Chapter Six

APPLYING THE RESULTS

We now discuss how the results of this study can be applied to future aircraft programs. First, we discuss how the aggregate airframe data survey results in Table 5.1 can be used to estimate the effect of material mix on airframe labor hours. For recurring manufacturing hours, we show how using the part-level cost ratio information in Tables 4.13, 4.14, and 4.15 can be used to estimate the effects on cost of part geometric complexity and manufacturing technique as well as material mix.

APPLYING THE SURVEY COST RATIOS

First, the results in Table 5.1 can be used to estimate the effect of material mix on airframe labor hours. For any given composition of structural weight by material (i.e., the S_m of Chapter Five), a weighted material cost factor $(WMCF)_l$ for each labor category can be computed using Equation 5.3.[1] The γ_l^m from Table 5.1 can be used if the program is expected to employ technology comparable to that of the late 1990s. The effect of material mix on each labor category can be explored by calculating $(WMCF)_l$ for various material mixes (i.e., sets of S_m). The effect of material mix on total recurring hours can be

---

[1] To refresh the reader's memory, we repeat the definitions of the symbols used from Chapter Five. The index m runs over material types, and the index l runs over labor categories. S_m is the share of material m in the airframe; $(WMCF)_l$ is the weighted material cost factor for each labor category l; and γ_l^m is the cost ratio associated with material m and labor category l at the all-airframe hour level. (Table 5.1 shows one such set of γ_l^m.)

calculated by taking a weighted sum of the $(WMCF)_l$'s . If the appropriate weights for the labor categories for the future aircraft under consideration are known, they should be used. Otherwise, one can use the weights shown in Table 5.4 for "all production lots" as representative of recent fighter aircraft. The implications of any projections of future γ_l^m, such as the "optimistic" projections we give below, can be compared with the 1990s experience as represented in Table 5.1 by comparing the $(WMCF)_l$'s calculated with the two sets of γ_l^m.

The procedures discussed so far allow for relative comparisons only across material mix alternatives—i.e., they can estimate the percentage changes in hours associated with different mixes but do not address absolute numbers of hours. For recurring labor needed to produce fighter aircraft, the hours can be projected based on Equation 5.4 in Chapter Five. A projection of the AUW of the aircraft is needed along with a projected production profile, since the CERs are rate dependent. Given the material mix assumed, the associated $(WMCF)_l$'s can be plugged directly into Equation 5.4. (We note that for this procedure to be valid, the $(WMCF)_l$'s must be based on γ_l^m calculated on the assumption that mid-1980s aluminum hours equal 1.0. This is true of the γ_l^m from Table 5.1 and of our future "optimistic" projections, given in Table 6.6.)

We note that these equations are relevant only to fighter/attack-class aircraft. Previous statistical work on CERs (e.g., Hess and Romanoff, 1987) that included non–fighter/attack-class aircraft such as cargo and aerial refueling aircraft found that maximum speed was an important determinant of hours required. Each doubling of speed was found to lead to a 40 to 115 percent increase in hours, depending on the labor category. Speed is highly correlated with the fighter/nonfighter split, of course.[2] Therefore, we recommend that Equation 5.4 *not* be used for non–fighter/attack-class aircraft, since we believe it would overpredict hours. (We do note that the AV-8B is subsonic, so this argument is not pure. However, we still believe that

---

[2] This previous work did not include material effects. It is possible that the higher advanced-material content in some high-speed aircraft, especially titanium, led to the statistical association between speed and cost. This issue needs further investigation to be resolved.

the recommendation is correct.) We *do* recommend these equations for future fighter/attack-class aircraft.

APPLYING THE PART-LEVEL DATA

For recurring manufacturing hours, the information in Tables 4.13, 4.14, and 4.15 can be used to estimate the effects of part geometric complexity and manufacturing technique on cost as well as the effect of material mix. For this, estimates of the percentage of structural weight accounted for by each material/manufacturing-technique/geometric complexity category would be needed. An index of the material/manufacturing-technique combination—say, τ—can be defined as shown in Table 6.1. (For clarity, we also show the associated cost ratio for "complex" parts from Tables 4.13, 4.14, and 4.15.) We require a set of S_τ^c, the shares of airframe structural weight accounted for by each (c, τ) category: $\sum_{\tau=1}^{12} \sum_{c=1}^{4} S_\tau^c = 1$. We define $(\phi_\tau^c, \tau = 1, \ldots, 12; c = 1, \ldots, 4)$ as the cost ratios from Tables 4.13, 4.14, and 4.15. (For example, $\phi_1^1 = 0.7$.) We use them to compute a new weighted material cost factor for recurring manufacturing, which we will designate (*WMCF*)*.

$$(WMCF)^* = \sum_{\tau=1}^{12} \sum_{c=1}^{4} S_\tau^c \phi_\tau^c \tag{6.1}$$

This can be used to compare the recurring manufacturing cost implications of different sets of S_τ^c, regardless of whether they vary by material, manufacturing technique, or part geometric complexity distribution. (Note that this is possible only because the cost ratios were defined on an "all-airframe basis," as discussed in Chapter Four.) We then define an index of part geometric complexity (c) as shown in Table 6.2.

Table 6.1

Definition of Material/Manufacturing (M/M) Technique Index (τ)

M/M Index(τ)	M/M Technique	Cost Ratio Value for "Complex" Parts
1	Aluminum/conventional machining	1.5
2	Aluminum-lithium/conventional machining	1.6
3	Titanium/conventional machining	1.7
4	Steel/conventional machining	1.8
5	Aluminum/HSM	1.0
6	Aluminum-lithium/HSM	1.1
7	Titanium/HPM	1.5
8	Titanium/HIP investment casting	1.0
9	Composites/hand layup	2.2
10	Composites/hand layup with OLPA	1.9
11	Composites/automated fiber placement	1.7
12	Composites/resin transfer molding	1.4

Table 6.2

Definition of Part Geometric Complexity Index (c)

Complexity Index (c)	Geometric Complexity Category
1	Simple
2	Medium
3	Complex
4	Very complex

COMPARISON OF AIRFRAMES MANUFACTURED USING TRADITIONAL TECHNIQUES WITH THOSE USING ADVANCED TECHNIQUES

We illustrate such a comparison using two structural weight breakdowns for a notional future fighter. Each is assumed to have the same material mix and part geometric complexity, but different manufacturing techniques are assumed. Tables 6.3 and 6.4 show the two assumed sets of S_τ^c.

Table 6.3

S_τ^c for a Notional Future Fighter: Traditional Manufacturing Techniques[a]

	Part Complexity Index Value (c)	1	2	3	4
M/M Index (τ)	M/M Technique	Simple	Medium	Complex	Very Complex
1	Aluminum/ conventional machining	6.2	13.1	9.2	
2	Aluminum-lithium/conventional machining		2.7		
3	Titanium/conventional machining	0.3	10.9	8.5	
4	Steel/conventional machining		0.9	6.6	
5	Aluminum/HSM				
6	Aluminum-lithium/HSM				
7	Titanium/HPM				
8	Titanium/HIP investment casting				
9	Composites/hand layup	1.8	17.8	17.0	5.0
10	Composites/hand layup with OLPA				
11	Composites/automated fiber placement				
12	Composites/resin transfer molding				

[a] Table values are 100 * S_τ^c.

Table 6.4

S^c_τ for a Notional Future Fighter: Advanced Manufacturing Techniques

	Part Complexity Index Value (c)	1	2	3	4
M/M Index (τ)	M/M Technique	Simple	Medium	Complex	Very Complex
1	Aluminum/ conventional machining				
2	Aluminum-lithium/conventional machining				
3	Titanium/conventional machining				
4	Steel/conventional machining		0.9	6.6	
5	Aluminum/HSM	6.2	13.1	9.2	
6	Aluminum-lithium/HSM		2.7		
7	Titanium/HPM	0.3	10.9	8.5	
8	Titanium/HIP investment casting				
9	Composites/hand layup				
10	Composites/hand layup with OLPA	1.8	13.8	5.0	2.5
11	Composites/automated fiber placement		4.0	10.4	
12	Composites/resin transfer molding			1.6	2.5

The value of *(WMCF)** is 1.61 using Table 6.3 shares and 1.34 using Table 6.4. In this example, changing from a largely 1980s-type manufacturing mix to a more advanced one decreases recurring manufacturing labor hours by 17 percent.

That example was done on a CAC100 basis assuming an average part weight of 15 pounds, as was used in normalizing the ϕ^c_τ estimates. The factors in Tables 4.16 and 4.17 could be used to calculate relative costs under different cumulative production and average part weight assumptions.

These comparisons are still for *relative* costs across material/manufacturing-technique/complexity mixes—i.e., the percentage by which the recurring manufacturing hours of one mix will differ from those of another. We now turn to absolute calculations.

We use the recurring manufacturing equation shown in Equation 5.4. However, $(WMCF)^*$ is not exactly comparable to $(WMCF)_{manu}$. $(WMCF)^*$ is calculated from ratios of labor hours divided by 1990s aluminum conventionally machined medium-complexity part labor hours. $(WMCF)_{manu}$ is calculated from ratios of labor hours divided by 1980s average aluminum labor hours. To make these comparable, we need an estimate of average aluminum hours per pound for the MACDAR aircraft at CAC100. Based on Equation 5.4 for manufacturing labor and an average production profile across the five aircraft (shown in Table 6.5), this is 7.86 hours per pound. Thus, recurring manufacturing hours for future fighter aircraft can be estimated by plugging in $[(7.65/7.86)\ (WMCF)^*]$ instead of $(WMCF)_{manu}$ in Equation 5.4 for manufacturing.[3]

Table 6.5

Average Lot Size for MACDAR Aircraft[a]

Lot	Number Produced
EMD	11
1	21
2	50
3	80
4 and beyond	110

[a] The pattern of production decrease at the end of the production run is very irregular across aircraft.

---

[3] The figure 7.65 is 1990s aluminum conventionally machined medium-complexity part labor hours per pound (corresponding to the cost ratio "1.0" in Table 4.13) ("all-aircraft basis") as discussed in Chapter Four.

We illustrate this with the two notional fighter aircraft characterized in Tables 6.3 and 6.4. We assume a pattern of production timing shown in Table 6.5, the MACDAR averages across airframes. We assume an AUW of 15,355 pounds in EMD and 15,800 pounds in all other lots; these are also the MACDAR averages (illustrating the weight growth that typically occurs between the EMD aircraft and the regular production aircraft). Using traditional manufacturing techniques (the Table 6.3 S_{τ}^{c}), CAC100 recurring manufacturing hours per pound total 12.3. Using advanced techniques (the Table 6.4 S_{τ}^{c}), the figure is 10.2.

This example indicates that airframe manufacturing hours should decrease as modern manufacturing techniques are introduced, but the increased complexity of the next-generation airframes to meet future military requirements must also be taken into account.

COST RATIOS IN THE 2000s: OPTIMISTIC AND PESSIMISTIC PROJECTIONS

Can we expect production improvement in airframe labor hours in the coming decade? We asked industry to project future cost ratios, but most did not, citing the high uncertainty associated with the future environment. We did engage in many discussions with industry of how different future environments might change costs, and some companies ventured projections of cost ratios given specific futures. We also reviewed many studies done by industry on the cost implications of potential future technologies. Based on this information, we have prepared two projections for the 2000s, “optimistic” and “pessimistic.” (We note explicitly that this means optimistic or pessimistic with respect to airframe costs; we take no position on the overall desirability of futures leading to high or low costs.) Table 6.6 contains an “optimistic” set of cost ratio projections for the mid-2000s. Table 6.6 is based on an “all-airframe labor” basis and is thus comparable with Table 5.1.

Table 6.6

Optimistic Mid-2000s Cost Ratio Projections, All-Airframe Labor Basis[a]

Material	Nonrecurring Engineering	Nonrecurring Tooling	Recurring Engineering	Recurring Tooling	Recurring Manufacturing	Recurring Quality Assurance
Aluminum	1.00	0.88	0.91	0.86	0.82	0.95
Aluminum-lithium	1.00	0.99	0.94	0.97	0.87	1.04
Titanium	1.00	1.26	0.97	1.26	1.29	1.18
Steel	1.02	0.97	1.02	1.12	1.05	1.12
Carbon-epoxy	1.14	1.21	1.18	1.33	1.17	1.50
Carbon-BMI	1.16	1.29	1.21	1.44	1.24	1.52
Carbon-thermoplastic	1.14	1.44	1.15	1.50	1.27	1.58

[a] Late 1980s aluminum = 1.0.

Table 6.6 assumes the use of higher-productivity part fabrication processes such as HSM/HPM for metals and automated fiber placement and RTM for composites. It also assumes increased unitization and thus assembly labor savings. Some innovations in assembly are now being introduced whose labor savings in large-scale production and ultimate market penetration are not yet clear. (We had no access to data from production applications.) They include self-locating parts, reduced tooling, and single-pass drilling. In Table 6.6, we assume that they will lead to some labor savings as well.

These optimistic projections are the same as the figures in Table 5.1 for nonrecurring engineering and in recurring quality assurance for metals. We did not see any compelling evidence for significant advances in technology in these areas in the next few years.

This set of cost factors, assuming increased industry penetration of advanced technology, is optimistic basically because of the high level of uncertainty concerning future military aircraft production levels. Every program existing today is controversial in some government and policy circles, and each is seriously challenged on a regular basis.

Thus, the incentives for industry to introduce new techniques, with their capital and training costs and uncertainty about precise effectiveness, are low. The optimistic projections of Table 6.6 are ones that might hold if the military aircraft production climate were to become robust—with, say, annual production in the several hundred range and high confidence in program stability. For any given composition of structural weight by material (i.e., the S_m of Chapter Five), one can compute a weighted material cost factor $(WMCF)_l$ for each labor category using Equation 5.3. One can use the γ_l^m from Table 6.6 if our "optimistic" future scenario seems appropriate.

Our pessimistic projection would be no change from today—i.e., that the cost ratios of Table 5.1 will continue for the rest of the decade. This would be consistent with relatively low levels of production (say, less than 100 per year) and with high program instability and uncertainty. Industry would have little reason to make the investments required to reach the higher productivities shown in Table 6.6, since there would be little confidence in recouping the investments.

COST-ESTIMATING CONSIDERATIONS FOR AIRFRAME STEALTH REQUIREMENTS

One notable subject not explicitly addressed in this report is the impact of LO materials and structures on the cost of airframe production. Because of the classification of the entire subject of LO materials and structures, this issue could not be addressed in detail in this report. However, anecdotal discussions with some of the participating contractors indicate that the fabrication of these materials and their installation were not significantly greater in terms of production costs than those associated with non-LO materials. The major difference is an increase in the complexity of structural parts such as inlets and edges and in the nonrecurring design and testing of the LO materials and structure.

The cost analyst has two options on how to handle LO materials in a production estimate. The first is to obtain data by material type for the proposed airframe structure, including the LO materials and the geometric complexity of the associated parts, and proceed to calculate the $(WMCF)^*$ as described in this chapter. This assumes that the materials used for the LO purposes and the complexity of the parts are accurately reflected in the overall S_{τ}^{c}. Also, if part of the LO requirement is met by internal carriage, for example, the added weight, advanced materials, and complexity of a “bomb bay” would be included in the weight and material distribution estimate for the structure. The other option is to obtain access to what is normally a highly classified body of data, establish discrete cost estimates for the fabrication and assembly tasks for the LO materials, and add that to the cost estimate for the rest of the structure.

LEAN MANUFACTURING AND ACQUISITION REFORM

As mentioned in Chapter One, two companion reports to this one—Cook and Graser (2001) and Lorell and Graser (2001)—present research on the effects of lean manufacturing and acquisition reform on military aircraft costs. This section summarizes their results and discusses how they can be integrated into the overall costing methodology presented in this chapter. A list of specific subjects addressed in the three reports can be found in Appendix E. This is a brief review of two rich and detailed reports, and interested readers are urged to read the reports themselves.

One kind of acquisition reform is regulatory and oversight relief, including relief from government-mandated accounting and record-keeping standards, cost-reporting requirements (including Truth in Negotiation Act provisions), and audit and oversight practices. Based on the data available, the best estimate of the effect on total program cost of *all* such proposed regulatory/oversight acquisition reform measures is a savings of 3 to 4 percent. This range is substantially less than had been projected earlier. Furthermore, all such acquisition reform measures must be implemented together if these effects are to be attained. In addition, industry must perceive acquisition reform measures as permanent, since a major part of the savings accrue from personnel reductions among those who administer the government regulations such reform would do away with. If a given case of relief from regulations is not viewed as permanent, industry will be wary of reducing the workforce that has been trained to deal with such regulations in the event that they are reimposed. In any case, acquisition reform of this sort will generally affect overhead personnel rather than those billing to specific programs. Thus, our best estimate is that the vast majority of such savings should be reflected in lower wage burden or other overhead rates rather than in labor hours associated with the program.[4] A reduction of these rates equivalent to a 3.5 percent decrease in total program costs would be a justifiable estimate assuming that *all* regulatory and oversight relief measures now being proposed are implemented and that industry *perceives these measures as permanent*. If either of these conditions is violated, no savings should be attributed to acquisition reform.

Some programs, such as Joint Direct Attack Munition (JDAM), have seen savings as a result of a commercial approach to many program elements, such as part selection and qualification, cost-benefit tradeoff analysis, requirements definition, contracting, and buyer-seller relations. However, there is no evidence to date that this approach can work on a more sophisticated system such as a combat aircraft.

Multiyear procurement programs have a proven record of decreasing costs by about 5 percent compared to year-to-year programs.

Lean manufacturing is a set of practices meant to reduce the labor, material, and interest costs of manufacturing. It includes practices such as just-in-time inventory control, reengineering of factory layout and process sequencing to minimize idle time by personnel and machinery, and closer integration of manufacturing experts with designers during product development. Impressive savings have been associated with lean practices at the level of individual processes or manufacturing cells. However, because of limited enterprise-wide implementation of lean practices by military aircraft manufacturers, there is no systematic industry-wide evidence to date that lean practices can significantly affect overall airframe costs (although there *is* evidence that such practices have significantly lowered automobile costs). We therefore recommend that overall CERs estimated from historical data *not* be modified to reflect lean manufacturing efficiencies unless and until there is more evidence to support this

---

[4] One of the few acquisition reform measures that would be reflected in labor hours is the Single-Process Initiative, which combines multiple process and inspection standards such as those for welding into one. This should increase labor efficiency by lowering the number of specific tasks in which a worker must maintain expertise and increasing repetitions—and thus specific task learning—for each task.

practice. In cases in which specific savings can be demonstrated at the process level, appropriate marginal adjustments to CERs would be justified. If lean manufacturing becomes a general practice throughout the industry, future data-based updates of material cost factors and CERs will reflect these practices. In that case, no further adjustments for lean manufacturing should be made, to avoid double counting of improvements.

CONCLUSION

This report has presented estimates of the effect of material mix, manufacturing technique, and part geometric complexity on airframe recurring costs. We discussed the results of an industry survey of aggregate airframe cost factors and then presented a quantitative analysis of actual part data we collected from industry. These factors were integrated with a historical data set, MACDAR, to estimate airframe recurring hour CERs.

One finding of our part-level data analysis was that recurring manufacturing hours could decrease by roughly 17 percent as a result of advances in manufacturing technology, but the increased airframe complexity of future fighters may offset some of this potential savings. Future overall airframe cost factors, assuming increased industry penetration of advanced manufacturing technology, were presented as an “optimistic” forecast. We noted the high level of uncertainty surrounding any such forecast, primarily as a result of the high level of uncertainty about future military aircraft production levels. We illustrated the application of our overall cost-estimating methodology with a notional aircraft example using both conventional and advanced manufacturing techniques.

In view of the high level of uncertainty about the future military aircraft environment, cost analysts should continue working with industry to follow what changes in practice and technology are actually occurring. They should also continue to collect actual part- and airframe-level cost data. Both practices will serve to continually improve the quality of cost-estimating tools available.