001}$	31.8	24
$C_j = -35.17 + 0.01385\ T_j + 5.448\ R_j$	0.86	$64.47 > F^{0.001}$	34.1	24
$C_j = -15.17 + 0.01363\ T_j$	0.85	$124.74 > F^{0.001}$	34.8	24

2) With reference to subcontracting, an assumption is made that a subcontractor incurs the same costs as the prime manufacturer.

3) The costs of the research and development study program and the spares provisioning program must be estimated separately.

4) Major model changes may alter the continuous progress curve. However, the original curve remains a valuable tool for projecting the costs of newly changed models.

Propulsion

The costing procedure for the aircraft propulsion varies according to the availability of appropriate propulsion systems. If an existing engine is selected for use, the specific cost curve for that engine is used. Further, if the engine is currently in production, it is necessary to determine the position of the engine on its learning curve so that the production sequence is appropriate for the airframe cost curve.

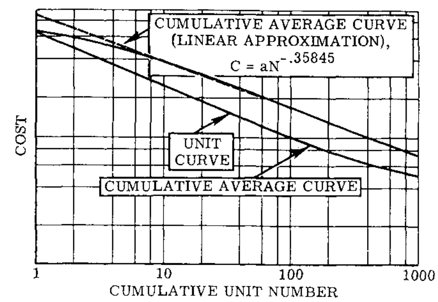

Fig. 4 Average labor learning curve for post World War II aircraft.

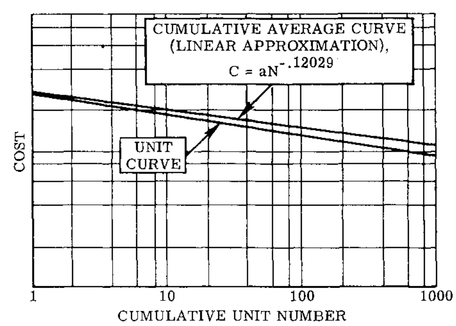

Fig. 5 Average materials learning curve for post World War II aircraft.

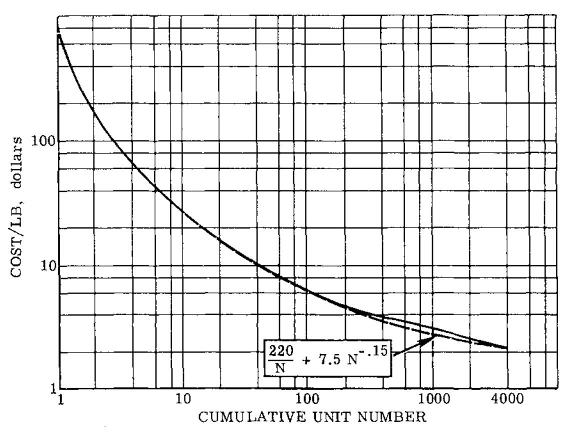

Fig. 6 Cumulative average engineering and tooling cost per pound of airframe (1959 = 100).

Table 7 Cost estimating equations for other GFAE

Type aircraft	Estimating equation	R^2	F test	σ	m
Fighters	$C_e = -275 + 0.312S + 11.7\ W_e$	0.71	$9.79 > F^{0.01}$	101	11
	$C_e = -329 + 0.400S + 17.3\ W_a$	0.71	$9.79 > F^{0.01}$	101	11
Recon. fighters	[a] $C_e = -3690 + 3.27S + 92.4\ W_e$	0.35	$0.26 < F^{0.10}$	2800	4
	[a] $C_e = -8080 + 3.56S + 520\ W_a$	0.65	$0.93 < F^{0.10}$	2070	4
Bombers	$C_e = 1280 + 2.32S + 8.22\ W_e$	0.80	$10.0 > F^{0.025}$	354	8
	$C_e = -1280 + 2.37S + 11.8\ W_a$	0.78	$8.85 > F^{0.025}$	366	8
Recon. bombers	[a] $C_e = 952 - 1.72S + 3.67\ W_e$	0.66	$2.85 < F^{0.10}$	287	6
	[a] $C_e = 932 - 1.69S + 5.53\ W_a$	0.68	$3.18 < F^{0.10}$	278	6
Fighters, recon. fighters	[a] $C_e = -1120 + 1.15S + 33.2\ W_e$	0.19	$1.38 < F^{0.10}$	1018	15
	[a] $C_e = -1320 + 1.36S + 57.2\ W_a$	0.19	$1.38 < F^{0.10}$	1028	15
Bombers, recon. bombers	$C_e = -1000 + 2.00S + 6.49\ W_e$	0.62	$8.96 > F^{0.01}$	373	14
	$C_e = -1020 + 2.03S + 9.44\ W_a$	0.61	$8.58 > F^{0.01}$	374	14
Fighters, recon. fighters; bombers, recon. bombers	$C_e = -909 + 1.52S + 7.64\ W_e$	0.25	$4.29 > F^{0.025}$	748	29
	$C_e = -925 + 1.56S + 11.2\ W_a$	0.25	$4.29 > F^{0.025}$	751	29
Transports, tankers	$C_e = -14.8 - 0.228S + 4.22\ W_e$	0.48	$4.14 > F^{0.05}$	126	12
	$C_e = -3.76 - 0.105S + 4.79\ W_a$	0.46	$3.82 > F^{0.10}$	128	12
Trainers	$C_e = -33.4 + 0.0141S + 10.3\ W_e$	0.97	$48.4 > F^{0.01}$	25	6
	$C_e = -37.7 + 0.0331S + 15.2\ W_a$	0.96	$36.0 > F^{0.01}$	28	6

[a] Equations not significant at the $F^{0.10}$ level.

Since engines are usually designed for application to more than one aircraft, the engine learning curves are often comparatively "flat" by the time a new aircraft model requires the engine. For example, production unit number 5000 of an engine may be delivered for use on production unit number 1 of a new aircraft. When multiengined aircraft are considered, care must be taken to combine cumulative engine quantities with airframe quantities properly. Additionally, spare engines must be accounted for when plotting the cumulative average engine curve with the airframe curve since the spare engines are usually purchased concurrently with the engines installed in the aircraft. A common ratio of spare engines plus installed engines to installed engines is 1.33:1, although this ratio is somewhat lower for one of the current aircraft programs.¶

If the engine designation is not specifically known, one of the following two estimating equations for a turboprop/shaft or turbojet engine can be used:

$$C_s = 9.686 + 0.02053\ P_t - 2.829\ R_t$$

or,

$$C_j = -62.99 + 0.01186\ T_j + 5.896\ R_j + 27.95\ M_j$$

The significance of the estimating equations is shown in Table 6 along with results of other multiple correlations between engine cost and other combinations of engine physical and performance characteristics. Several reservations should be mentioned concerning the data inputs to the correlations.

1) Because of the various ways that engine manufacturers "charge off" their research, development, and tooling, it is

Table 8 Generalized cost estimating equations

Airframe labor, overhead and miscellaneous charges	Airframe materials and miscellaneous charges	Engineering and tooling and miscellaneous charges
I(1) all aircraft where speed is a consideration		
$TC = 1.33[33.98\ W_a^{0.88}\ S^{0.32}\ N^{-0.36}]$	$+\ 1.33[0.007\ S^{1.24}\ W_a\ N^{-0.12}]$	$+\ 1.21\{W_a[(220/N) + 7.5\ N^{-0.15}]\}\ +$
or I(2) where speed is not a consideration		
$1.33[269.75\ W_a^{0.85}\ N^{-0.39}]$		

Propulsion			Other GFAE (electronic)
II(1) where engine is available at "level-off" production price	III(1) turbojet engine		IV(1) fighter
$P'[0.13$	$(-467.34 + 0.088\ T_j + 43.74\ R_j + 207.37 M_j)]$	+	$[-329 + 0.4\ S + 17.3\ W_a]$
Or II(2) where development of new engine is needed	or III(2) turboprop/shaft engine		or IV(2) bomber
$P'[(P' \cdot 1.33\ N)^{-0.22}$	$(71.85 + 0.15\ P_t - 20.99\ R_t)]$	+	$[-1280 + 2.37S + 11.8\ W_a]$
Adjustment factors (to account for unknowns and current price levels)	or III(3) turbojet engine when only thrust data available		or IV(3) transport or tanker
Quantity / Factor: 10 / 1.51; 100 / 1.49; 500 / 1.31; 1000 / 1.25	$(-112.54 + 0.10\ T_j)]$	+	$[-3.76 - 0.10\ S + 4.79\ W_a]$
	or III(4) turboprop/shaft engine when only horsepower data available		or IV(4) trainer
	$(12.75 + 0.15\ P_t)]$	+	$[-37.7 + 0.03\ S + 15.2\ W_a]$

Adjustment factors (to account for unknowns and current price levels)

Quantity	Factor
10	1.51
100	1.49
500	1.31
1000	1.25

¶ The ratio is reported to be 1.25:1 for an advanced bomber program.

Table 9 Example of computer output

INPUTS.							
W(A)	N	S	T(J)	R(J)	M(J)	P	CODE
+.13200000 52	10000000 52	+.12000000 54	+.15800000 55	+.29000000 51	+.24000000 51	+.10000000 51	1211000069
OUTPUTS.							
TOT CUM AV.	LABOR/OH.	MATERIALS.	ENG/TOOL.	PROPULSION.	OTHER GFAE.		
+.41851309 54	18699292 54	+.61845419 53	+.43618883 53	+.88119866 53	+.37936000 53	+.	1211000069
INPUTS.							
W(A)	N	S	T(J)	R(J)	M(J)	P	CODE
+.13200000 52	10000000 53	+.12000000 54	+.15800000 55	+.29000000 51	+.24000000 51	+.10000000 51	1211000069
OUTPUTS.							
TOT CUM AV.	LABOR/OH.	MATERIALS.	ENG/TOOL.	PROPULSION.	OTHER GFAE.		
+.22965637 54	81926638 53	+.46883232 53	+.95175617 52	+.53392936 53	+.37936000 53	+.	1211000069
INPUTS.							
W(A)	N	S	T(J)	R(J)	M(J)	P	CODE
+.13200000 52	50000000 53	+.12000000 54	+.15800000 55	+.29000000 51	+.24000000 51	+.10000000 51	1211000069
OUTPUTS.							
TOT CUM AV.	LABOR/OH.	MATERIALS.	ENG/TOOL.	PROPULSION.	OTHER GFAE.		
+.16562051 54	46016578 53	+.38631221 53	+.54187818 52	+.37617932 53	+.37936000 53	+.	1211000069
INPUTS.							
W(A)	N	S	T(J)	R(J)	M(J)	P	CODE
+.13200000 52	10000000 54	+.12000000 54	+.15800000 55	+.29000000 51	+.24000000 51	+.10000000 51	1211000069
OUTPUTS.							
TOT CUM AV.	LABOR/OH.	MATERIALS.	ENG/TOOL.	PROPULSION.	OTHER GFAE.		
+.14632425 54	35894270 53	+.35540827 53	+.46016935 52	+.32351454 53	+.37936000 53	+.	1211000069
INPUTS.							
W(A)	N	S	T(J)	R(J)	M(J)	P	CODE
+.56000000 52	10000000 52	+.52000000 53	+.59700000 54	+.22900000 51	+.17000000 51	+.60000000 51	1112000069
OUTPUTS.							
TOT CUM AV.	LABOR/OH.	MATERIALS.	ENG/TOOL.	PROPULSION.	OTHER GFAE.		
+.89201497 54	51143908 54	+.92904391 53	+.18504981 54	+.41301687 53	+.61320000 53	+.	1112000069
INPUTS.							
W(A)	N	S	T(J)	R(J)	M(J)	P	CODE
+.56000000 52	10000000 53	+.52000000 53	+.59700000 54	+.22900000 51	+.17000000 51	+.60000000 51	1112000069
OUTPUTS.							
TOT CUM AV.	LABOR/OH.	MATERIALS.	ENG/TOOL.	PROPULSION.	OTHER GFAE.		
+.43750262 54	22407525 54	+.70428142 53	+.40377535 53	+.41301687 53	+.61320000 53	+.	1112000069
INPUTS.							
W(A)	N	S	T(J)	R(J)	M(J)	P	CODE
+.56000000 52	50000000 53	+.52000000 53	+.59700000 54	+.22900000 51	+.17000000 51	+.60000000 51	1112000069
OUTPUTS.							
TOT CUM AV.	LABOR/OH.	MATERIALS.	ENG/TOOL.	PROPULSION.	OTHER GFAE.		
+.30950106 54	12585865 54	+.58031946 53	+.22988771 53	+.41301687 53	+.61320000 53	+.	1112000069
INPUTS.							
W(A)	N	S	T(J)	R(J)	M(J)	P	CODE
+.56000000 52	10000000 54	+.52000000 53	+.59700000 54	+.22900000 51	+.17000000 51	+.60000000 51	1112000069
OUTPUTS.							
TOT CUM AV.	LABOR/OH.	MATERIALS.	ENG/TOOL.	PROPULSION.	OTHER GFAE.		
+.27370699 54	98173412 53	+.53389547 53	+.19522336 53	+.41301687 53	+.61320000 53	+.	1112000069
INPUTS.							
W(A)	N	S	T(J)	R(J)	M(J)	P	CODE
+.11290000 53	10000000 52	+.54600000 53	+.11200000 55	+.26000000 51	+.18000000 51	+.80000000 51	1112000069
OUTPUTS.							
TOT CUM AV.	LABOR/OH.	MATERIALS.	ENG/TOOL.	PROPULSION.	OTHER GFAE.		
+.17790696 55	96397990 54	+.19899797 54	+.37307364 54	+.10839408 54	+.13462400 54	+.	1112000069
INPUTS.							
W(A)	N	S	T(J)	R(J)	M(J)	P	CODE
+.11290000 53	10000000 53	+.54600000 53	+.11200000 55	+.26000000 51	+.18000000 51	+.80000000 51	1112000069
OUTPUTS.							

not clear whether all of these charges are excluded from the cost data that were used as inputs to the correlations.

2) Where costs were not available at production quantity 10,000, extrapolations were made using average industry engine slopes reflecting the progress curve.

3) In some cases, the price level of the cost input was unknown, so a "best estimate" was made in order that all costs be in 1959 dollars.

4) Since there was a range of values for almost every cost or physical/performance characteristic input (varying with the source of data), a "best estimate" of the most realistic value was made.

5) An attempt was made to reflect the cost of a representative "dash number" engine.

Average production slopes derived from learning curves of 11 turbojet and 3 turboprop/shaft engines are shown in Figs. 7 and 8. The appropriate "typical" curve may be used to extrapolate the computed costs at unit 10,000 back to unit 1.

Other GFAE

The GFAE category normally includes the cost of fire control systems, airborne weapons, special electronics that are not an integral part of the airframe, and engines. The cost category considered here is designated "other GFAE" because the propulsion cost is estimated separately.

No cost/quantity relationships are evident for the "other GFAE" costs when they are considered in the aggregate and when all production units of an aircraft model are examined. This is partially explained by the way the government purchases these items in very large quantities; its cost-accounting system does not lend itself to allocating any benefits from the progress curve to individual manufacturers. Hence a "flat" progress curve is plotted for this cost element.

A correlation was found between the cost of "other GFAE" and aircraft speed and weight. The estimating equations for various classes of aircraft are as follows:

Fighters

$$C_e = -329 + 0.400S + 17.3\ W_a$$

Bombers

$$C_e = -1280 + 2.37S + 11.8\ W_a$$

Transports and Tankers

$$C_e = -3.76 - 0.105S + 4.79\ W_a$$

Trainers

$$C_e = -37.7 + 0.0331S + 15.2\ W_a$$

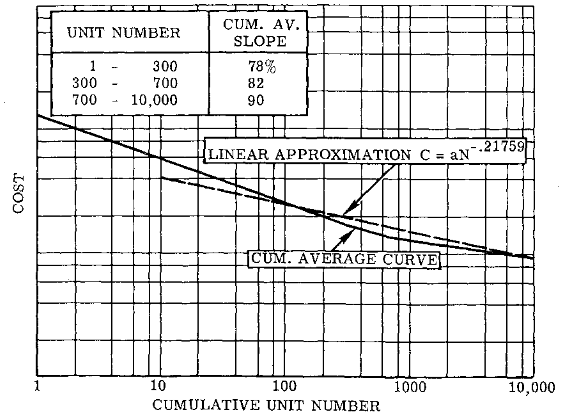

Fig. 7 Average production slopes for post World War II turbojet engines (including materials, labor, overhead, and miscellaneous expenses).

The significance of the estimating equations is shown in Table 7, with results of multiple correlations of other combinations of aircraft types.

The cumulative average "other GFAE" curve and the cumulative average propulsion curve are then considered together with the cumulative average airframe curve. The three components are summed to obtain the cumulative average total aircraft cost curve.

III. Generalized Aircraft Cost Equation

A generalized cost-estimating equation for a complete aircraft was derived by combining the individual aircraft component cost functions. This algebraic equation is presented in Table 8 and has been programed for a computer.

The generalized equation may be extremely useful in a system selection study in which the cost implications of varying the aircraft physical and performance characteristics can be examined. It can be included with other system costs and used to obtain an optimum over-all combination of aircraft characteristics to achieve a given effectiveness. For example, relationships have previously been established for aircraft maintenance and petroleum, oil, and lubricant (POL) costs where these two costs are functions of some of the same variables as developed in the aircraft cost equation. It is necessary for the user to furnish only the following information: aircraft type, maximum speed, airframe weight, type of engine, engine weight, and (if turbojet) engine design Mach number limit.

The machine time required for obtaining values for five cost components (labor and overhead, materials, engineering and tooling, propulsion, and other GFAE) and total cost for five "N" values of one aircraft program is 45 sec on the IBM 650. Approximately 35 sec of this time is used in punching the output headings and titles. An example of the computer output is shown in Table 9.

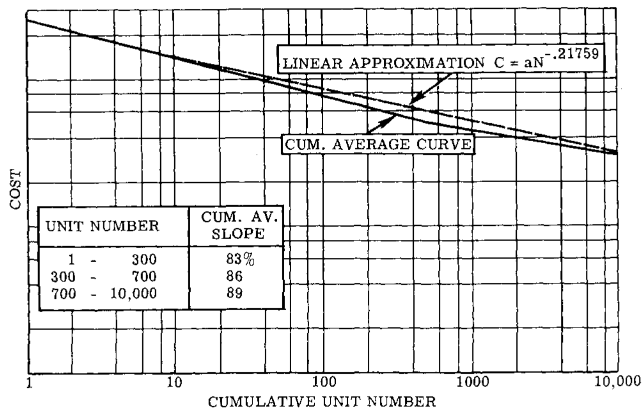

Fig. 8 Average production slopes for post World War II turboprop/shaft engines (including materials, labor, overhead, and miscellaneous expenses).

Table 10 Comparison of actual or extrapolated costs with machine-computed costs

Aircraft	"N" value	Cumulative average cost in dollars at 1959 price level: Actual or extrapolated, C	Computed, $\hat{C}$	Difference, $(C - \hat{C})/C$
B-1	100	4300	4375	−0.02
	500	2700	3095	−0.15
	1000	2550	2737	−0.07
B-2	100	14,600	8976	0.38
	500	8000	6509	0.19
	1000	6400[a]	5818	0.09
F-1	100	2000	1428	0.29
	500	1140	1027	0.10
	1000	1010	913	0.10
F-2	100	3560	1746	0.51
	500	2300[a]	1318	0.43
	1000	1900[a]	1195	0.37
F-3	100	2500	1423	0.43
	500	1260[a]	1032	0.18
	1000	1100[a]	914	0.17
F-4	100	6200	2174	0.65
	500	2400[a]	1558	0.35
	1000	1550[a]	1373	0.11
C-1	100	6800[a]	5454	0.20
	500	4000[a]	3527	0.12
	1000	3100[a]	2984	0.04
C-2	100	6500	5121	0.21
	500	3700[a]	3489	0.06
	1000	3000[a]	3033	−0.01

[a] Indicates extrapolated cost.

The cost estimating program was evaluated by comparing costs estimated by the foregoing program with the actual or extrapolated costs for eight aircraft programs. This is shown in Table 10. Of the eight aircraft sampled for cost testing and evaluation, the average estimating errors (of predicted to actual) ranged from 33% (−2% to 65%) at unit 100 to 12% at unit 1000. Differences exist because of varying airframe and engine learning curves, extensive model changes, manufacturers with different overhead rates, and other unknown factors. Because of the limited amount of data available to the author on engineering and tooling costs, it is suggested that a more penetrating analysis be made of this cost function with more comprehensive data.

As an afterthought, it was decided that a table of "factors of compensation" might lend more reality to the final cost

Table 11 Adjustment factors

	Quantity	Percentage adjustment, %
1) Factors of compensation: to compensate for uncertainties and extra charges added to contracts	10	35
	100	33
	500	17
	1000	12
2) Price level adjustment: to compensate for price level changes from 1959 to 1963	10	12
	100	12
	500	12
	1000	12
		Factor to multiply by
3) Total adjustment: sum of 1 and 2 above	10	1.51
	100	1.49
	500	1.31
	1000	1.25

estimating equation. This table was derived from the differences between actual total costs and the sum of the predicted costs of components. Additionally, a conversion is necessary to adjust the 1959 price level costs (used in this analysis) to more current dollars (1963 price levels).

These two kinds of adjustments and their sum are shown in Table 11 and also footnoted in Table 8.

References

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