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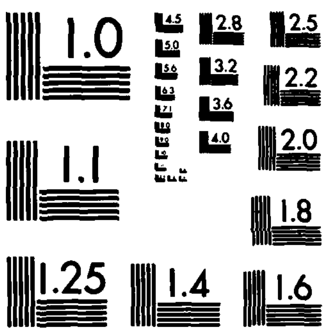

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A COMPARISON OF COST MODELS FOR FIGHTER AIRCRAFT

Joseph P. Large

September 1977

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A COMPARISON OF COST MODELS FOR FIGHTER AIRCRAFT

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This paper was prepared for presentation to the tenth session of the ASD/Industry Cost Estimating Workshop, September 27-29, 1977.

One of the perennial subjects for discussion among persons interested in parametric cost models is that of the degree of homogeneity required in the data sample. For example, is it better to develop separate models for fighter aircraft, bombers, transports, etc., than to rely on a single model for all types? Intuitively, it seems obvious that we should get better estimates of fighter aircraft cost from a fighter aircraft model than from a model derived from a sample including the KC-135 tanker and the C-5 cargo aircraft. Yet, because of the size and nature of the samples, it sometimes develops that what seems intuitively obvious is difficult to demonstrate in practice. This paper describes an exercise in which a fighter-only model was developed, not to settle a methodological issue but to assist in a specific cost-estimating problem. The results are being published because of the widespread interest in DOD and the aerospace industry in estimating models.

The most recent Rand aircraft airframe cost model is generally referred to as DAPCA III.* The equations in that model were derived from a sample of 26 U.S. military aircraft as described in *Parametric Equations for Estimating Aircraft Airframe Costs*.** To develop a model that would be more suitable to fighters the sample was initially reduced to attack and fighter aircraft, the B-58 (because of its high speed) and the T-38 (because of its similarity to the F-5).

Then, to increase the size of the sample several older aircraft were added--the F-84A, F-86A, F-86D, F-89, F3D, and F-101--as well as one new fighter, the F-15. To accommodate the older aircraft for which less detailed data were available it was necessary to combine two of the cost categories in DAPCA III--nonrecurring manufacturing labor and materials--into a single category, Development Support. Regression analysis was then used to derive estimating equations for the functional cost elements listed below at four production quantities--25, 50, 100, and 200:

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*H. E. Boren, Jr., *A Computer Model for Estimating Development and Procurement Costs of Aircraft* (DAPCA III), The Rand Corporation, R-1854-PR, March 1976.

**J. P. Large, et al, The Rand Corporation, R-1693-1-PA&E, February 1976.

Cumulative total engineering hours
Cumulative total tooling hours
Development support cost
Flight test cost
Cumulative recurring manufacturing hours
Cumulative recurring manufacturing materials cost
Cumulative recurring quality control hours

In all previous airframe cost models developed at Rand airframe unit weight and maximum speed were found to be the most reliable independent variables. This exercise, however, afforded an opportunity to examine an explanatory variable that was thought to have special applicability to fighter aircraft, i.e., specific power, which is equal to:

$$\frac{\text{(Static thrust)(Max speed)}}{\text{Combat weight}} \times .003069$$

Both speed and specific power were considered separately along with airframe weight and other variables in the regression analyses, and, as we shall see, specific power does improve the goodness of fit in some instances.

The initial regression analyses of a somewhat heterogeneous sample of 26 aircraft showed that fighters are sufficiently different as a class to warrant a separate category. Attack aircraft, the B-58 and the T-38, had to be deleted from the sample to obtain some homogeneity in cost as well as in weight and speed. At the same time, since previous experience had shown that good results can be obtained with a more heterogeneous sample, a parallel investigation was carried on with a larger sample of 31 aircraft. The two samples from which the final equations were derived were:

Fighters	31 Aircraft
F3D	All fighters
F-3(F3H)	A-3
F-4	A-4
F-6(F4D)	A-5
F-14	A-6
F-15	A-7
F-84A	B-47
F-86A	B-52
F-86D	B-58
F-89	B-66
F-100	C-5
F-101	C-130
F-102	C-133
F-104	KC-135
F-105	C-141
F-106	T-38
F-111	

The final equations for each cost element are given here along with those from DAPCA III. The estimates obtained from those equations are compared with actual costs of four fighters, the F-4, F-111, F-14, and F-15. The term *actual cost* is somewhat inaccurate, because hours were converted to dollars using the same nominal 1973 hourly rates for all aircraft. Actual rates for the various companies differed substantially from those shown below.

Engineering	$20.06
Tooling	18.63
Quality Control	16.83
Manufacturing	15.77

Those are wraparound rates, i.e., they include burden, G&A, and miscellaneous direct charges. Admittedly, they are far below current rates, but we show only relative costs and they should suffice for that purpose.

Engineering Hours

Engineering refers both to engineering for the basic airframe and to the system engineering performed by the prime contractor. Engineering hours not directly attributable to the aircraft itself (e.g., those charged to ground handling equipment, spares, and training equipment) are not included. Engineering hours expended as part of the tool and production-planning function are included with the cost element *Tooling*.

Table 1 shows four regression equations for estimating cumulative total engineering hours for 100 aircraft. The statistical parameters suggest that the all-fighter equations should be superior, and of the two, the one incorporating specific power as a variable instead of speed should be preferred.

Table 1

ENGINEERING HOUR REGRESSION EQUATIONS

	R^2	SEE(%)	F	N
All-Fighter				
$E_{100} = .000015\ W^{1.14}\ S^{1.29}$ (.000) (.000)	.93	+27,-21	96	17
$E_{100} = .0276\ W^{1.24}\ P^{.72}$ (.000) (.000)	.96	+21,-17	161	16
31-Aircraft				
$E_{100} = .000275\ W^{.82}\ S^{1.33}$ (.000) (.000)	.83	+44,-31	72	31
DAPCA III				
$E_{100} = .0234\ W^{.66}\ S^{.96}$ (.000) (.008)	.95	+30,-23	26	9

Where: E_{100} = Cumulative total engineering hours at 100 aircraft (thousands)

W = Airframe unit weight (lb)

P = Specific power (hp/lb)

S = Maximum speed (kn)

Figures in parentheses are levels of significance of independent variables.

SEE = Standard error of estimate. N = Sample size.

If we look at a sample of four existing fighters, we find some corroboration of that. Shown below are ratios of estimated engineering hours at 100 aircraft to actual engineering hours.

	F-4	F-111	F-14	F-15	Mean Absolute Relative Deviation (%)
All-fighter-specific power	.97	.80	1.06	.92	9
All-fighter-speed	.98	.99	1.00	.72	8
31 aircraft	.98	.80	.88	.71	16
DAPCA III	1.28	.93	1.03	.90	12

Note that no model is consistently reliable, and the all-fighter models are not perceptibly better than the others. What is more noteworthy, however, is the tendency of all models to underestimate. That bias should be considered when using any of the models to estimate engineering hours for a modern fighter.

Tooling Hours

Tooling refers only to the tools designed for use on a particular program, e.g., assembly tools, dies, jigs, fixtures, work platforms, and test and checkout equipment. Tooling hours include all effort expended in tool and production planning; design, fabrication, assembly, installation, modification, maintenance, and rework of tools; and programming and preparation of tapes for numerically controlled machines. Tooling hours are less well predicted by aircraft characteristics than are the other major cost elements, and none of the equations shown in Table 2 can be highly recommended. Careful observers will remark the absence of a production rate variable in the equations; and while we concede that such a variable would be logical and desirable, rate was not even remotely significant in any of the analyses.

Again we are interested in knowing how estimates differ when the sample is changed and whether an all-fighter sample offers any perceptible

Table 2

TOOLING HOUR REGRESSION EQUATIONS

All-Fighter	R^2	SEE(%)	F	N
$T_{100} = 4.754\ W^{.715}\ P^{.446}$ $(.010)\ (.015)$	.71	+42,-30	16	16
$T_{100} = .0583\ W^{.657}\ S^{.760}$ $(.035)\ (.040)$	.67	+46,-32	13	16
31-Aircraft				
$T_{100} = .094\ W^{.65}\ S^{.61}\ R^{.68}$ $(.000)\ (.002)\ (.042)$	.77	+46,-32	30	31
DAPCA III				
$T_{100} = .47\ W^{.64}\ S^{.50}$ $(.000)\ (.025)$	.71	+51,-34	27	25

Where: T_{100} = Cumulative total tooling hours at 100 aircraft (thousands)
R = Gross takeoff weight/Airframe unit weight

advantages. Ratios of estimates to actuals for four aircraft are shown below.

	F-4	F-111	F-14	F-15	Mean Absolute Relative Deviation (%)
Fighters-specific power	.96	.71	1.27	1.32	23
Fighters-speed	.96	.81	1.22	1.13	14
31 aircraft	1.02	.84	1.00	1.01	5
DAPCA III	1.03	.86	1.26	1.18	15

All equations overestimate the F-15 and all underestimate the F-111. No best overall equation stands out, and again the case for an all-fighter sample is not persuasive.

Manufacturing Labor

Recurring manufacturing labor is all the direct labor necessary to machine, process, fabricate, and assemble the major structure of an aircraft and to install purchased parts and equipment, engines, avionics, and ordnance items, whether contractor-furnished or government furnished. The labor component of off-site manufactured assemblies is included in this cost element.

Table 3 shows two regression equations for the all-fighter sample and two DAPCA III equations, one with time of first flight as an independent variable and one without. In the second fighter equation speed is not statistically significant, and on the basis of statistical measures the specific-power equation is less attractive than the other three. It generally estimates higher, and in none of the cases examined does it produce the best estimate.

Table 3

MANUFACTURING HOUR REGRESSION EQUATIONS

All-Fighter	R^2	SEE(%)	F	N
$ML_{100} = .878\ W^{.986}\ P^{.246}$ (.000) (.111)	.76	+37,-27	21	16
$ML_{100} = .097\ W^{1.01}\ S^{.306}$ (.001) (.324)	.73	+40,-29	17	16
31-Aircraft				
$ML_{100} = .205\ W^{.82}\ S^{.461}$ (.000) (.005)	.86	+38,-27	83	31
DAPCA III				
$ML_{100} = .79\ W^{.85}\ S^{.56}\ T^{-.53}$ (.000)(.004)(.057)	.87	+37,-27	48	25
$ML_{100} = .35\ W^{.79}\ S^{.42}$ (.000) (.021)	.85	+40,-29	62	25

Where: ML_{100} = Cumulative recurring manufacturing labor hours at 100 aircraft (thousands)

T = Number of quarters after 1942 that first flight of a production aircraft occurred

	F-4	F-111	F-14	F-15	Mean Absolute Relative Deviation (%)
Fighters-specific power	.72	1.18	1.16	1.09	18
31 aircraft	.71	1.14	1.06	.97	13
DAPCA III-Time	.79	1.04	.91	.81	13.3
DAPCA III-No Time	.66	1.05	.99	.91	12.3

The DAPCA III equation that includes time as a variable estimates lowest for more recent aircraft because the negative exponent implies a secular trend toward fewer factory labor hours. The cumulative effect of that trend is shown by the substantial differences in th APCA III estimates of the F-15 compared to a 1967 aircraft, the F-11 The utility of that variable for contemporary and future aircra is dubious. We believe that DAPCA III without time is the preferred equ for such aircraft.

Manufacturing Materials

Manufacturing materials include raw and semifabricated materials plus purchased parts (standard hardware items such as electrical fittings, calves, and hydraulic fixtures) and purchased equipment (actuators, motors, landing gear, instruments, etc.). Both contractor-furnished and government-furnished equipment is included. All costs have been adjusted to 1973 dollars using one index for raw materials and purchased parts and a separate index for purchased equipment.

The two all-fighter equations shown in Table 4 are marginally preferable to the others on the basis of statistical indicators, but in both the weight variable has an exponent greater than 1.0. That means that as airframe weight increases the cost per pound of materials increases, which is contrary to the normal rule and to the relationship in the other three equations. Note that the time variable in DAPCA III-Time has a positive sign which reflects the increasing cost of materials (apart from inflation). As shown next page, it manifests itself strongly in the more recent aircraft. For the F-14 and F-15 that variable causes cost to be greatly overstated.

Table 4

REGRESSION EQUATIONS FOR MANUFACTURING MATERIALS

	R^2	SEE(%)	F	N
All-Fighter				
$MM_{100} = .404\ W^{1.23}\ P^{.567}$ (.000) (.001)	.88	+35,-26	50	16
$MM_{100} = .0011\ W^{1.08}\ S^{1.11}$ (.000) (.001)	.89	+35,-26	50	16
31-Aircraft				
$MM_{100} = .00571\ W^{.96}\ S^{1.06}$ (.000) (.000)	.87	+44,-30	90	31
DAPCA III				
$MM_{100} = .025\ W^{.83}\ S^{.75}\ T^{.46}$ (.000)(.000)(.013)	.87	+42,-29	49	25
$MM_{100} = .050\ W^{.88}\ S^{.87}$ (.000) (.001)	.86	+43,-30	67	25

Where: MM_{100} = Cumulative recurring materials cost at 100 aircraft (thousands of 1973 dollars)

	F-4	F-111	F-14	F-15	Mean Absolute Relative Deviation (%)
Fighters-Power	.76	.74	1.13	1.16	20
Fighters-Speed	.80	.86	1.10	.99	11
31 aircraft	.85	.84	1.10	1.05	11
DAPCA III-Time	.78	.86	1.24	1.22	21
DAPCA	.87	.82	1.08	1.06	11

Judging from its performance on the sample above, DAPCA III-Time is likely to overestimate all new aircraft because of the increasing influence of its Time variable. The Fighter-Speed equation is as good as but no better than those derived from more heterogeneous samples.

Development Support

As mentioned previously, the category Development Support refers to the nonrecurring manufacturing effort required to produce mock-ups, static test items, and other items of hardware (excluding complete flight test aircraft) during the development phase of an aircraft program. In DAPCA III manufacturing labor and materials were estimated separately, but they are combined here because data on the older fighters that were added to the sample were available only in that form.

Table 5 shows that all equations have high standard errors, and the ratios below confirm their unreliability. All equations overestimate the F-4 and F-14--in some instances by over 100 percent--and all equations substantially underestimate the F-111. The inclusion of the number of flight test aircraft as an additional independent variable does not appear to reduce estimating errors even though it is shown to be statistically significant in the three new equations.

	F-4	F-111	F-14	F-15	Mean Absolute Relative Deviation (%)
Fighters-Power	1.45	.47	2.19	.76	60
Fighters-Speed	1.41	.55	2.02	.58	58
31 aircraft	1.40	.44	1.76	.60	53
DAPCA III	1.28	.49	1.93	.65	52

Fortunately, the dollar amounts are not a large enough proportion of total program cost to cause concern, because all this exercise really shows is that none of the equations captures an important element of Development Support cost. It is of less importance that we find no basis for preferring either of the all-fighter equations to DAPCA III.

Flight Test

Flight test includes all costs incurred by the contractor in the flight test program--engineering planning, data reduction, manufacturing support, instrumentation, etc. Cost of flight test aircraft and costs incurred by the Air Force or Navy are excluded. From Table 6 we note that all equations include the number of flight test aircraft as an explanatory variable, which makes sense because many of the costs included in this

Table 5

REGRESSION EQUATIONS FOR DEVELOPMENT SUPPORT

Equation	R^2	SEE(%)	F	N
All-Fighter				
$DS = .037\ W^{1.13}\ P^{.53}\ FTA^{.98}$ (.018) (.122) (.021)	.78	+84,-46	14	16
$DS = .00032\ W^{1.17}\ S^{.63}\ FTA^{1.10}$ (.034) (.367) (.018)	.75	+92,-48	12	16
31-Aircraft				
$DS = .00429\ W^{.77}\ S^{.95}\ FTA^{.88}$ (.000) (.009) (.000)	.77	+71,-41	30	31
DAPCA III				
$DS = 15.77\ ML_{NR} + MM_{NR}$				
$ML_{NR} = .0007\ W^{.69}\ S^{1.21}$ (.000) (.003)	.53	+106,-52	12	24
$MM_{NR} = .000024\ W^{.72}\ S^{1.92}$ (.000) (.000)	.68	+94,-49	23	24

Where: DS = Development Support cost (thousands of 1973 dollars)

FTA = Number of flight test aircraft

ML_{NR} = Nonrecurring manufacturing labor hours (thousands)

MM_{NR} = Nonrecurring manufacturing materials cost (thousands of 1973 dollars)

category are a function of the number of aircraft involved. Ordinarily, however, we would expect to find some economies of scale—the cost per aircraft should decrease as the number of flight test aircraft increases. In the all-fighter equations the opposite occurs; that fact plus their high-standard errors suggest that they will not be reliable despite the relatively good R^2s. On the other hand, the 31-aircraft and DAPCA III are also undistinguished when judged on their statistical parameters.

Table 6

REGRESSION EQUATIONS FOR FLIGHT TEST

	R^2	SEE(%)	F	N
All Fighter				
$FT = 1.053\ W^{.72}\ P^{.71}\ FTA^{1.16}$ (.060) (.020) (.003)	.85	+67,-40	22	16
$FT = .00104\ W^{.65}\ S^{1.14}\ FTA^{1.22}$ (.149) (.074) (.004)	.81	+75,-43	18	16
31 Aircraft				
$FT = .0022\ W^{.59}\ S^{1.33}\ FTA^{.76}$ (.000) (.000) (.004)	.73	+75,-43	24	31
DAPCA III				
$FT = .13\ W^{.71}\ S^{.59}\ FTA^{.72}$ (.000) (.084) (.001)	.81	+55,-36	21	25

Where: FT = Flight test cost (thousands of 1973 dollars)

As shown below, none of the equations gives good estimates for the F-4 or F-111. For the other two aircraft the estimates are generally better. On the basis of the limited information presented here we are inclined to believe that the DAPCA III model is a better model for estimating fighter flight-test costs than either of the all-fighter models.

	F-4	F-111	F-14	F-15	Mean Absolute Relative Deviation (%)
Fighters-Power	1.38	.47	1.12	1.24	32
Fighters-Speed	1.39	.57	1.04	.95	22
31 aircraft	1.45	.64	1.15	1.07	25
DAPCA III	1.29	.61	1.04	.91	20

Quality Control

Quality control or quality assurance refers to such tasks as receiving inspection; in-process and final inspection of tools, parts, subassemblies, and complete assemblies; and reliability testing and failure-report reviewing. In DAPCA III it was estimated as a percentage of manufacturing labor hours, but in this exercise we used quality control hours on samples of eight fighters and 16 assorted aircraft to derive the equations in Table 7. Statistically, the equations are roughly comparable and, as shown below, estimates from those three equations do not differ much for any of the aircraft.

Table 7

QUALITY CONTROL REGRESSION EQUATIONS

All-Fighter	R^2	SEE(%)	F	N
$QC_{100} = .0321\ W^{1.08}\ P^{.57}$ (.022) (.096)	.84	+32,-24	13	8
$QC_{100} = .00029\ W^{.64}\ S^{1.35}$ (.169) (.055)	.86	+28,-22	16	8
31-Aircraft				
$QC_{100} = .000031\ W^{.86}\ S^{1.36}$ (.000) (.000)	.87	+38,-28	44	16
DAPCA III				
$QC_{100} = .12\ ML_{100}$				

Where: QC_{100} = Cumulative recurring quality control hours at 100 aircraft (thousands).

	F-4	F-111	F-14	F-15	Mean Absolute Relative Deviation (%)
Fighters-Power	1.14	.86	1.46	.84	22
Fighters-Speed	1.24	.88	1.33	.76	24
31 Aircraft	1.24	1.46	1.02	.77	24
DAPCA III-Time	.84	1.04	.91	.52	19
DAPCA III-No Time	.70	1.06	.98	.59	20

No interpretation of the results would be justified, because the change in procedure is more significant than the change in sample. Had a flat 12 percent of manufacturing labor been used in all cases, the 31-aircraft sample would have produced results very close to those for DAPCA III. Mean deviations for the fighter models would be somewhat lower, but no strong preference for any of the models is warranted.

Total Cost

Up to this point we have seen little reason to believe that a model based on fighter aircraft only will give better estimates of fighters than a more broadly based model. It is always interesting, however, to examine the sum of the parts as well as the parts themselves. That comparison is shown below.

	F-4	F-111	F-14	F-15	Mean Absolute Relative Deviation (%)
Fighters-Power	.89	.79	1.18	1.05	14
Fighter-Speed	.87	.87	1.13	.82	14
31 Aircraft	.86	.86	1.13	.89	13
DAPCA III-Time	.89	.84	1.11	.89	12
DAPCA III-No Time	.85	.84	1.11	.90	13

In every instance but one all models err in the same direction, and deviations are all of about the same magnitude. One is inclined to believe, therefore, that when estimating total cost it makes little difference which of the models is used. Since the original purpose of this exercise was to provide a fighter-based model for estimating F-16 costs, estimates of that aircraft were made to determine the extent of the differences that would result from using an all-fighter sample. Table 8 shows the results.

The estimates range from $429 million to $501 million, and four of the estimates are within about five percent of each other. Only the fighter model with speed as an independent variable is outside that range, and it is suspect for statistical reasons. Consequently, if a consensus means anything, an estimate of $475 million to $500 million should be in the right ballpark. That does not settle the question of whether an all-fighter sample is better than an assorted-aircraft sample for developing an F-16 estimating model, but the advantage of the former has yet to be demonstrated.

Table 8

COMPARISON OF F-16 ESTIMATES AT 100 AIRCRAFT
(millions of 1973 dollars)

	Fighter Sample			DAPCA III	
	With Power	With Speed	31-Aircraft Sample	With Time	Without Time
Development Support	20	14[a]	20	41	41
Flight Test	25	19[a]	30	27	27
Engineering	109	108	107	114	114
Tooling	103	89	113	93	93
Mfg Labor	148	129[a]	145	99	140
Mfg Material	59	49	61	89	67
Quality Control	20	21[a]	19	13	19
Total	484	429	495	476	501

[a]Included for completeness even though one variable in the equation has a level of significance below 0.10.

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