Chapter Four

AIRFRAME COST INFORMATION

This chapter presents our results on the cost implications of using different materials to produce airframes. It is based on industry data that we collected of two primary types. The first was an industry survey on the relative costs of producing airframe structures from various materials. This survey followed the same format as that in Resetar, Rogers, and Hess (1991). It collected estimates on the relative costs of seven materials by six labor categories, as described below. The second type of data we collected consisted of actual recurring manufacturing labor hours for a large sample of parts. These data allowed us to estimate the cost implications of part geometric complexity and manufacturing technique as well as material type. The data consisted primarily of actual manufacturing cost data from production runs. For some newer manufacturing techniques that are not yet in widespread use, however, the data were from experiments or demonstrations specifically designed to measure the costs of using different techniques. The implications of these two kinds of data are discussed below. Finally, we collected data on raw material costs and BTF ratios, discussed at the end of the chapter.

REVISITING THE RESETAR, ROGERS, AND HESS STUDY

We begin the chapter with the results of the industry survey. We first review the results of Resetar, Rogers, and Hess, who performed a similar survey in the late 1980s. This survey first asked industry to estimate, for each of several material and labor categories, the hours per pound needed to produce airframe structure from the given material at the time of the survey (i.e., the late 1980s). The ground rules for these estimates were as follows:

- Labor hours included all structural fabrication and assembly up through the airframe group level (wing, fuselage, and empennage). They did not include final assembly and checkout or any subsystem installation.
- Labor hours represented cumulative average values for a quantity of 100 aircraft and a finished material weight of 1000 pounds.
- Responses assumed whatever mix of material forms (e.g., tape versus fabric, sheet versus plate) and fabrication techniques that were in use for each company at the time of the survey.

Results from this part of the survey are given in Table 4.1. Labor categories included the following:

- Nonrecurring engineering labor
- Nonrecurring tooling labor
- Recurring engineering labor
- Recurring tooling labor
- Recurring manufacturing labor
- Recurring quality assurance labor.

Results are given as the *ratio* of aggregate airframe hours per pound for the given labor category/material combination to hours per pound for aluminum for that labor category. Thus, all entries in the first row of Table 4.1 are unity.

The recurring manufacturing column, for example, has the following interpretation. Recurring manufacturing hours per pound of titanium structure were estimated to be 60 percent higher than hours per pound of aluminum and 80 percent higher for carbon-epoxy. Similarly, recurring tooling hours per pound of titanium structure were estimated to be 90 percent higher than hours per pound of aluminum and 120 percent higher for carbon-epoxy.

Table 4.1

Late 1980s Cost Ratios from Resetar, Rogers, and Hess (1991)[a]

Material	Nonrecurring Engineering	Nonrecurring Tooling	Recurring Engineering	Recurring Tooling	Recurring Manufacturing	Recurring Quality Assurance
Aluminum	1.0	1.0	1.0	1.0	1.0	1.0
Aluminum-lithium	1.1	1.2	1.1	1.1	1.1	1.1
Titanium	1.1	1.4	1.4	1.9	1.6	1.6
Steel	1.1	1.1	1.1	1.4	1.2	1.4
Carbon-epoxy	1.4	1.6	1.9	2.2	1.8	2.4
Carbon-BMI	1.5	1.7	2.1	2.3	2.1	2.5
Carbon-thermoplastic	1.7	2.0	2.9	2.4	1.8	2.6

[a] Late 1980s aluminum = 1.0.

The survey then went on to ask industry to forecast what the hours-per-pound numbers would be in the mid-1990s time frame. The first two ground rules were the same; for the third, industry was asked to assume whatever mix of material form and fabrication techniques they expected in the mid-1990s. Table 4.2 shows these results, given as the ratio of hours per pound to *late 1980s* aluminum hours per pound. Thus, the aluminum numbers are no longer necessarily unity. Indeed, as Table 4.2 shows, industry respondents expected a 10 percent improvement in hours per pound of aluminum structure in all recurring labor categories. Because the denominator of the ratio—1980s aluminum hours per pound—was held constant, all other figures in Tables 4.1 and 4.2 can be compared to reveal expected productivity changes in any category. A comparison of the two tables shows that no productivity decreases were expected (all numbers in Table 4.2 are less than or equal to corresponding numbers in Table 4.1), and in most categories productivity was expected to rise. For example, recurring manufacturing hours per pound of titanium structure were expected to fall by 12.5 percent (1.4 versus 1.6), and hours per pound of carbon-epoxy were expected to decrease by 16.7 percent (1.5 versus 1.8).

Table 4.2

Expected Mid-1990s Cost Ratios from Resetar, Rogers, and Hess (1991)[a]

Material	Nonrecurring Engineering	Nonrecurring Tooling	Recurring Engineering	Recurring Tooling	Recurring Manufacturing	Recurring Quality Assurance
Aluminum	1.0	1.0	0.9	0.9	0.9	0.9
Aluminum-lithium	1.0	1.1	1.0	1.1	1.0	1.0
Titanium	1.0	1.4	1.2	1.6	1.4	1.4
Steel	1.1	1.1	1.1	1.4	1.2	1.4
Carbon-epoxy	1.2	1.4	1.5	2.0	1.5	1.8
Carbon-BMI	1.3	1.5	1.6	2.1	1.8	2.1
Carbon-thermoplastic	1.4	1.6	1.4	2.4	1.6	2.0

[a]Late 1980s aluminum = 1.0.

CURRENT STUDY RESULTS: AGGREGATE AIRFRAME DATA BY FUNCTIONAL LABOR CATEGORY

In the survey we conducted, we asked industry respondents to estimate what their actual mid-1990s experience had been using the same ground rules as Resetar, Rogers, and Hess. The next sections show the results of the survey, with results again expressed as a ratio of hours per pound to late 1980s aluminum hours per pound. Thus, comparisons with the expected mid-1990s values from the earlier survey are direct. The companies that responded to the survey are as follows:

- Boeing
- Hexcel (composites information only)
- Lockheed Martin
- Northrop Grumman
- Sikorsky (composites information only)

For some companies, we received more than one set of estimates from different divisions at different locations.

A section follows below for each of the six labor categories included in the survey. For each category, we present a table with the average value of the cost ratio for each material as well as the range of responses.

Nonrecurring Engineering

Nonrecurring engineering includes the engineering hours spent developing the airframe. We note that such hours are incurred throughout an aircraft program's life, since design change effort, which often continues until program termination, is included in nonrecurring engineering. Specifically, nonrecurring engineering includes hours expended for (1) design, consisting of trade studies, stress analysis, aerodynamic performance analysis, weight and balance analyses, and airframe integration; (2) wind-tunnel models and mockups; (3) laboratory testing of components and subsystems and static and fatigue articles; (4) preparation and release of drawings; and (5) process and material qualification. Excluded are engineering hours not directly attributable to the airframe: flight testing, ground-handling equipment, spares, and training equipment.

Table 4.3 shows that on average, nonrecurring engineering hours were estimated to be 30 to 40 percent higher for composites than for metals. Some of the reasons for this difference were discussed in Chapter Two. Composite part designers must consider the direction-

Table 4.3

Late 1990s Nonrecurring Engineering Cost Ratios[a]

Material	Average	Minimum/Maximum
Aluminum	1.00	1.00/1.00
Aluminum-lithium	1.00	1.00/1.00
Titanium	1.00	1.00/1.00
Steel	1.05	1.00/1.10
Carbon-epoxy	1.33	1.00/2.00
Carbon-BMI	1.38	1.10/2.00
Carbon-thermoplastic	1.33	1.20/1.40

[a] Late 1980s aluminum = 1.00.

tionality of fiber alignment and how that property should be adjusted to load patterns; designers must choose the number of plies in a part and their individual shape and alignment and must prepare instructions for ply cutting and layup. There are also increased material qualification costs if there is no extensive industry experience with the specific material. Additional design time is required to analyze and specify bonding and assembly techniques and to choose the degree of unitization—i.e., to determine how large and complex to make integral structures.

Nonrecurring Tooling

Tooling refers to the tools designed solely for use on a particular airframe program and includes layup tools, autoclave tools, assembly tools, dies, jigs, fixtures, work platforms, and test and checkout equipment. Not included are general-purpose tools or machinery such as automated cutting machines, automated fiber placement machines, autoclaves, NDI/T equipment, milling machines, presses, routers, drilling equipment, and the like, whose cost would be captured in factory overhead rates. Nonrecurring tooling hours are those required to plan fabrication and assembly operations and to design, fabricate, assemble, and install the initial set of tools as well as all duplicate tools required for the planned rate of production. Nonrecurring tooling costs occur not only during development but also during the production program if rate or airframe changes require new tools. Survey results appear in Table 4.4.

Table 4.4

Late 1990s Nonrecurring Tooling Cost Ratios[a]

Material	Average	Minimum/Maximum
Aluminum	0.96	0.90/1.00
Aluminum-lithium	1.10	1.10/1.10
Titanium	1.44	1.30/1.80
Steel	1.08	1.00/1.10
Carbon-epoxy	1.38	1.00/1.80
Carbon-BMI	1.48	1.08/1.80
Carbon-thermoplastic	1.68	1.30/2.40

[a] Late 1980s aluminum = 1.00.

On average, nonrecurring tooling hours were estimated to be 40 to 70 percent higher for composites than for aluminum. This difference is attributable to tool exposure to high temperatures and pressures in the autoclave; requirements to build tools with appropriate CTEs that will not lead to unacceptable part spring-back during cure; tool complexity resulting from the complex shapes of unitized structures; and the difficulty of working with composite tooling material. Thermoplastic tooling hours are the highest owing to the high autoclave processing temperatures involved. Tools used to machine titanium are often made of very strong and very hard material such as carbide, which is difficult to work and thus requires increased hours for fabrication.

Recurring Engineering

Table 4.5 shows recurring engineering hours, which represent the effort required to initiate, analyze, and implement minor engineering changes and product improvements that do not specifically change product form, fit, or function. Some of these improvements may enhance performance, but most are done for producibility reasons. This category also includes any modifications to CAD/CAM software. (Major changes that do affect product form, fit, or function are documented in formal Engineering Change Orders [ECOs], and the hours spent on these changes would be counted as nonrecurring regardless of when in the program they were incurred.)

Table 4.5

Late 1990s Recurring Engineering Cost Ratios[a]

Material	Average	Minimum/Maximum
Aluminum	0.92	0.77/1.00
Aluminum-lithium	1.00	1.00/1.00
Titanium	1.09	0.91/1.47
Steel	1.08	0.91/1.23
Carbon-epoxy	1.68	1.00/2.40
Carbon-BMI	1.75	1.00/2.40
Carbon-thermoplastic	1.60	1.00/1.93

[a] Late 1980s aluminum = 1.00.

Recurring engineering labor associated with composites was estimated to be 60 to 75 percent more than that for metals. We do not believe that the minor difference in the averages for epoxy and BMI is significant because during our interviews, industry engineers said that the recurring engineering efforts associated with the two materials were equal.

Recurring Tooling

Recurring or sustaining tooling (Table 4.6) refers to all labor associated with tool cleaning, repair, maintenance, rework, modification, and replacement.

Recurring tooling labor for composites is higher than that for aluminum because the tools used to form composite parts go into the autoclave. They must therefore be cleaned after every cure, which is a time-consuming process. These tools also sustain extensive temperature and pressure cycling in the autoclave, resulting in flaws that can require extensive repair. Tools for composites are complex and must be replaced more often than those required for metal manufacturing, also as a result of the rigors of the autoclave.

Tools used to machine titanium require replacement more often than do those used to machine aluminum. Carbide cutters require more frequent maintenance and replacement than do their counterparts used on aluminum. Moreover, titanium requires complicated tools, since titanium parts are on average more complex than aluminum parts.

Table 4.6

Late 1990s Recurring Tooling Cost Ratios[a]

Material	Average	Minimum/Maximum
Aluminum	0.93	0.82/1.00
Aluminum-lithium	1.07	1.00/1.11
Titanium	1.44	0.91/2.03
Steel	1.25	0.91/1.46
Carbon-epoxy	1.62	0.82/2.38
Carbon-BMI	1.77	0.82/2.49
Carbon-thermoplastic	1.86	0.82/2.61

[a] Late 1980s aluminum = 1.00.

Since the nonrecurring tooling hours used to *make* the original tools for use with both composites and titanium are relatively high, the recurring hours used to *replace* them are also high.

Recurring Manufacturing

Recurring manufacturing (Table 4.7) includes all hours expended on production scheduling, fabrication, processing, reworking, modification, minor assembly, and major assembly of the airframe structure.

As Table 4.7 shows, the manufacturing hours required to make aluminum-lithium parts are slightly higher than those required for aluminum, largely because the chips resulting from machining must be segregated from regular aluminum chips and carefully disposed of for health and environmental reasons. Titanium machining is considerably more time-consuming than aluminum machining because it requires much lower spindle feed and speed rates. This is primarily due to the heat generated at the tool as a result of the low thermal conductivity of titanium alloys. Finally, composites use much more manufacturing labor than does aluminum because they require a significant amount of handling during the fabrication process, as described in Chapter Three. During our discussions with industry, most technical personnel said that the manufacturing hours required for toughened epoxies and BMI should be the same, but the survey results showed roughly a 7.5 percent penalty for BMI. This difference

Table 4.7

Late 1990s Recurring Manufacturing Cost Ratios[a]

Material	Average	Minimum/Maximum
Aluminum	0.90	0.82/1.00
Aluminum-lithium	1.00	1.00/1.00
Titanium	1.61	1.18/2.36
Steel	1.27	1.09/1.61
Carbon-epoxy	1.58	1.00/2.36
Carbon-BMI	1.71	1.00/2.52
Carbon-thermoplastic	1.77	1.09/2.82

[a] Late 1980s aluminum = 1.00.

might be due to the fact that not all respondents had significant experience with the new BMI materials and may have based their response on older BMI matrices that were more difficult to handle.

In the 1980s, some industry analysts predicted that thermoplastics would be the composite material of the future. Indeed, early F-22 designs and one early JSF design included large amounts of thermoplastic, but these were significantly reduced in later configurations. Thermoplastics are currently used in military aircraft only in areas that require significant toughness, such as in underbody doors and access panels (Harper-Tervet et al., 1997). As discussed in Chapter Two, thermoplastics are hard to work with in that they lack drapability and tack. In addition, some thermoplastics require solvents to soften them for forming. These solvents must be recaptured during the curing process and, owing to their toxic nature, disposed of carefully. This adds to the complexity and hours required for the layup, bagging, and autoclave curing processes.

Recurring Quality Assurance

Recurring quality assurance (QA) includes hours expended in the in-process and final inspection of tools, parts, subassemblies, and final assembly. It also includes the hours used for nondestructive testing, MRBs, and quality monitoring processes such as statistical process control (SPC), design of experiments (DOE), and the like. Industry practices for estimating QA hours vary from direct time recording to estimation by multiplying recurring manufacturing hours by a QA "factor."

Metal parts are inspected for dimensional tolerances and surface finish. Using a fluorescent dye penetrant technique, they are inspected for cracks and other physical imperfections.

The estimates for composite QA hours per pound (Table 4.8) were significantly higher than those for aluminum for the following reasons:

- Increased inspection hours are required because of composite failure modes not present in metals, such as ply delamination, foreign object inclusion, and resin and fiber ratio imbalance.

Table 4.8

Late 1990s Recurring Quality Assurance Cost Ratios[a]

Material	Average	Minimum/Maximum
Aluminum	0.91	0.83/1.00
Aluminum-lithium	1.06	1.00/1.18
Titanium	1.30	1.00/1.83
Steel	1.20	1.00/1.50
Carbon-epoxy	2.04	1.09/3.17
Carbon-BMI	2.08	1.09/3.33
Carbon-thermoplastic	2.18	1.09/3.50

[a] Late 1980s aluminum = 1.00.

Other failure modes, such as porosity and loss of bond integrity, require more testing in composites than in metals.

- Ultrasonic inspection techniques used on composites are more labor intensive than X-ray, liquid penetrant, and other techniques used for aluminum.
- There are inspection requirements for composite surface finish problems, which result from the less durable tools used to form composites.
- There are higher inspection failure rates for composites than for metals, leading to increased material disposition activities, including additional hours for MRB- and scrap-related activities.

Some parts of industry and government are still wary of composites and impose more stringent QA procedures on them than on metals.

COMPARISON TO 1980s SURVEY RESULTS

Table 4.9 summarizes the results from the above sections in the same format as Tables 4.1 and 4.2. It is of interest to compare these results with those projected for the mid-1990s in Resetar, Rogers, and Hess. Table 4.10 displays such a comparison.

Table 4.9

Late 1990s Cost Ratios[a]

Material	Nonrecurring Engineering	Nonrecurring Tooling	Recurring Engineering	Recurring Tooling	Recurring Manufacturing	Recurring Quality Assurance
Aluminum	1.00	0.96	0.92	0.93	0.90	0.91
Aluminum-lithium	1.00	1.10	1.00	1.07	1.00	1.06
Titanium	1.00	1.44	1.09	1.44	1.61	1.30
Steel	1.05	1.08	1.08	1.25	1.27	1.20
Carbon-epoxy	1.33	1.38	1.68	1.62	1.58	2.04
Carbon-BMI	1.38	1.48	1.75	1.77	1.71	2.08
Carbon-thermoplastic	1.33	1.68	1.60	1.86	1.77	2.18

[a] Late 1980s aluminum = 1.0.

Table 4.10

Comparison of Late 1990s Cost Ratios to Projected Mid-1990s Cost Ratios from Resetar, Rogers, and Hess (1991)[a]

Material	Nonrecurring Engineering	Nonrecurring Tooling	Recurring Engineering	Recurring Tooling	Recurring Manufacturing	Recurring Quality Assurance
Aluminum	1.00/*1.0*	0.96/*1.0*	0.92/*0.9*	0.93/*0.9*	0.90/*0.9*	0.91/*0.9*
Aluminum-lithium	1.00/*1.0*	1.10/*1.1*	1.00/*1.0*	1.07/*1.1*	1.00/*1.0*	1.06/*1.0*
Titanium	1.00/*1.0*	1.44/*1.4*	1.09/*1.2*	1.44/*1.6*	1.61/*1.4*	1.30/*1.4*
Steel	1.05/*1.1*	1.08/*1.1*	1.08/*1.1*	1.25/*1.4*	1.27/*1.2*	1.20/*1.4*
Carbon-epoxy	1.33/*1.2*	1.38/*1.4*	1.68/*1.5*	1.62/*2.0*	1.58/*1.5*	2.04/*1.8*
Carbon-BMI	1.38/*1.3*	1.48/*1.5*	1.75/*1.6*	1.77/*2.1*	1.71/*1.8*	2.08/*2.1*
Carbon-thermoplastic	1.33/*1.4*	1.68/*1.6*	1.60/*1.4*	1.86/*2.4*	1.77/*1.6*	2.18/*2.0*

[a] Late 1980s aluminum = 1.0. Late 1990s cost ratios are the top entry; mid-1990s cost ratios expected in the late 1980s are the bottom entry (in italics).

The results of the current survey show no significant differences from the 1980s projections for nonrecurring engineering and nonrecurring tooling.

The recurring engineering results of the current survey for aluminum, aluminum-lithium, and steel are also roughly the same as the 1980s projections, and the results for titanium indicate lower recurring engineering than had been forecast. Recurring engineering estimates for composites are consistently higher than had been forecast in the 1980s; however, they are lower than the survey level *for* the 1980s. Thus, the productivity improvements that are estimated to have occurred are not as large as had been projected. (About a 35 percent productivity improvement had been projected, a roughly 25 percent improvement is evidenced in the survey.)

The recurring tooling estimates from the survey are almost uniformly lower than had been projected earlier, by about 20 percent.

The recurring manufacturing category makes up some 60 percent of all recurring labor hours, so it is the most important cost driver. The survey results for aluminum and aluminum-lithium do not differ from 1980s projections for them. Estimates for titanium and steel are higher than had been projected and are in fact slightly above the survey estimates of cost for those materials in the 1980s. Thus, manufacturing productivity for making airframes from these materials is estimated to have stagnated at best. A reasonable explanation for this finding lies in the dramatic reduction in military aircraft production that occurred in the 1990s, which lowered opportunities for economies of scale. This might have been expected to have hit manufacturing the hardest, since development activity did not decrease as much and since development has higher engineering and tooling content. (See Chapter Five for more detail on how labor hours by category change as a program proceeds.)

Manufacturing productivity in composites is assessed to have changed its pattern. Carbon-epoxy is assessed to have improved since the 1980s by 12 percent rather than by the 17 percent that had been forecast.[1] Carbon-epoxy and carbon-BMI are now assessed to

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[1] Of course, it may well be that this difference merely reflects variations in individual judgment rather than a true consensus that realized productivity is less than had been

be closer in cost than had been projected, with BMI productivity improvement somewhat higher than projected (20 versus 15 percent). Thermoplastics are estimated to have had no productivity improvement, which is no doubt associated with the fact that their anticipated penetration into the market has not occurred. More analysis would be needed to disentangle the "chicken-and-egg" issues here; lack of productivity growth would discourage use, but some of the productivity growth was expected to occur as experience and hence learning accumulated with thermoplastics. In any case, the current survey's picture of relative composite costs is different from the earlier one. This survey shows both epoxy and BMI improving in productivity and thermoplastics stagnating, thus increasing in cost relative to epoxy and BMI. By contrast, the earlier survey showed epoxy and thermoplastics to be roughly equal in cost, with BMI being the relatively more expensive material.

As discussed earlier, during our industry visits many industry analysts and engineers said that manufacturing costs for toughened carbon-epoxy composites and carbon-BMI composites were the same. Why did the formal survey fail to yield the same result? This discrepancy may be due to a lack of BMI experience on the part of some of the respondents or to the use of data reflecting older BMIs, which were more difficult to use in fabrication. BMI is still not as widely used as epoxies.

QA results show an increase for carbon-epoxy and carbon-thermoplastics from what had been projected, although again, these estimates are still better than those *for* the 1980s. Thus, productivity growth is assessed to have occurred, but not as rapidly as had been projected. BMI figures approximate the projected levels, again reflecting *relative* improvement in this material from what had been projected. Metals are in general seen to have improved more in QA productivity than had been projected. This is an interesting reversal

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expected. We do not think any meaningful statistical significance levels can be assigned to this survey process, since the estimates were derived in a series of meetings between RAND researchers and industry with much discussion on clarifying ground rules and definitions. This was also the case for the Resetar, Rogers, and Hess survey. We discuss differences between the surveys only when it is our judgment that these differences are meaningful, but these judgments are inherently subjective, are based on the full content of our interactions with industry, and cannot be formally justified.

from the manufacturing results, which showed relatively little improvement, since manufacturing and QA hours are often thought to move together. (Indeed, as mentioned above, many companies estimate QA hours simply as a fraction of manufacturing hours.)

CURRENT STUDY RESULTS: PART-LEVEL DATA BY MATERIALS, MANUFACTURING PROCESS, AND PART GEOMETRIC COMPLEXITY

We now turn to the statistical analysis of part cost data we received from various companies. We believed that while the survey results were useful, it would also be useful to analyze real data on parts made of varying materials and to make inferences about the cost implications of material composition based on that analysis. The companies we visited agreed and generously supplied us with the data required to make such analysis. These data were provided to us on a proprietary basis, so we cannot identify any specific costs but instead report average results. These observations are all from the 1990s.

As discussed above, the data came in two forms. Most were actual manufacturing cost data from production experience. For some newer manufacturing techniques that are not now in widespread use, however, the data were derived from experiments or demonstrations specifically designed to measure the costs of using different techniques. How well the results of such studies represent what would actually happen if the techniques were used on the factory floor in a production environment is uncertain, and the results should be interpreted with that caveat in mind. All results will be identified as based on either "manufacturing data" or "experiment/demonstration data."

Table 4.11 shows the sources of the "manufacturing data" part data. We had the advantage of being able to disaggregate the data both by part geometric complexity and by manufacturing technique. Thus, we can identify separate cost ratios for these. Unfortunately, only recurring manufacturing labor data were sufficient to allow for analysis; the other labor categories could not be estimated using these data.

Table 4.11

1990s Part-Level Manufacturing Data

Program	Composite Manufacturing Labor Data	Metal Manufacturing Labor Data	Contractors
F-22	Yes	Yes	Alliant Techsystems, Boeing, GKN Westland, Lockheed Martin
F/A-18 E/F	Yes	Yes	Alliant Techsystems, Boeing, Northrop Grumman
Comanche	Yes	No	Sikorsky
V-22	Yes	No	Alliant Techsystems, Bell Textron, Boeing
F-16	Yes	Yes	Lockheed Martin

Part Geometric Complexity

It is intuitive that the cost of parts made of either metal or composites should be a function of the complexity of the shape of the part. To empirically estimate such an effect, we divided airframe parts into four geometric complexity categories: simple, medium, complex, and very complex.

Simple parts are defined here as monolithic, minimally contoured, or flat parts. Examples include covers, doors, fittings, flat skins, and panels.

Medium parts are defined as surfaces with moderate curvature and thickness, with stiffeners and cutouts, or parts with a moderate amount of unitization. Examples include chines, contoured skins, equipment trays, floor panels, fuel decks, fuel tank sidewalls, and stiffened skins.

Complex parts are defined as surfaces with complex curvatures or primary internal structures, or parts with an extensive amount of unitization or varying thickness. Examples include beams, bulkheads, frames, inlet ducts, keels, longerons, multicurvature skins, pylons, ribs, spars, and webs.

Very complex parts are defined as those with complex geometry or extensive dimensional control and tolerance requirements. Examples include intake diverter lips, edges, hubs, inlet lips, and spindles.

This taxonomy is meant to be exhaustive. Some technical and engineering judgment is obviously required to assign any given part to one of these four bins. We thus categorized all the parts for which we received cost data. We reviewed the categorization with some outside experts, but it remains true that the validity of our statistical results depends on the quality of our categorization judgments.

Table 4.12 illustrates the part categories.

Methodology

We also categorized the part data we received by material and by fabrication process (categories shown in tables that follow). For each part geometric complexity/material/fabrication process combination, we calculated average recurring manufacturing hours per pound. To account for learning effects, we normalized the data to cumulative average cost (CAC) for quantity 100, and we also normalized to a part weight of 15 pounds. The part/labor hour data we received included part weight and cumulative production level, so this normalization was possible. Estimates of learning rates and weight-sizing factors also come out of these normalization calculations and are reported below.

The raw data we used consisted of part fabrication hours per pound only. To facilitate use of the cost ratios for overall airframe cost estimates (described in Chapter Six), we converted these data to an "all-airframe labor basis" by adding an estimate of assembly hours per pound—3.05 hours per pound (CAC 100) in this case—to all estimates of part hours per pound.[2] Thus, the cost ratios in Tables 4.13,

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[2] This assembly-hours-per-pound estimate (CAC 100), along with an estimate that assembly hours would be 40 percent of total recurring manufacturing hours for an all-aluminum aircraft (also CAC 100), was based on averages of some industry data that had such a categorization. These data, like the part cost data, were proprietary and were provided to us under an agreement that we would use only averages.

Table 4.12

Part and Geometric Complexity Cross-Reference Matrix

Part	Simple	Medium	Complex	Very Complex
Beams			X	
Bulkheads			X	
Chines		X		
Contoured skins		X		
Covers	X			
Diverter lips				X
Doors	X			
Edges				X
Equipment trays		X		
Fittings	X			
Flat skins	X			
Floor panels		X		
Frames			X	
Fuel decks		X		
Fuel tank sidewalls		X		
Hubs				X
Inlet ducts			X	
Inlet lips				X
Keels			X	
Longerons			X	
Multicurvature skins			X	
Panels	X			
Pylons			X	
Ribs			X	
Spars			X	
Spindles				X
Stiffened skins		X		
Webs			X	

4.14, and 4.15 are precisely defined as follows: Let x be the estimated recurring manufacturing fabrication hours per pound required for a part of a given geometric complexity/material/fabrication process combination. The quantity 4.60 hours per pound (CAC 100) is our estimate, based on our data, of the recurring manufacturing fabrication hours per pound required for a medium-complexity aluminum part made by conventional machining. The *cost ratio* for the given geometric complexity/material/fabrication process combination is then (x + 3.05)/7.65. The quantity 7.65 is the sum of 4.60 and 3.05. Thus, cost ratios are defined as the ratio of "all-airframe labor basis" hours, where these hours include both fabrication and a fixed estimate of assembly hours. Ratios are relative to medium-complexity aluminum parts made with conventional machining.[3]

The companies that provided us with part cost data were as follows:

- Alliant Techsystems
- Bell Textron
- Boeing
- GKN Westland
- Lockheed Martin
- Northrop Grumman
- Sikorsky.

Results

Table 4.13 shows recurring manufacturing labor hour cost ratios for conventionally machined metals. These data show the expected pattern. Part costs increase with geometric complexity, since more complex parts require more machining than simple parts, and aluminum is the least costly material. The cost penalties due to complexity are larger than those due to material differences.

Table 4.14 shows cost ratios for metals produced using advanced methods. As one would expect, part labor hour costs are lower for the advanced techniques than for the conventional methods. This relative advantage tends to increase for more complex parts, partly because unitization opportunities are greater. The advantage is greater for aluminum and aluminum-lithium HSM than for titanium HPM.

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[3] Conventional machining is currently the dominant aluminum fabrication process. For example, 46 percent of the aluminum used in the F-16 structure is conventionally machined.

Table 4.13

1990s Cost Ratios Based on Part Data Analysis: All-Airframe Labor Basis, Conventionally Machined Metal[a,b]

Material/Fabrication Process	Simple	Medium	Complex	Very Complex
Aluminum/conventional machining	0.7	1.0	1.5	2.3
Aluminum-lithium/conventional machining	0.7	1.0	1.6	2.5
Titanium/conventional machining	0.7	1.2	1.7	2.9
Steel/conventional machining	0.7	1.1	1.8	2.9

[a] 1990s medium-complexity, conventionally machined aluminum = 1.0.

[b] Based on manufacturing data except for aluminum-lithium, which is based on experiment/demonstration data.

Table 4.14

1990s Cost Ratios Based on Part Data Analysis: All-Airframe Labor Basis, Advanced Manufacturing Metal[a,b]

Material/Fabrication Process	Simple	Medium	Complex	Very Complex
Aluminum/HSM	0.6	0.8	1.0	1.5
Aluminum-lithium/HSM	0.6	0.8	1.1	1.6
Titanium/HPM	0.7	1.1	1.5	2.5
Titanium/HIP investment casting	Not available	Not available	1.0	Not available

[a] 1990s medium-complexity, conventionally machined aluminum = 1.0.

[b] Based on manufacturing data except for aluminum-lithium/HSM and titanium/HPM, which are based on experiment/demonstration data.

Table 4.15

1990s Cost Ratios Based on Part Data Analysis: All-Airframe Labor Basis, Composites[a,b]

Fabrication Process	Simple	Medium	Complex	Very Complex
Hand layup	1.3	1.8	2.2	3.0
Hand layup with OLPA	1.1	1.6	1.9	2.6
Automated fiber placement	0.7	1.3	1.7	Not available
Resin transfer molding	Not available	Not available	1.4	2.3

[a] 1990s medium-complexity, conventionally machined aluminum = 1.0.

[b] Based on manufacturing data except for OLPA, which is based on experiment/demonstration data.

Table 4.15 shows cost ratios for composites. The data we received showed no systematic differences between carbon-epoxy and carbon-BMI, so we have combined the two in Table 4.15. (This is consistent with what many in industry told us if not with the survey results, as noted above.) We received no data for thermoplastics, so they are not included. Table 4.15 shows the expected results: hours per pound increase with complexity and fall with automation. The fiber placement factor for the simple category represents a tape layup machine; the medium and complex factors represent a tow/contoured tape placement machine. We stated above that the RTM process is most suitable for internal primary structure and for parts with strict dimensional tolerances and complex geometry. The data reflected this, as we received RTM data only for complex and very complex parts. One implication of Tables 4.13 through 4.15 is that, overall, part geometric complexity is a more important cost driver than material or process.

We asked industry for part-level cost data for the other labor categories: tooling, engineering, and quality assurance. However, we obtained little such data because most companies did not keep part-level data for those categories. Many companies did not collect any data by part for the nonmanufacturing labor categories but instead used standard factors based on manufacturing hours to estimate these categories.

The information we did obtain indicated that nonmanufacturing labor requirements increase with part complexity in roughly the same way as do manufacturing requirements. However, the data are so sparse that we did not feel average numbers would be reliable, so we do not show any. Our judgment would be that modifying nonmanufacturing ratios for part complexity proportional to manufacturing ratios would be a reasonable procedure, but this should be viewed as a hypothesis rather than as a finding of the study. On the basis of the little data we have and our conversations with industry, we would not modify nonmanufacturing ratios based on manufacturing technique, but this too is merely a hypothesis. We do not have sufficient data to justify more definitive statements about how nonmanufacturing hours vary with part complexity or manufacturing technique.

COST IMPROVEMENT SLOPES

One of the most well-known properties of aircraft production lies in the reduction of labor hours per pound that occurs as cumulative production increases—a phenomenon also called "learning by doing."[4] This is a result not only of workers "learning" the fabrication and assembly processes better but also of manufacturing and engineering planning improvements and producibility innovations. The part data we received allowed us to calculate cost improvement slopes by material and manufacturing process. However, there were not enough data to yield confident estimates of differences in learning rates by part geometric complexity; this is an important area for further research.

Table 4.16 shows estimated cost improvement slopes for four fabrication categories.[5] We estimate that all metal fabrication and composite hand layup fabrication have slopes of 86 percent, while the two primary composite automation techniques have a lower rate of

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[4] Among the early references to this are Asher (1956) and Wright (1936). A good introduction to learning theory can be found in Lee (1997). A recent study that estimates both learning and "forgetting" effects in commercial aircraft manufacturing is Benkard (2000).

[5] We use "unit learning" theory in this report. (See Lee, 1997, for a discussion of various approaches to modeling learning.) A "cost improvement slope" of x% indicates that each time cumulative production doubles, unit cost falls $(100 - x)$%.

learning of 90 percent. This can be paraphrased in the statement “machines don’t learn as fast as people.” It reflects the fact that because automated processes must initially be carefully designed in order to program the machines, such processes have less potential room for learning than do manual processes, which are generally described only verbally during airframe development. As production occurs, workers learn the most efficient routines through trial and error.

The figure in the table for “all-manufacturing” labor for metals and hand-laid-up composites—80 percent—is based on the airframe CERs described in Chapter Five. The 71 percent slope for assembly is derived from the assumption that, using the estimate discussed above, 60 percent of hours are fabrication and 40 percent assembly. As discussed below, we assume in this study that assembly labor required is independent of manufacturing technique for parts, so we apply the 71 percent across Table 4.16. The all-manufacturing slope of 81 percent for automated composites is then derived from these figures. We took into account the 51 percent reduction in fabrication hours that occurs when automated techniques are used, based on Table 4.15.

WEIGHT-SIZING SLOPES

Another well-known property of aircraft production is the reduction of part fabrication labor hours per pound that occurs as part weight increases. The magnitude of this effect is represented by a “weight-sizing factor,” also known as an ARCO factor.[6] Table 4.17 shows by fabrication technique the ARCO factors we estimated from the part data.

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[6] ARCO is an acronym for Aircraft Resources Control Office, which was the agency that controlled aircraft production during World War II. ARCO factors are similar to cost improvement slopes. An ARCO factor of x% indicates that each time part weight doubles, labor hours per pound fall (100 – x)%.

Table 4.16

Cost Improvement Slopes (in percentages)

Process	Fabrication Slope	Assembly Slope	All-Manufacturing Slope
Composite—hand layup	86	71	80
Composite—fiber placement	90	71	81
Composite—RTM	90	71	81
Metal—all machining	86	71	80

Table 4.17

Weight-Sizing (ARCO) Factors

Process	Labor Weight-Sizing Factor (%)
Composite—hand layup	75
Composite—fiber placement	80
Composite—RTM	75
Metal—machining	75

MATERIAL COSTS

Two main elements determine the total cost of material: raw material cost and BTF ratios. We collected data on these elements in our discussions with industry and present average results here. All prices are in dollars of FY2000 purchasing power. We note that raw material prices fluctuate frequently; thus, anyone doing cost-estimating work involving such prices must check current market conditions, as the prices quoted here may well have changed.

Raw Material Costs

Composite raw material costs depend on fiber type, fiber form, resin type, and the size of the buy. Table 4.18 shows our estimates of FY2000 prepreg prices as a function of these four factors. As discussed in Chapter Two, composites can be purchased in the form of unidirectional tape or fabrics. Table 4.18 shows that fabrics are more expensive per pound, primarily as a result of the additional labor

Table 4.18

Composite Prepreg Costs[a]

Material	Unidirectional Tape—Small Buy	Unidirectional Tape—Large Buy	Fabric—Small Buy	Fabric—Large Buy
SM/epoxy	85	50	115	60
IM/epoxy	120	90	185	125
SM/BMI	95	60	135	70
IM/BMI	145	100	185	135
SM/thermoplastic	195	155	255	195
IM/thermoplastic	250	190	295	230

[a] FY2000 dollars per pound.

required for weaving. Fiber quality is represented by the IM/SM distinction. IM is stiffer and is thus required for airframe parts that endure high stress. SM is acceptable for airframe parts that endure lower loads. Table 4.18 shows the price premium required for the higher-quality product. It also shows that BMI is currently more expensive than epoxy and that thermoplastic is more costly than both.

Composite costs can vary greatly with the size of the buy. Table 4.18 shows costs both for a relatively small buy (e.g., during the aircraft development phase—approximately 50,000 pounds in total) and for a large buy (e.g., during the production phase—approximately 250,000 pounds or more per year). For even larger buys, additional price reductions were said to be possible, but we have no data on this.

One of the factors affecting market prices for composites is the level of commercial (i.e., nongovernment) demand for the material. In the short run, increases in commercial demand tend to increase price, as more buyers bid for existing production capacity. In the long run, however, an increased market may lead to lower prices, as producers can often move to lower unit-cost production techniques if volume is sufficiently large. Industry-wide learning occurs with commercial market growth as well. It is not possible to predict with precision either the future level of commercial demand or the ultimate effect of such demand on price. This underscores the fact that cost analysts must watch the market or monitor current bill-of-material data to ensure that their raw material cost estimates reflect changing market conditions. In recent years, increased commercial use of composites has tended to lower price.

The state of industry competition also influences raw material cost. Through normal competitive processes, industries with a relatively large number of producers tend to be characterized by lower prices. Some of the composites of most interest to aircraft manufacturing are produced by a limited number of domestic companies, and currently there are legal restrictions on using foreign sources of composite material in military aircraft programs. Changes in competitive structure are hard to predict (depending partly on government policy) and can lead to changed prices, representing still another reason cost analysts must watch industry developments.

Metal raw materials are purchased in sheet and plate form.[7] Table 4.19 shows our estimates of FY2000 metal prices as a function of metal form and size of buy (using the same definition of “size of buy” as for composites). The differences in price between a small and a large buy tend to be less than those for composites because aerospace-grade metal is more similar to commercial-grade metal than is the case with composites. Thus, more sources are available to produce these metals, and a single large military aircraft buy may not be large in comparison to the overall market. Titanium cost has increased in recent years owing to its extensive use in sporting goods and to the geologic limitations on expanding titanium ore mining capacity. As mentioned above, the PPI for titanium rose 56 percent between 1987 and 1999, while that for all metals rose only 16 percent over the same time period.

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[7] Aircraft manufacturers are increasingly purchasing metal parts or near-net forms such as castings, extrusions, and forgings from other suppliers and thus are not purchasing the raw materials themselves.

Table 4.19

Metal Costs[a]

Metal Type	Metal Form	Small Buy	Large Buy
Aluminum	Plate	4	3
	Sheet	3	2.50
Titanium	Plate	22	21
	Sheet	28	23
Steel	Plate	3	2
	Sheet	2	2
Aluminum-lithium	Plate	16	12
	Sheet	16	12

[a] FY2000 dollars per pound.

BUY-TO-FLY

The BTF ratio (Table 4.20) is the ratio of total purchased material weight to the weight of the finished parts that are installed on the aircraft. Aggregate BTF ratios include material lost as a result of handling problems, machining and cutting processes, parts that are eventually scrapped, and other steps in the manufacturing process that cause material loss. Some companies calculate separate BTF ratios for each of these loss modes.

BTF ratios vary by manufacturing process. Composite automated processes result in a lower BTF than does hand layup. Material losses in hand layup include cutting table scrap, lost or misplaced plies, operator errors, and loss of prepreg by virtue of excessive time out of the freezer.[8] The estimated BTF for RTM is the same as that for hand layup, since the fabrication of a preform is comparable to a hand layup process in this respect. If a company buys RTM preforms from a supplier, then the BTF for that company would be much lower (roughly 1.2), since the only material loss would be from excess resin, trimming, or defective parts. (Of course, the supplier would incur the material losses associated with making the preform, which would presumably be reflected in the preform price.)

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[8] See Boeing (1999) for more details.

The BTF ratios of metals vary by manufacturing process and are independent of the type of metal. There is a great deal of variation in these ratios because different part types generate different levels of material loss. More geometrically complex parts and unitization, for example, lead to higher BTF ratios for metals.

Table 4.20

BTF Ratios

Fabrication Process	BTF Ratio	Remark
Composite—hand layup	2.5–1.9	Fabric and wide tape
Composite—fiber placement	1.5–1.3	Tape and tow
Composite—RTM	2.5–1.2	Fabric and preform
Metal—machining	20–16	NC[a] and HSM—independent of metal type
Metal—forming	3–2	Sheet forming, SPF/DB
Metal—casting	2–1	Results in near-net shape casting
Metal—forging	6–5	Independent of metal type
Metal—extrusion	3–2	Independent of metal type

[a] NC = numerically controlled.