AD-783 639

WEAPON SYSTEM COSTING METHODOLOGY FOR AIRCRAFT AIRFRAMES AND BASIC STRUCTURES. VOLUME I. COST METHODS RESEARCH AND DEVELOPMENT

R. E. Kenyon, et al

General Dynamics/Convair

Prepared for:

Air Force Flight Dynamics Laboratory

December 1973

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AD 783 639

REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER: AFFDL-TR-73-129, VOLUME I
2. GOVT ACCESSION NO.:
3. RECIPIENT'S CATALOG NUMBER:
4. TITLE (and Subtitle): WEAPON SYSTEM COSTING METHODOLOGY FOR AIRCRAFT AIRFRAMES AND BASIC STRUCTURES
5. TYPE OF REPORT & PERIOD COVERED: Interim Report, July 1972 - September 1973
6. PERFORMING ORG. REPORT NUMBER:
7. AUTHOR(s): R. E. Kenyon, J. M. Youngs
8. CONTRACT OR GRANT NUMBER(s): F33615-72-C-2083
9. PERFORMING ORGANIZATION NAME AND ADDRESS: Convair Aerospace Division of General Dynamics, Kearny Mesa Plant, San Diego Operation, 5001 Kearny Villa Rd., San Diego, CA 92112
10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS: Project 1368, Task 136802
11. CONTROLLING OFFICE NAME AND ADDRESS: Air Force Flight Dynamics Laboratory, Advanced Structures Division, Air Force Systems Command, Wright Patterson AF Base, Ohio
12. REPORT DATE: December 1973
13. NUMBER OF PAGES: 233
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office):
15. SECURITY CLASS. (of this report): Unclassified
15a. DECLASSIFICATION/DOWNGRADING SCHEDULE:
16. DISTRIBUTION STATEMENT (of this Report): Approved for public release; distribution unlimited.
17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report):
18. SUPPLEMENTARY NOTES:
19. KEY WORDS (Continue on reverse side if necessary and identify by block number):

parametric estimating; design to cost; aircraft structure cost estimating; trade study costing; composite structure costs; airframe costs; airframe cost estimating; first unit costing; aerodynamic surfaces costing

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This report presents the interim results of a study aimed at extending cost estimating techniques developed and demonstrated under a previous contract. The previous study resulted in two separate estimating methods: a trade study and a system costing method. These methods provided two essential estimating capabilities:

a. The capability of assessing the relative difference in the cost of the basic structures attributable to variations in type of construction and material in an

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20. iterative fashion to support tradeoff studies during the preliminary design process.

b. The capability of accurately estimating total airframe costs in manhours and materials for selected design while retaining sensitivity to type of material and construction.

The previous study provided these capabilities for empennage elements and demonstrated their feasibility in that context.

During the initial phase of the current study, these capabilities have been extended to include the complete set of aerodynamic surfaces: horizontal stabilizer, vertical stabilizer, canards treated as a stabilizer, and wings, including secondary structure. Primary emphasis has been given to the trade study estimating method, since the principal objective of the study is the support of tradeoff studies involving the selection of material and type of construction. Tradeoff capability has been provided for a range of alternative structure and material combinations. Cost data has been collected to establish baseline estimating reference values. Methods for handling special structures and processes are given and demonstrated. A technique for independently assessing complexity factors has been developed and demonstrated. Manufacturing costs are separately estimated for the primary elements of substructure: ribs, spars, covers, leading edges, trailing edges, tips, etc. The trade study cost estimating method has been designed to provide an iterative estimating capability that suits it to design-to-cost and other trade study questions. This capability stems primarily from the direct interface with design synthesis programs.

A high degree of modularity is being sought in the development of estimating methods. The same cost estimating relationships are used in both methods for nonrecurring costs. In addition to this overlapping, when adequate input data is available, the detailed CERs of the trade study method may be substituted in the framework provided by the system costing method.

The final phase of the study will complete the extension of the method to the remaining elements of basis structure. In addition, advanced structures and materials will be investigated, the system costing method will be elaborated, an integrated computer program will be developed, and the overall method will be demonstrated.

☆U.S.Government Printing Office: 1974 — 758-432/467

AFFDL-TR-73-129-Vol. I

WEAPON SYSTEM COSTING METHODOLOGY FOR AIRCRAFT AIRFRAMES AND BASIC STRUCTURES

VOLUME I - COST METHODS RESEARCH & DEVELOPMENT

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FORWORD

This report was prepared by the Convair Aerospace Division of General Dynamics, San Diego, California, under USAF Contract F33615-72-C-2083. The contract titled "Weapon System Costing Methodology for Aircraft Airframes and Basic Structures," was initiated under Project 1368, "Advanced Structures for Military Aerospace Vehicles," Task 136802, "Structural Integration for Military Aerospace Vehicles."

The work was administered under the direction of the Air Force Flight Dynamics Laboratory, Structures Division, Wright-Patterson Air Force Base, Ohio, under the direction of Mr. R. N. Mueller (AFFDL/FBS) as Project Engineer.

This report covers work conducted from July 1972 to September 1973 and was submitted by the author in September 1973, under General Dynamics Report CASD-AFS-73-001 as an Interim Technical Report.

This report includes three additional volumes: Volume II, Supporting Design Synthesis Programs, Volume III, Cost Data Base, and Volume IV, Estimating Techniques Handbook.

The principal author and project leader on this program is Mr. R. E. Kenyon, under the administration of Mr. G. E. Vail, Chief of Economic Analysis and Mr. A. Van Duren, Manager of Operations Research. Others who contributed to the studies and who contributed in the preparation of this report include Messrs. J. L. Youngs and R. J. Reid, Economic Analysis; B. H. Oman and W. D. Honeycutt, Mass Properties; L. M. Peterson, Structural Analysis; and T. E. Brents and J. D. Jackson, Fort Worth Operation.

This technical report has been reviewed and is approved.

KEITH I. COLLIER
Chief, Advanced Structures Branch
Structures Division
Air Force Flight Dynamics Laboratory

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SECTION I

INTRODUCTION

This is a study to develop preliminary design level techniques for estimating the cost of flight vehicle structures in a way that provides sensitivity to the structural concepts and materials used. Two techniques, or capabilities, are involved:

a. The ability to generate relative costs of different airframe structures to support the introduction of cost into tradeoff studies involved in the design process.

b. The ability to estimate accurately total airframe costs in terms of manhours and materials for system study purposes.

The first estimating method produces what is referred to in this study as trade costs. This method requires the development of a technique that allows the designer to compare competing designs on a relative cost basis where the relative cost of each design is accurately represented and the inputs required for cost estimating are within the data base normally generated during preliminary design. The second estimating method produces what is referred to as system study costs. It requires the development of a technique that is also sensitive to design concepts and materials and that also supports estimating on an absolute cost basis for designs chosen for inclusion in system concepts studies.

The current effort is an extension of the methodology developed under a previous Air Force contract and documented in Reference 1. That contract resulted in the development of a methodology for airframe structural cost estimation and the demonstration of the method based on horizontal stabilizer examples. The extension of the method encompasses the remaining major items of the airframe basic structure; i.e., vertical tail, wing, fuselage, landing gear, and air induction/nacelle. This report covers the effort on the wing, vertical stabilizer, and horizontal stabilizer, combined as to methodology under the classification of aerodynamic surfaces. The final phase of the study will be devoted to the fuselage and remaining structural components, the system costing method, refinements for advanced materials and structural concepts, predesign applications, computer programming, and final demonstration.

As the cost of building and operating aircraft increases, it becomes increasingly important to have an accurate system cost estimate before committing to a final design.

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1. R. E. Kenyon, "Techniques for Estimating Weapon System Structural Costs," AFFDL-TR-71-74, Final Report (Contract F33615-70-C-1340), April, 1972

Also, as the number of materials and structural design concepts applicable to flight vehicles increase, it becomes necessary to know the detailed relative costs of equal performance designs, so that the impact of design options can be assessed. Past experience and a review of available literature describing current estimating methods reveal major deficiencies in these methods with respect to: (1) oversimplification of cost models and the lack of depth of analysis required to evaluate cost sensitivity to design tradeoff choices in terms of construction methods and structural material, and (2) over-reliance on weight estimates as a single cost-driving variable and especially ignoring the discontinuity in the cost-weight relationship brought about by the advent of increasingly exotic materials and fabrication complexities that can create an inverse cost-weight relationship. Each of these shortcomings has contributed to the cost estimator's difficulties in responding to the requirements for costing new airframe designs and for providing inputs to the designer in a design tradeoff process.

1.1 STUDY OBJECTIVES

The specific objectives of this phase of the study were:

a. To extend the trade study costing method to the remaining elements of the aerodynamic surfaces; i.e., the vertical stabilizer, canards, and the wings.

b. To initiate the extension of the trade study cost estimating method for fuselages, nacelles, and air induction system.

c. To initiate an updating of the method to consider advanced structures and composite materials.

d. To provide a computerized module for aerodynamic surfaces that is compatible with the final cost model. The model will interface with supporting structural synthesis and weight estimating programs to provide a preliminary design level technique for estimating the cost of aerodynamic surface structural components.

e. To extend the system costing method to the vertical stabilizer, canards, and wings.

1.2 SCOPE AND LIMITATIONS

A subset of cost categories with which the study was to be concerned was defined out of a total set of weapon system cost categories. The major cost categories included nonrecurring design and development, recurring design and development, and recurring production. These categories were further broken down in a conventional manner. A typical set of total system costs was analyzed and categorized into:

a. Costs excluded from the airframe; i.e., avionics and propulsion.

b. Costs excluded on the basis that they are identified to the total vehicle and not relatable to the airframe, such as aircraft flight tests.

c. The remaining costs that are the subject of study.

The study has carried forward the idea of two different time frames with respect to the availability of cost data. This concept of availability is referred to as limited data estimation and unlimited data estimation. Limited data is that which is reasonably available at the present time. Unlimited data is that which can reasonably be made available in a future time period.

A limited literature survey of specific references has been accomplished during these studies to investigate representative estimating approaches as an aid in developing cost estimating relationship forms. This survey has been augmented by continuing Convair Aerospace Division research programs to develop unique methods for estimating cost tradeoff penalties and payoffs. This research has been devoted to (1) identifying cost-related variables, (2) development of structural and weight analysis tools, and (3) developing the groundwork for the application of these tools to the analysis of costs.

Primary emphasis has been given to the trade study cost method, inasmuch as the principal objective of the study is to support tradeoff studies in system design to answer specific questions regarding selection of type of material and construction. Tradeoff capability has been provided for a range of alternative structure and material combinations based on the present analytic capability of the multistation structural synthesis program used. These combinations are first categorized by basic aircraft structural concepts: skin stringer or multirib type applicable to a wide range of aircraft having moderate speed and load factor requirements; multispar structure that characterizes the high-speed, high-load factor; and full-depth sandwich, which is usually confined to very thin surfaces such as tails. The primary elements of substructure; that is, ribs, spars, and covers, are further categorized by basic types of construction. Methods and examples are given for aluminum, titanium, steel and composites. Methods for special structures and bonding of structure are given and demonstrated.

The trade study cost method uses weight and dimensional data obtained from a multistation structural synthesis program as the primary cost-related variables in the cost estimating relationships. The structural synthesis program provides stress and dimensional analyses of structural components and weight data in accordance with input choices of type of structure and material and provides the basis for interrelating the results of these analyses with cost. The structural synthesis program is in turn driven by a vehicle synthesis program, with the result that a preliminary design study loop can be operated to evaluate the impact of airframe configuration changes generated by variations in performance requirements.

Estimating techniques are updated by a plan covering incorporation of new materials and concepts, labor and material price changes, an expanded treatment of composite materials, and the impact of new aerodynamics on construction methods. Design studies seem to show that, at least for the next generation of aircraft, composites will not be used exclusively for all components of the aircraft, but will be used for individual parts on a selective basis. This estimating method is well suited to cost the partial applications of composites believed to be typical and has been shown to be feasible at a detailed level of analysis. The method is, of course, not yet fully developed but provides a sound basis for systematic enlargement to provide the analyst with the detailed insights for effective cost analysis.

1.3 BACKGROUND

The present contract is a follow-on to Air Force Contract F33615-70-C-1340 sponsored by the Structures Division of the Flight Dynamics Laboratory. This study included the investigation of representative approaches to cost estimating as they are described in the available literature, the conception and evaluation of new approaches, the final selection of an approach for each of the two required types of estimating, and the development of the selected approaches to the point that their feasibility could be demonstrated. The methods developed are eclectic in that they combine elements of each of the basic estimating methods that can be categorized from the literature; i.e., the industrial engineering approach, statistical estimation, and estimating by analogs.

The feasibility study was followed by a second contract, which is currently in progress. The follow-on study provides for extending the trade study cost estimating techniques from the horizontal stabilizer to the entire basic structure. The results and findings of the first phase are being combined with the results of the additional research and study to produce an expanded and updated estimating system. The initial estimating techniques were demonstrated using the horizontal stabilizer for evaluation purposes. Additional test cases have been run, based on all elements of the aerodynamic surfaces. Additional demonstrations based on fuselage and nacelle components and a final demonstration based on all elements are planned later in the study.

It should be noted that different areas of cost are covered by each estimating method and also that different levels of detail are involved. Trade study costs cover only that part of the airframe referred to as basic structure (i.e., wing, tail, fuselage, nacelles, air induction, landing gear), whereas system costs include, in addition, aircraft subsystems except for propulsion and avionics. This distinction applies to each cost category: nonrecurring first unit, and recurring, both development and production. In terms of level of detail, both methods use the same cost estimating relationships for nonrecurring costs, but for first unit and recurring costs, the trade study method generally follows the AN 9102 weight statement form, while system costs generally follow the AN 9103 level of detail. A high degree of modularity is achieved by using the detailed CERs of the trade study method for costing airframe basic structure when adequate input data is available. Alternative CERs are available at the wing, tail, and fuselage level for system costing, however, when the detailed inputs required by the trade study method are lacking.

1.4 ORGANIZATION OF THE REPORT

This interim report is presented in four volumes. Volume 1 includes the introduction; a discussion of cost methods research and development; conclusions and recommendations from the research, operation of the methods and from other study results; and appropriate appendixes. Volume 2 consists of a description and discussion of the development and integration of supporting programs: multistation structural synthesis programs, secondary structure synthesis, and weight estimating methods. Volume 3 contains the cost and technical data used in the development and verification of the cost methods. Data is organized according to cost estimating method. Cost trend data is included representing various summaries of cost made available as a basis for system cost level comparisons. Volume 4 consists of an estimating techniques handook for both estimating methods and a user's guide to the computerized programs.

SECTION II

COST METHODS RESEARCH AND DEVELOPMENT

This section of the report describes the continuing cost methods research and development involved in extending the cost estimating capability beyond the horizontal stabilizer to the remaining aerodynamic surface structural components. The starting point for the effort was the initial estimating methods as described in Reference 1. During the study improvements in these methods were made. A limited review of the literature preceded the development of the expanded trade study cost estimating method.

2.1 LITERATURE REVIEW UPDATE

For the initial study, a review of cost-estimating literature was based on specific references cited by the study contract. Cost-estimating approaches were investigated to determine forms and requirements of typical CERs as background for an approach to the development of the estimating methods. The additional review of subsequent publications is the subject of this section.

The literature review concentrated primarily on specialized studies related to structural concepts, the impact of alternative material use, cost data, and manufacturing methods. Reports on more general cost subjects have been reviewed, however, in connection with system cost estimating data and methods.

Reference 2, by Fetter and Stalmack, describes the general tactical support aircraft cost model used by ASD to estimate the cost of proposed new tactical aircraft systems. A CER is described for first unit airframe cost, where airframe is defined in the system-level sense. It is derived by regression analysis using AMPR weight as the single cost-related variable. Factors are applied to account for V/STOL, titanium use, and the use of other nonstandard material. These factors form the basis for giving effect to alternative types of material and construction. The report also contains various estimating factors that will be used to provide comparative data in the later study of system costing.

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2. Donn Fetter and David Stolmack, "Tactical Support Aircraft Cost Model," Report ASB68-5, March 1968.

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Reference 3, a study by Stolmack, develops two estimating relationships: one for development program airframes and the other for production program airframes, which result in estimating factors that can be applied to standard airframe CERs to evaluate the cost delta attributable to the use of titanium. The relationships are based on a consideration of fabrication labor, material, assembly labor, and other costs.

Labor and material cost mixes by major component and by labor operation and material category are developed and factored according to the complexity associated with the percentage of titanium used. The method assumes that a given percentage of titanium in the AMPR weight results in a constant percentage of titanium in each of the major components. Associated with this percentage is a percentage breakdown by labor operation, and this operation can be factored according to the type of material involved. Points are plotted at the endpoints of the range of titanium/AMPR ratios (percentages) for each of the airframe major components, and a weighted average is taken to give two points that are used to develop the equation for labor complexity by titanium percentage. The assumption of a constant ratio of titanium in a given AMPR percentage does not address the question that the AFFDL method seeks to answer: What is the cost of varying mixes of type of construction and material?

Reference 4, NADC Report NADC-SD-6925, describes an approach to logistics support and operations costs based on the use of three separate models, VALUE, MCM, and SCORE. The VALUE model simulates aircraft system operational activity, generating as output the maintenance requirements or demands of the total system and its parts. The MCM model translates the maintenance material demands of an aircraft system, as generated by the VALUE model, into cost. The SCORE model computes total cost of ownership (life cycle cost) for aircraft systems. The estimating method is very detailed in the area of operating cost and very gross in the area of acquisition costs. Airframe costs are estimated by a choice of either Rand, PRC or CNA methods. These methods were reviewed in the previous study.

Reference 5, NADC Report NADC-AW-6734, provides a conceptual description of the Navy SCORE model, illustrating the flexibility provided . . . "in order that (1) full advantage can be taken of alternative cost estimating relationships and techniques, (2) sensitivity analyses can be performed, and (3) the consequences of different force level and design discussions can be assessed." The model includes a force structure section as well as the cost section.

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3. David R. Stolmack, "Titanium Cost Estimating Relationships," Report ASB 70-5, March 1970.

4. "Techniques for Estimating Logistics Support and Operations Cost of Naval Airborne Weapon Systems," Naval Air Development Center, Report No. NADC-SD-6925, 30 April 1969.

5. "SCORE (System Cost and Operational Resource Evaluator) Executive Routine: Phase I Report," Naval Air Development Center, Report No. NADC-AW-6734, 30 November 1967.

Reference 6 presents the results of a study to investigate the estimating accuracy of two different cost prediction procedures that predict the cost runout of a quantity of an aircraft of a new design given the first unit cost. The two procedures were: (1) a single-slope log-linear unit cost-quantity curve, and (2) a three-slope log-linear unit cost-quantity curve. The second procedure represents a combination of the Stanford "B" curve and the findings of Harold Asher of the tendency of the cost-quantity curve to flatten at around three-hundred units. The first procedure reflects the application of a single curve as would be obtained from a standard set of learning-curve tables. The study found an insignificant difference in the predictive accuracy of the two methods and suggested that the difference that was found might be the effect of an additional factor, such as production rate for example.

Reference 7 is a handbook produced in connection with an Air Force Material Laboratory contract. The machining data contained in this handbook is too detailed to be of significant use in this study. Data is given for some thirty-seven different types of materials and twenty-four different machining operations. Relative machining times for these combinations of materials and machining processes are given.

Reference 8 deals with a standard process of manufacturing cost estimating as would be used for commercial manufacturing. It probably cannot be used directly in this study.

Reference 9, by J. W. Noah, classifies, describes, and compares techniques used to summarize total costs as used in system analysis. Five cost summarization procedures are discussed: Five-Year System Cost, Period Outlay, Net Cost, Present Cost, and Annual Cost. Distinctions in method of summarizing total costs are not expected to be a factor in the required cost estimating techniques.

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6. R. J. Reid, "Examination of Cost Projection Accuracy Comparing Two Different Cost-Quantity Analysis Procedures," Research Paper, May 1972.

7. Machining Data Handbook, 2nd Edition, Machinability Center, Metail Research Associates, Inc., Cincinnati, Ohio, 45209, 1972 Library of Congress Catalog Card No. 66-60051.

8. Ivan R. Vernon, "Realistic Cost Estimating for Manufacturing," Ed., 1968, Society of Manufacturing Engineers, Dept. PS70-0[illegible], 2050[illegible] Ford Road, Dearborn, Michigan, 48128.

9. J. W. Noah, "Concepts and Techniques for Summarizing Defense System Costs," Center for Naval Analyses, Washington, D.C., SEG RD #1. AD 6[illegible]4-17.

Reference 10, by Yates et al, deals with techniques for estimating uncertainties. It is postulated that when cost estimates are made for a weapon system far in advance of the actual development, large uncertainties are created. It states that when these uncertainties cannot be eliminated, it becomes desirable to estimate them also.

The treatment of the problem is to regard the cost estimates for the various elements of cost as random variables and to determine their distribution. If this is done, then in principle, the distribution of total cost can be found. The cost estimate can then be formulated in such terms as, "The total cost will be between A and B with probability P." It is not proposed that this procedure can be applied in an exact form, since t bution of costs are not in general available. However, an approximate a ay yield estimates of cost uncertainty that are more meaningful than the alte /e: stating simple upper and lower bounds. Cost estimating errors arising from system components not foreseen in the estimate and changes in system specifications after the estimate are not considered.

Reference 11 is a report representing the input data of some 70 participants representing key management and technical specialists from 25 industrial firms and several Air Force organizations who met during the week of 28 August 1972 at the Sagamore Conference Center, Sagamore, New York. This study sought to define the cost of major airframe/propulsion structural components, to determine the best approach to cost reduction, and to define specific activities to demonstrate cost saving approaches. Data is presented that shows the relative magnitude of various functional costs; i.e., detail fabrication, assembly and material procurement; the relationship of cost between structural components; the costs of detailed parts; and an assessment of factors having the greatest influence on cost.

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10. E. H. Yates, H. M. Stanfield and D. K. Nance, "A Method for Deriving Confidence Estimates in Cost Analysis," Defense Research Corp, Santa Barbara, Calif., 1966, Technical Memorandum 231, AD 811 034.

11. "Summary of Air Force/Industry Manufacturing Cost Reduction Study," 28 August -1 September 1972, AFML-TM-LT-73-1, January 1973, Manufacturing Technology Division, AFML, AFSC, WPAFB, Ohio, 45433.

Reference 12 is the result of a NASA contract to produce a summarization of key technical, schedule, and cost data for the B-58 weapon system. Cost data is broken down to the aircraft subsystem level of detail and will be used in the development of the system costing method.

Reference 13 is the result of an update by Rand of previously developed cost-estimating relationships for aircraft airframes. Estimating techniques are provided for costs related to aircraft airframes for prototype, development, and production program phases. Cost categories covered include engineering labor and cost, development support, flight test operations, tooling hours and cost, manufacturing labor and cost, quality control, and material. Costs are estimated parametrically, solely in terms of the following variables: AMPR weight, speed, quantity produced, and production rate.

2.2 THE TRADE STUDY OF COST ESTIMATING METHOD FOR AERODYNAMIC STRUCTURES

The study reported in Reference 1 resulted in the development of a basic trade study cost estimating approach that was applied and demonstrated on the horizontal stabilizer. This method has been expanded and revised to some extent, resulting in a set of estimating techniques for use on the aerodynamic surfaces. A summary of the current estimating approach is given in the following section. This may be compared to the preliminary version described in Reference 1.

2.2.1 SUMMARY OF THE AERODYNAMIC SURFACES TRADE STUDY COST ESTIMATING METHOD. The unique aspect of this cost estimating method lies in its capability to analyze cost variations attributable to changes in the type of construction and material in an iterative manner to provide information feedback into a design tradeoff process as the basis for cost-oriented structural design decisions. The tradeoff capability is further enhanced by the use of a unique coupling of synthesis programs to provide for tradeoff and sensitivity studies involving vehicle sizing and performance, and for more rigorous cost-risk assessment, than is possible with other estimating methods. The methodology is also unique in the level of detail to which hardware costs are broken down. A separate labor and material unit cost is

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12. "B-58 Aircraft Cost Study for NASA, Manned Spacecraft Center," General Dynamics/Convair Aerospace Division (FWO), Report FZM-5931-1, dated May 1972.

13. G. S. Levenson, et al, "Cost-Estimating Relationships for Aircraft Airframes," The Rand Corporation, R-761-PR (Abridged), February 1972.

produced for the ribs, spars, and covers of the wing structural box, and for the leading edges, trailing edges, tips, hinges, doors, actuator attachments, pivots and folds, center section, fairings, and elevators. An example of the level of estimating detail in terms of actual structure can be seen in Figure 1. An illustration of the types of ribs and covers that the method is capable of evaluating is shown in Figures 2 and 3. An example for spars would be similar. The methodology provides for the alternative consideration of various types of materials. In terms of the capability of the structural synthesis program and the development of cost estimating factors, these are:

a. Aluminum.

b. Titantium.

c. Low and high carbon steel.

d. Various composites.

The cost output format of the existing program is shown in Figure 4. This printout illustrates the concept of first unit cost introduced at the airframe basic structure level as a means of estimating hardware manufacturing costs. Cost estimating relationships to synthesize a manufacturing first-unit cost were developed for individual structural elements as indicated by the "Flyaway First Unit Cost," printout pages 2 and 3.

A general flow diagram of the present method is shown in Figure 5. The method can be divided into four major segments: the costs estimated, cost estimating relationships used for these estimates, inputs required by these relationships, and sources of these inputs. One or more CER is required for each of the costs displayed in Figure 4. Each of the CERs may in turn require from one to several inputs.

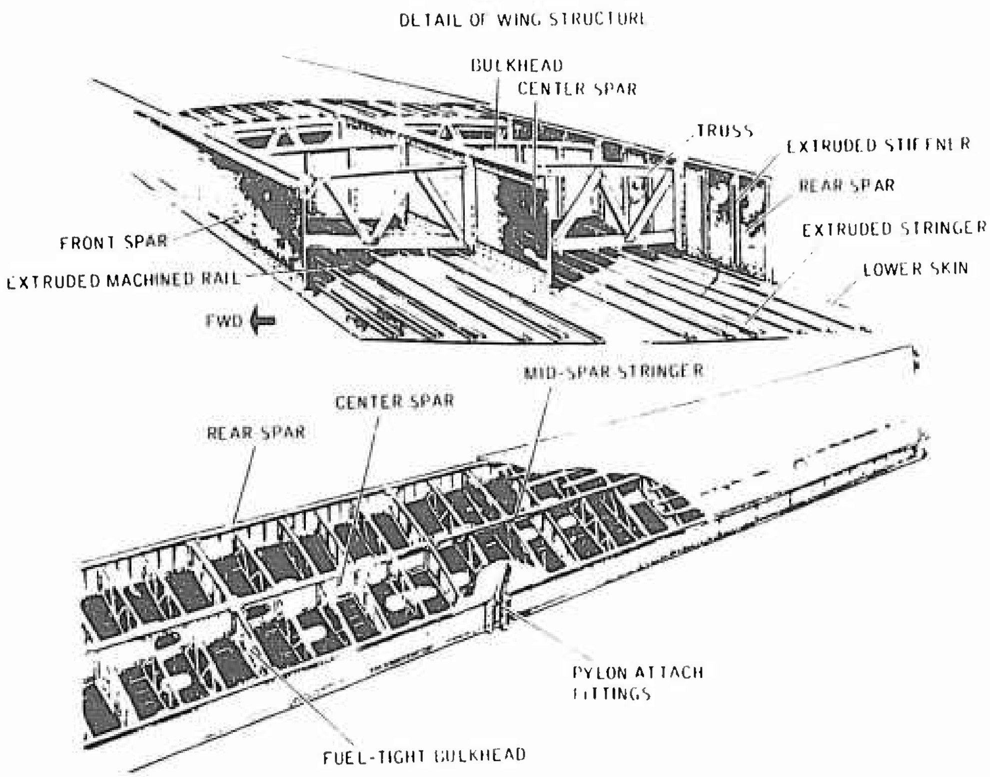

Figure 1. Skin-stringer Construction

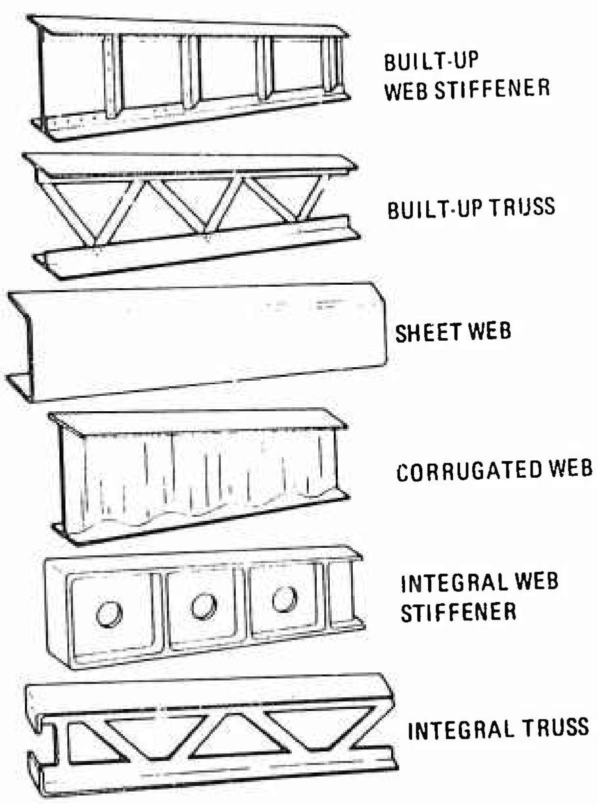

Figure 2. Examples of Rib Construction

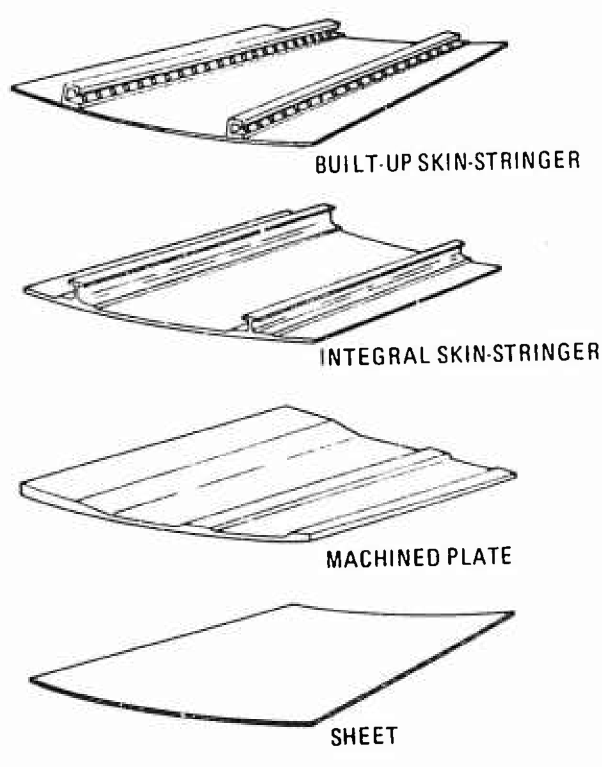

Figure 3. Examples of Cover Construction

AEROSPACE VEHICLE STRUCTURAL COSTS

NONRECURRING DESIGN AND DEVELOPMENT COSTS

12.56.12.   08/02/73

F-111A WING   C-5A HSTAB   F-111A VSTAB

	EMPEN NAGE HOURS	WING HOURS	FUSE LAGE HOURS	NACE LLE HOURS	SUB-TOTAL HOURS	DOLL AR COSTS
BASIC STRUCT DESIGN ENGR HRS	75202	212159			288360	
CONFIGURATION DESIGN ENGR HRS					346332	4.6508
ENGINEERING MATERIAL						1.7302
TOTAL TRAD STUDY ENGR						10.3809

12.56.12.   08/02/73

F-111A WING   C-5A HSTAB   F-111A VSTAB

	HORIZ ONTAL STAB	VERT ICAL STAB	WING	FUSE LAGE	NAC ELLE	SUB-TOTAL	DOL LAR COSTS
BASIC TOOL MFG HOURS	133000	110560	1118000			1358560	
RATE TOOLING MFG HOURS						1352064	
TOTAL TOOL MFG HOURS						2710564	37.9479
BASIC TOOL ENGRG HOURS						611325	
RATE TOOL ENGRG HOURS						334016	
TOTAL TOOL ENGRG HOURS						945341	14.2401
MFG DEVEL + PLANT ENGR HRS						271056	4.0658
TOOLING MATL + OTHER DOLLARS							5.4211
MANUFACTURING SUPPORT DOLLARS							9.5159
QUALITY CONTROL HOURS						543637	9.9218

FIRST UNIT COST

12.56.12.   08/02/73

F-111A WING   C-5A HSTAB   F-111A VSTAB

	WING DFAB HOURS	SUB-ASSY HOURS	WING MATL $	HSTAB DFAB HOURS	SUB-ASSY HOURS	HSTAB MATL $	VSTAB DFAB HOURS	SUB-ASSY HOURS	VSTAB MATL $
STRUCTURAL BOX									
RIBS	1043		3997	2363	554	4456	635		826
SPARS	7420		15304	4444	1906	10131	1970		3333
COVERS	4193		27411	5391	1296	17237	1241		6763
SUB-TOTAL	12656		45314	12099	3955	31824	3846		10923
MAJOR ASSY		33385	31685		17142	11640		3691	4240
SECONDARY STRUCTURE									
LEADING EDGE	1309	1142	1375	1479	1296	2373	3025	994	1557
TRAILING EDGE	173	771	2040	912	724	443			
AILERONS									
FAIRINGS				7315	7187	6465			
TIPS	503	502	709	1940	1470	2944	466	349	569
SPOILERS									
FLAPS + FLAPERONS	4429	4343	6952						
ATTACHMENT STRUCTURE				105	103	412			
ACCESS + OTHER DOORS				215	464	1361			
AIR INJECTION									
HIGH LIFT DUCTING									
SLATS									
HINGES, BRACKETS, SEALS				625	525	2182			
RIVETS + BOLTS				533	533	5213			
CENTER SECTION									
ELEVATORS				5894	5894	9267			
BALANCE WEIGHTS				176	176	2994			
RUDDER							1642	1232	2422
OTHER	4299	2573	6014						
SUB-TOTAL	11911	9138	16192	14231	13355	15952	3133	2475	4548
FINAL ASSY		14301	3948		6569	2032		1092	1265

Figure 4. Trade Study Cost Estimating Breakout

12.56.12. 08/02/73

F-111A WING C-5A HSTAB F-111A VSTAB

	FUSLG DFAB HOURS	SUB-ASSY HOURS	FUSLG MATL $	NACEL DFAB HOURS	SUB-ASSY HOURS	NACEL MATL $
BASIC STRUCTURE						
SUBTOTAL						
MAJOR ASSEMBLY						
SECONDARY STRUCTURE						
SUBTOTAL						
FINAL ASSEMBLY						

12.56.12. 08/02/73

F-111A WING C-5A HSTAB F-111A VSTAB

	WING HOURS	WING $	HSTAB HOURS	HSTAB $	VSTAB HOURS	VSTAB $	FUSLG HOURS	FUSLG $	NACEL HOURS	NACEL $	BASIC STRUC HOURS	BASIC STRUC $
SUMMARY												
DETAIL FABRICATION	24467	342538	26889	376444	6979	97704					58335	816686
SUBASSEMBLY	9138	127930	17310	242340	2475	34656					28923	404926
MAJOR ASSEMBLY	33185	467193	12182	170554	3681	51533					49248	689471
FINAL ASSEMBLY	14091	197276	6509	91123	1082	15151					21682	303550
MAJOR MATL												
MATERIAL		105539		101488		20976						228003
TOTALS											158188	2442636

AEROSPACE VEHICLE STRUCTURAL COSTS

RECURRING AIRFRAME PRODUCTION COSTS

12.56.12. 08/02/73

F-111A WING C-5A HSTAB F-111A VSTAB

RDT+E (300)	HORIZ STAB	VERT STAB	WING	FUSE LAGE	NAC ELLE	HOURS	$
SUSTAINING ENGRG						212799	5.3200
SUSTAINING TOOLING						1373017	20.5953
MANUFACTURING							
DETAIL FAB HOURS	237386	61512	216004			514999	7.2100
ASSEMBLY HOURS	431896	86939	679181			1197906	16.7707
QUAL CONTL HOURS						342581	5.9239
MATERIAL + OTHER	1632064	337315	1697209				3.6666
PROCUREMENT ARTICLES							
SUSTAINING ENGRG						182357	9.5589
SUSTAINING TOOLING						2042936	30.6425
MANUFACTURING							
DETAIL FAB HOURS	1522956	345274	1385788			3304618	46.2562
ASSEMBLY HOURS	4745981	954472	7465059			13.1665	184.331
QUAL CONTL HOURS						3294106	55.9994
MATERIAL + OTHER	29.3329	6.0335	30.1316				65.2249

Figure 4. Trade Study Cost Estimating Breakout (Concluded)

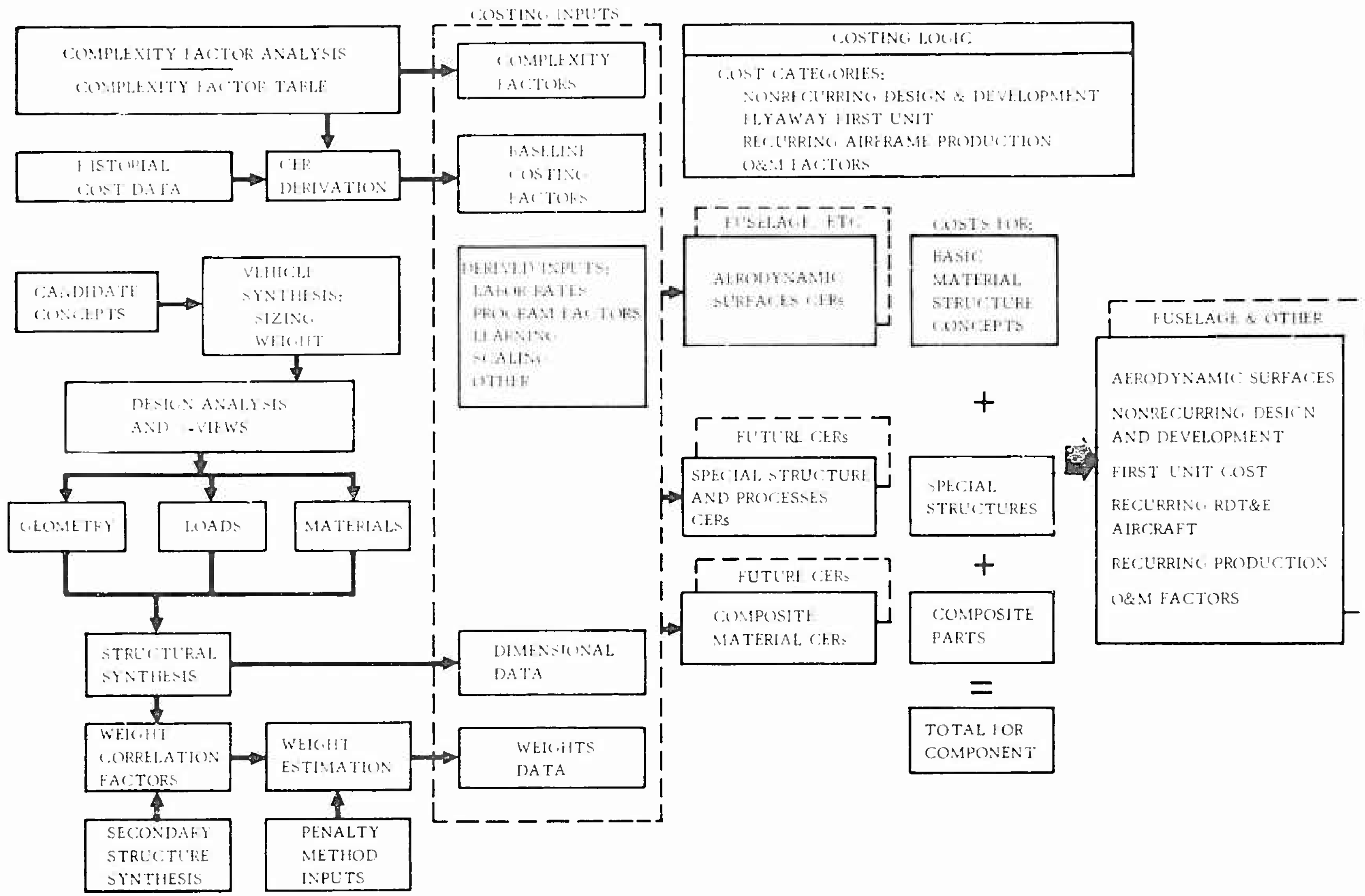

Figure 5. AFFDL Trade Study Cost Estimating Method

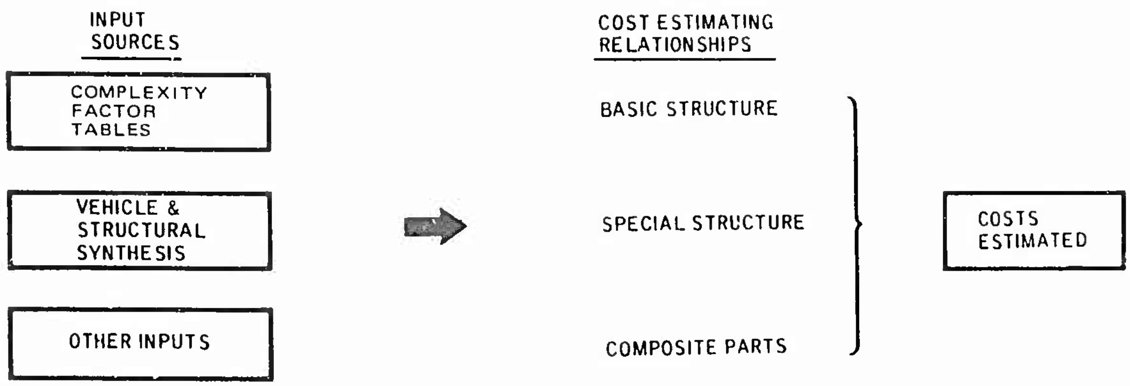

Figure 6. Inputs to Trade Cost Estimating Method

As shown in a simplified manner in Figure 6, inputs are obtained primarily from complexity factor tables and vehicle and structural synthesis programs. The inputs not so provided are obtained from sources such as program plans (development and production hardware quantities, test program hardware requirements, and production schedules and rates) and statistical data (learning curves, labor rates, scaling factors); a very few are based on judgment. Figure 6 also illustrates a categorization of cost estimating relationships. Basic structure includes the CERs for conventional metallic structures. The special structure category includes special estimating relationships for structural features that are estimated using relationships designed for that feature. Examples are: full-depth sandwich, sandwich skin, high-lift devices, bonding processes. Composite parts are also separately estimated with the CERs used being similar to the other two categories but using coefficients and estimating factors based on historical data for composite materials.

Examples of typical cost estimating relationships are shown in Table 1. Only first-unit cost CERs are represented. These illustrate the combination of structural synthesis and complexity factor data. Weights data are obtained from the structural synthesis, and the indicated complexity factors are obtained from complexity factor tables, whose development is explained in section 2.2.4.3. The derivation of CER coefficients, such as E and WH_F, is explained in section 2.2.4.4.

The use of complexity factor tables provides a powerful tool for systematically dealing with changes in design concepts associated with alternative types of materials and construction.

The types of input supplied by the vehicle and structural synthesis are indicated in Figure 7. A general description of the supporting synthesis program is given in section 2.2.2. A more complete description of these programs appears in Volume 2.

Table 1. Typical Aerodynamic Surfaces First-Unit CER

Rib Detail Fabrication Hours

$$WH_1 = \frac{W_1\ CF_1 + W_2\ CF_2 + W_3\ CF_3\ (WH_{F1})\ (W_T)^{E_1}}{W_T}$$

where: W_1 = Weight of ribs of construction and material type represented by complexity, CF_1; W_2 and W_3 other rib weights of other complexities CF_2 and CF_3.

$W_T = W_1 + W_2 + W_3$

WH_{F1} = Fabrication hours per pound for structural component for baseline configuration.

E_1 = Weight-sealing exponent.

Rib Subassembly Hours

$$WH_2 = \frac{W_1\ CM_1 + W_2\ CM_2 + W_3\ CM_3\ (WH_{F2})\ (W_T)^{E_2}}{W_T}$$

where: CM = Complexity factor for given material and construction technique.

WH_{F2} = Subassembly hours per pound for baseline configuration.

E_2 = Weight-sealing exponent.

Rib Structural Material Cost

$$WM_1 = W_1\ (RMC_1)\ (SF_1)$$

where: RMC_1 = Raw material cost per pound.

SF_1 = Scrappage factor.

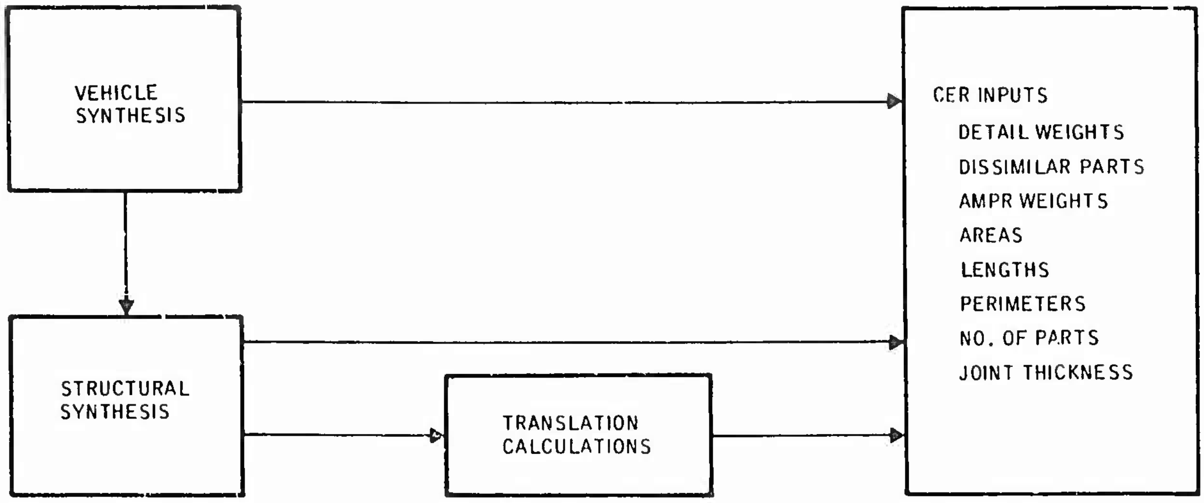

Figure 7. Synthesis Data Used in CERs

The existing synthesis program provides the capability for analyzing combinations of configurations as listed in Table 2.

Table 2. Configuration Combination Feasibility

STRUCTURAL COMPONENTS	BASIC STRUCTURAL CONCEPTS		
	Skin Stringer (Multirib)	Multispar	Full-Depth Sandwich
Covers			
Built-up Skin-Stringer	X		
Integral Skin-Stringer	X		
Machined Plate		X	
Sheet		X	X
Spars			
Corrugated Web	X		
Built-up Web/Stiffener	X		
Integral Web/Stiffener	X	X	
Built-up Truss	X		
Integral Truss	X	X	
Sheet Web			X
Ribs			
Corrugated Web	X		
Built-up Web/Stiffener	X		
Integral Web/Stiffener	X	X	
Built-up Truss	X		
Integral Truss	X	X	
Sheet Web	X		
Core			X

The following sections discuss the interrelationship and development of the principal features of this estimating method.

2.2.2 INTERFACE WITH SUPPORTING DESIGN SYNTHESIS PROGRAMS. The trade study cost estimating method relies on the output of various design synthesis programs (vehicle synthesis, primary structure synthesis, the secondary structure synthesis, as well as the weight estimating procedures embodied in weight correlation factors and the so-called penalty method of weight estimating, Reference 14) when operating in an iterative mode for preliminary design trade studies. Although it can be used for a single point-design estimate using manually derived inputs, the basic costing concept requires an interface with computerized design synthesis programs for design inputs.

Structural synthesis is a way of satisfying the design problem of defining a piece of structure that fulfills requirements of strength, geometry and other criteria. It combines material properties, structural analysis techniques, and loading environments to produce a consistent design. The interface between the cost estimating procedures and the design synthesis is depicted in Figure 8. The structural synthesis replaces hand calculations with an automated series of logical steps. It offers advantages in solution speed and accuracy. Mathematical optimization techniques have been incorporated that are untractable by hand calculations.

A multi-station synthesis approach is used for aerodynamic surfaces, including wings other than deltas, and for simple fuselages. Design synthesis proceeds systematically from root to tip, in discrete steps, usually at a rib location, in a two-phase system. In the first phase of the synthesis process, a set of initial member size estimates is analyzed.

Margins of safety are computed. Thickness variables of all elements are adjusted by iterative steps until each element has a zero margin of safety or until a minimum gage constraint is encountered. The second phase seeks to maximize margins of safety by refinement of element geometry while holding structural weight constant. When this has been accomplished, the design is recycled through phase one to further refine structural weight. This logic is repeated until satisfactory convergence is obtained. Margin of safety minimization, rather than weight minimization, in the second phase permits use of unconstrained function optimization methods.

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14. H. L. Roland and R. E. Neben, "Aircraft Structural Weight-Estimating Methods," General Dynamics Report, ERR-FW-242, 15 September 1964.

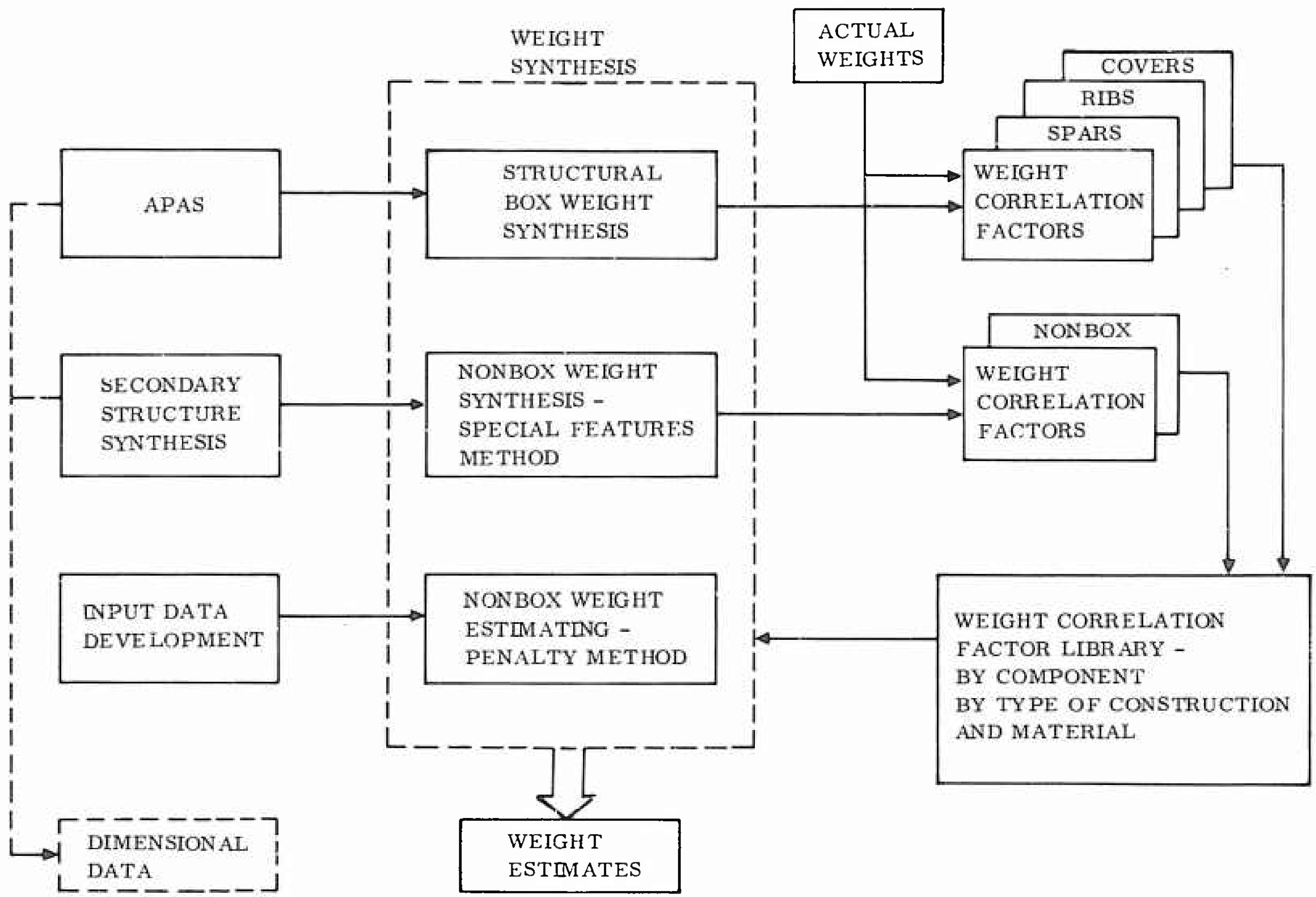

Figure 8. Cost Estimating Procedures-Design Synthesis Interface

An accurate representation of geometry is permitted by defining discrete nodes on the contour of the surface. The calculation of internal loads distribution is improved over previous programs by incorporation of methodology for analysis of a multi-cell box beam. Complex bending, shear and torsional loads may be applied. Axial loads and shear flows are computed for each node point and panel. Beams are limited to a maximum of four cells.

The discrete nodes used in defining the contours are also used as elemental centers of mass. A spinoff of this modeling scheme is the ability to represent surfaces using the dated constructional mode of concentrating the bending material in the spar caps.

The nature of the element determines the failure modes that receive investigation. Typically gross stress, buckling and crippling checks are appropriate. Dimensional constraints may also be viewed as failure modes and geometric margins of safety may be computed.

Flight safety criteria other than static strength are also considered. Aero-elastic phenomena may be investigated to determine flutter and divergence speeds. Review of structural integrity for a given service loading environment can be accomplished by safe-life, failsafe, or fatigue analysis. These routines and checks are informative in nature and do not initiate a redesign cycle, but serve as flags that a design decision is required. Decisions such as material change, criteria revision, mission revision, etc. are typically considered at this point in design evolution. Each of the flight safety studies requires the attention of specialists in those disciplines, hence the checks should be considered as indicative rather than definitive.

The multistation structural synthesis program has been modified to add a weight estimating capability for primary structure for use in the aerodynamic surfaces module. Weight correlation factors are used in the methodology as illustrated in Figure 8. References 15 and 16 provide a complete description of the multi-station structural synthesis program development.

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15. Larry M. Peterson, "Multiple Station Structural Synthesis for Lifting Surfaces," General Dynamics Report, GDCA-ERR-1732, November, 1972.

16. Gary S. Kruse and Larry M. Peterson, "Automated Structural Sizing Techniques for Aircraft and Aerospace Vehicle Structures," General Dynamics Report, GDCA-ERR-1748, December, 1972.

Development work is currently underway to adapt finite element synthesis methods for use in conjunction with cost estimating procedures for delta wing aircraft such as the B-58 and for aircraft with complex fuselages such as the F-111A. Interface with the finite element method requires revisions in weight estimating methods and modifications to weight correlation factors. The estimation of weight for secondary structure would be handled entirely by the penalty (statistical) method.

Development is being undertaken to interface the APAS program with the cost estimating relationships that will be used for trade study cost estimates for the fuselage. A subroutine will be developed to take available geometric information to compute volume and weight of structural material. Additional correlation factors will also be required to adjust the computed weight from a theoretical value to a representation of expected values. Here again, the estimation of weight for secondary structure will be handled by the penalty method.

Figure 9 is an expanded flow diagram showing the required inputs to the structural synthesis and secondary synthesis programs and the penalty weight estimating method. The sets of inputs used in each method differ, however, and also differ according to structural elements.

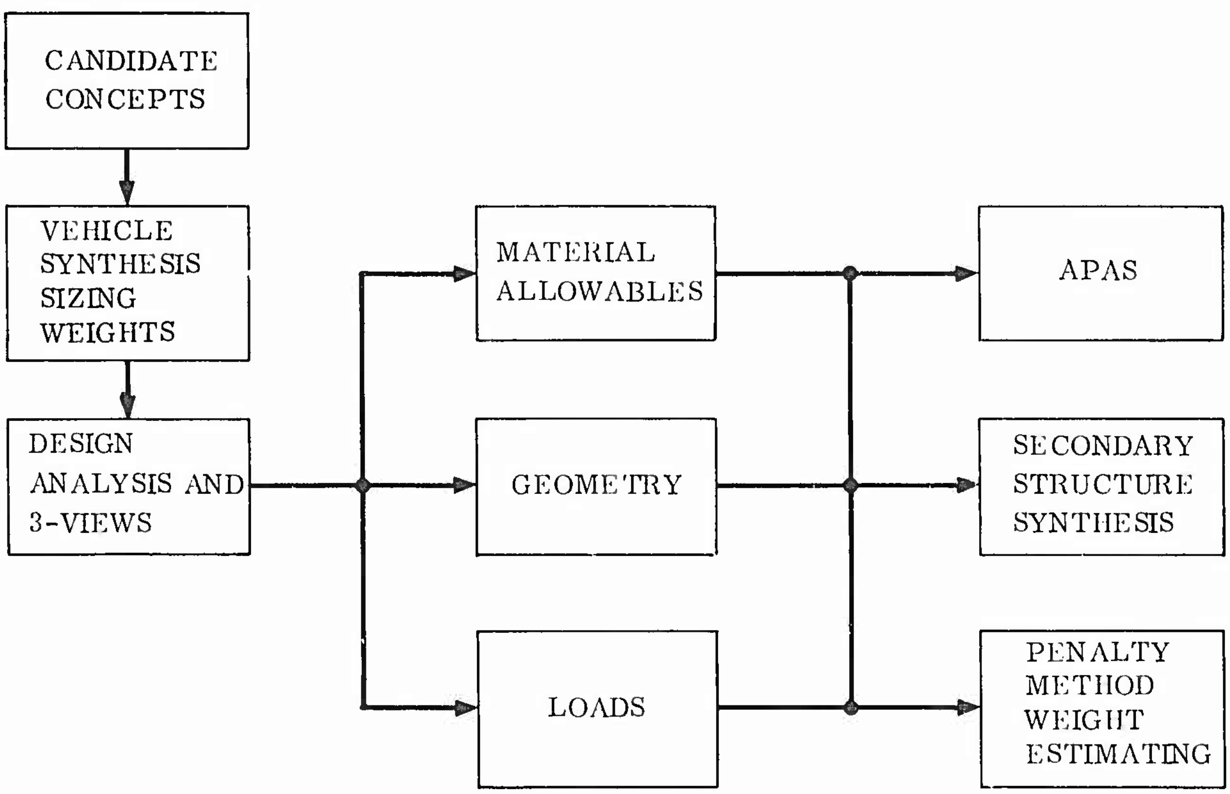


Figure 9. Flow Diagram for Synthesis Program Inputs

2.2.3 <u>COST DATA COLLECTION</u>. Availability of cost data has been a major consideration in this study. A significant portion of the cost data collection effort has resulted from independent research, since the contractual effort was to be based on data already available to the study contractor where possible. Collection of the very detailed cost data required, in conjunction with the derivation of baseline first-unit manufacturing CER coefficients, is being accomplished as a part of the contract.

The total set of aircraft from which aerodynamic surfaces cost data has been or is being collected and analyzed consists of the following aircraft.

a. F-111A wing, horizontal stabilizer and vertical stabilizer.

b. B-58 empennage.

c. C-5A empennage.

d. C141A empennage.

e. B-52 outer wing panel and vertical fin.

f. Convair Aerospace proposed VSX, VFX and A-X aircraft.

g. Convair Aerospace Model 880.

h. F-106.

i. F-102.

j. Navy A-5A.

k. Navy T-2A.

l. Advanced fighter wing box.

Cost data has been found available at widely different levels of detail from program to program. An objective of the study was to make this level consistent with the CER structure, which varies according to the cost being estimated (Figure 4).

In the case of first-unit cost, the cost estimating method has been modified in consideration of cost data availability. Insufficient data was available to support a statistical approach. The method selected requires a minimum of one actual data point per CER for calibrating a structure of relative industrial engineering estimates. Additional data points are, however, useful and desirable to evaluate estimated relative costs. In the case of the nonrecurring cost categories, cost data is being collected at the subsystem level of detail. Recurring costs at present follow the nonrecurring level, although consideration is being given to a lower level; i.e., comparable to first-unit cost.

Construction and material types represented by the aircraft reviewed have been determined. Table 3 gives these results related to the horizontal stabilizer. These have been investigated further and a complete set of results is shown in Appendix A. This information illustrates the limitations of a methodology relying solely on historical data. Existing aircraft are somewhat repetitive in their use of material/construction types. Estimating new types of construction and materials requires a process capable of looking into the requirements of new features in terms of their inpact on functional procedures; i.e., manufacturing, quality control, tooling, etc.

A complete summary of cost data collected is given in Volume 3, including the data previously collected for the horizontal and vertical stabilizer for the feasibility study added to the wing data.

Table 3. Construction Types Represented by Cost Data

Aircraft	Skins	Ribs	Spars
C-141 Horizontal Stabilizer	Built-up skin stringer	Built-up and integral truss	Built-up web stiffener
C-141 Vertical Stabilizer	Built-up skin stringer	Built-up and integral truss	Built-up and integral truss Sheet web
C-5A Horizontal Stabilizer	Integral skin stringer	Built-up truss	Built-up web stiffener
C-5A Vertical Stabilizer	Integral skin stringer	Built-up truss	Built-up web stiffener
F-111A Horizontal Stabilizer (Conventional)	Machined plate	Honeycomb core	Integral web stiffener
F-111A Horizontal Stabilizer (Boron)	Sheet	Integral web stiffener honeycomb core	Sheet web
VSX	Sheet	Built-up web stiffener	Built-up web stiffener
AX	Machined plate	Built-up web stiffener	Built-up web stiffener
VFX	Integral skin stringer	Sheet web and integral web stiffener	Sheet web
B-52 Outer Wing Panel	Machined plate	Built-up web stiffener	Built-up truss
880/990 Horizontal Stabilizer	Built-up sheet stringer	Built-up truss	Built-up web stiffener
LIT	Sheet	Sheet web	Integral web stiffener
F-111 Vertical Fin	Machined plate	Integral web stiffener and integral truss	Integral web stiffener

2.2.4 DERIVATION OF COST ESTIMATING RELATIONSHIPS. A series of CERs has been created to provide the individual cost estimates required in the breakout of cost portrayed by Figure 4. The complete set for the trade study cost estimating method is shown in Appendix B, including both first unit, nonrecurring, and recurring cost estimating relationships. The following discussion of CER derivation is oriented to the cost breakout shown in Figure 4.

2.2.4.1 Nonrecurring Design and Development Costs. CERs are required for nonrecurring costs associated with basic airframe structures. This category, as in the previous study, has been defined on the basis of CIR cost elements. The treatment of CIR elements in this study is illustrated in Table 4. One CER is provided for each element defined to include all nonrecurring costs. The level of breakdown used within the WBS dimension; i.e., the hardware level of indenture, is the structural component subassembly level, in this case the major aerodynamic surfaces components: wing, horizontal stabilizer, vertical stabilizer, or canard treated as a horizontal stabilizer. This is the minimum level considered feasible for nonrecurring costs because of cost data availability and the nature of these activities.

The resulting list of CERs for nonrecurring costs is as follows:

CER ELEMENT	NONRECURRING TASK DESCRIPTION
Engineering direct labor hours	Basic design and development for the structural subassembly, design through first flight, related design support and subassembly integration.
Engineering material and other	Development material in direct support of design and development.
Tooling direct labor hours	Basic tooling, detail and assembly, for the horizontal stabilizer, including tool engineering, tool manufacturing, manufacturing aids, and manufacturing development.
Tooling material and other	Material required in direct support of the tooling program.
Quality Control direct labor hours	Quality control associated with prototypes or RDT&E test articles and nonrecurring production start-up costs excluding static and fatigue test articles.
Manufacturing direct labor hours	Manufacture of test hardware, special test equipment and direct support of basic engineering and basic tooling, excluding static and fatigue test articles.

Table 4. Treatment of CIR Elements

MIL-STD CIR Elements	Study CIR Elements
Engineering	
Direct Labor Hours	1) Direct Labor Hours
Direct Labor Dollars	2) Direct Labor Cost
Overhead	
Materials	3) Engr. Material and Other
Other Direct Charges	
Tooling	
Direct Labor Hours	4) Direct Labor Hours
Direct Labor Dollars	5) Direct Labor Cost
Overhead	
Materials	6) Tooling Material and Other
Other Direct Charges	
Quality Control	
Direct Labor Hours	7) Direct Labor Hours
Direct Labor Dollars	8) Direct Labor Costs
Overhead	
Other Direct Charges	
Manufacturing	
Direct Labor Hours	9) Direct Labor Hours
Direct Labor Dollars	10) Direct Labor Cost
Overhead	
Materials	11) Mfg. Material and Other
Other Direct Charges	
Purchased Equipment	12) Other Costs
Material Overhead	
Other Items	
G & A	
Fee or Profit	13) Fee or Profit

Manufacturing material and other	Material required for test hardware manufacture, and vendor and subcontractor design, development and production start-up.
Other costs	Various overhead factors and miscellaneous.
Fee or profit	Allowance for fee or profit.

The list of CERs also includes Engineering, Tooling, Quality Control, and Manufacturing direct labor cost that as CERs are simply the application of labor rates to the direct labor hours, except in the case of Quality Control, which also covers other direct charges. Static and fatigue testing has been omitted from trade costing consideration because test articles and the testing itself are related to the total airframe and any cost breakdown would have to be on an arbitrary basis.

Cost estimating is accomplished by dividing the elements of cost into two types according to whether they represent primary costs or cost-on-cost relationships. Primary cost elements consist of:

a. Engineering direct labor hours.

b. Tooling direct labor hours.

Each of the remaining CERs is defined as cost-on-costs against the above. Thus engineering material is a factor of engineering direct labor hours. Tooling material is a factor of tooling direct labor hours. Quality control direct labor hours are a factor of manufacturing direct labor hours. Other costs and the profit element are estimated as factors against various subtotals of these elements. Manufacturing direct labor hours and manufacturing material and other hours used during the nonrecurring development are combined into a category called manufacturing support hours and material, which is estimated as a cost-on-cost against engineering direct labor hours. Developing an estimating technique for nonrecurring costs then required developing CERs for the primary cost elements and the appropriate cost-on-cost factors for the other elements.

The overall framework of nonrecurring cost estimating remains the same as developed under the previous study. Changes have been made to the individual CERs, however.

<u>Engineering Direct Labor Hours.</u> The CER for engineering direct labor for trade studies is being revised to replace dissimilar parts as the cost related parameter. Correlation between engineering direct labor hours and number of dissimilar parts

has not been clearly established. A lack of correlation has been noted in new and advanced structures. AMPR weight is being used instead as the primary cost driver with the approach to derivation as described below:

Engineering direct labor is considered to be made up of the following components:

a. Basic Structure Design Engineering.

b. Configuration Design Engineering.

c. Equipment Design.

d. Vehicle Integration.

e. Weapon System Design and Integration.

f. Ground and Flight Test.

Basic Structure Design Engineering comprises the detail design of the elements of basic structure plus such supporting activities as lines and lofting, checking, stress, weights, and value engineering as they relate to the element of basic structure. Configuration design engineering includes support engineering consisting of preliminary design, aerodynamics, dynamics, and thermodynamics activity relatable to structure. Equipment design relates to the design and development of aircraft subsystems. Vehicle integration covers the activities dealing with integrating the design and selection of engine, avionics, and armament components. Weapon system integration relates to integration and design of the support subsystems of the weapon system: data, spares, support equipment, training equipment, personnel, etc. Ground and flight test covers test planning, instrumentation, testing, data reduction and analysis, reporting, and test support related to test programs.

Only the first three categories are considered in this study, since the last three each involves consideration of engines, avionics and armament. The first two are treated as part of the trade study cost method. The third category will be treated later as part of the system cost method.

Basic structure design engineering is estimated by basic structure component, i.e., wing, empennage, fuselage. Horizontal and vertical stabilizers have been combined inasmuch as historical data is not separated. Basic structure design engineering CERs are derived from data shown in Figures 10, 11, and 12. A CER of the form. $Y = ax^b$, is assumed based on other research studies. A series of CERs is derived for fighters and transports for each structural component. The resulting CER coefficients are summarized in Figure 13.

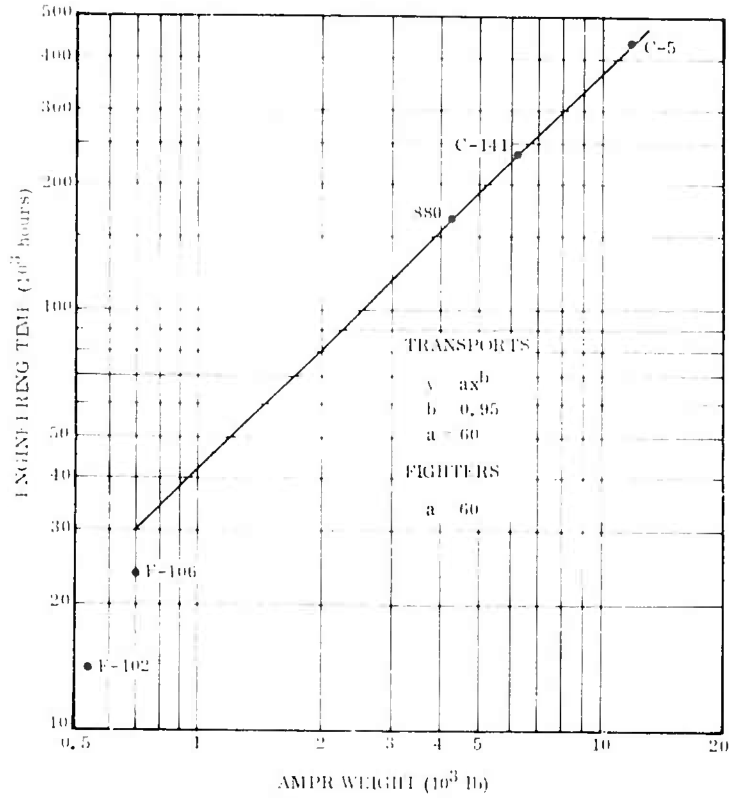


Figure 10. Empennage Design Hours

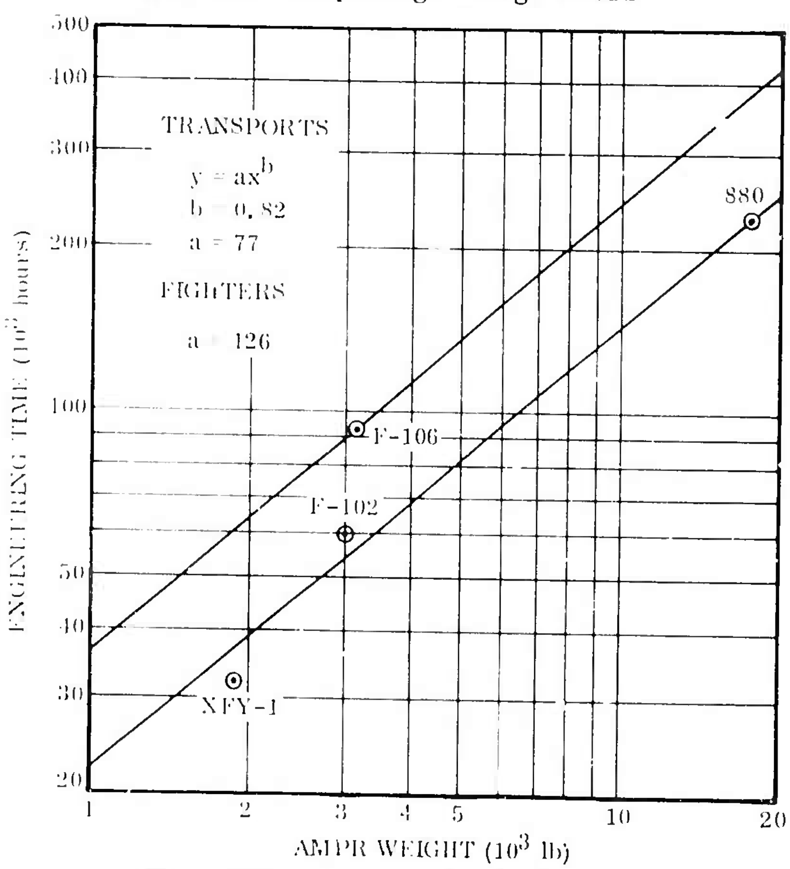


Figure 11. Wing Design Hours

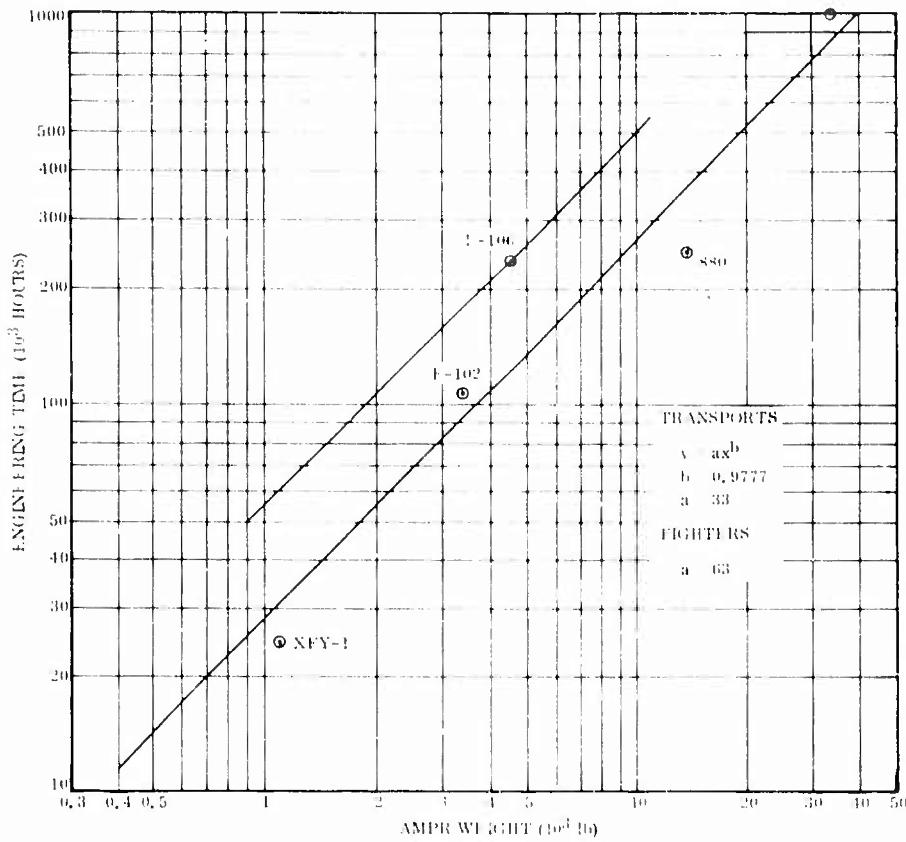


Figure 12. Fuselage Design Hours

COEFFICIENT	FIGHTERS			TRANSPORTS		
	Empennage	Wing	Fuselage	Empennage	Wing	Fuselage
b, scaling exponent	0.95	0.82	0.98	[illegible]	[illegible]	0.98
a, intercept at weight = 1 lb	60	126	63	60	77	33

Figure 13. Engineering CER Coefficients

The input value to be used for "a" can be interpolated from Figures 10, 11, and 12. As additional data is accumulated, it may be possible to develop a relationship for "a".

The difference between airframe and basic structure represents configuration design engineering hours as follows:

Aircraft	Hours	Percent of Basic Structure Design Hours
Model 880	153,000	12.0
F-106	131,900	12.1
F-111	243,000	15.1

Additional data is needed to generalize the value of this factor, although a fairly consistent ratio to basic structure design hours is indicated. The complete CER then becomes:

Fighters and transports:

Basic structure design engineering (Y) $= ax^b$ (1)

Configuration design engineering hours = YF (2)

where F is a percentage on the order of 12 to 15 percent.

Tooling Direct Labor Hours. Tooling was defined to comprise a number of subtasks including tool planning and design, basic tool manufacture, manufacturing aids, manufacturing development, and packaging engineering. The nonrecurring category is defined to encompass both basic and rate tool engineering and manufacture. Total tooling is built up from an estimate of basic tool manufacturing direct labor hours. Basic tool engineering is estimated as a factor of basic tool manufacturing, and rate tool engineering is a factor of rate tool manufacturing. Rate tool manufacturing is estimated from basic tool manufacturing according to required production rate. Tool material, manufacturing aids, and manufacturing development are estimated as factors of tool manufacturing hours. Basic tool manufacturing labor is thus the underlying relationship. It is expressed by the CER derived during the previous study.

The starting point for the derivation was the accumulation of available basic tool manufacturing hours data and data on other characteristics believed to be related to cost. These data are shown in Table 5. Basic tool manufacturing hours are defined as those required to produce a complete set of tools adequate to accomplish the manufacturing process. It is assumed that this set of tools will be capable of supporting a production rate of from one to three units per month. Rate tooling is defined as the tool provisioning required to increase the production rate capability to a given rate. Under the

Table 5. Tooling Cost Comparisons

Program	AMPR Wt.	Diss. Parts	Tot. Parts	Tls/Part	Tot. Tools	Av. Hr./Tl.	Tool Mfg. Hrs.	T.E. %
A	19,838	16,785		1.51	25,400	29.6	751,734	16.3
B	21,673	22,000		1.51	33,200	31.0	1,029,820	
C	65,700	51,000		1.77	90,181	50.2	4,526,110	
D	87,150				66,154	45.0	2,986,930	24.9
E	12,074	13,815		2.62	36,191	58.0	2,099,772	23.6
F	15,037	18,166		2.31	42,060	55.7	2,341,320	
G	32,830	35,866		1.44	51,751	40.6	2,100,000	
H	6,087	4,871	10,170	1.30	6,315	38.4	242,363	32.7
I	11,839	6,077	9,916	1.72	10,439	41.4	432,059	33.8
J	42,390	24,020		1.69	40,506	43.8	1,772,730	40.0 40.0
K	28,600	28,800	52,000	1.70	48,960	40.0	1,958,400	40.0 40.0
L	18,263	10,709		1.36	14,569	31.8	559,440	33.0
M	32,548	22,741		2.34	53,000	71.0	3,775,000	
N	25,365	24,300		1.7	42,200	77.0	3,250,000	40.0
O	33,166	11,367	33,185	2.13	24,174	55.0	1,314,467	36.0
P	15,500						2,165,600	

first contract, plots of these data were made in various combinations. Total number of tools was plotted against AMPR weight and number of dissimilar parts on the assumption that average hours per tool value could be developed. Average hours per tool evidenced a wide range of values. Plots of tool manufacturing hours versus AMPR weight and versus number of dissimilar parts were also made. The expressions for total number of tools run into the problem of the wide spread in the average hours per tool. In lieu of using AMPR weight, a better statistical fit is obtained by using the number of dissimilar parts as the explanatory variable for total number of tools, but lack of meaningful average hours per tool precludes its use. AMPR weight and number of dissimilar parts both turn out to be generally good predictors of tool manufacturing hours. The stratification of the data is more easily explained, however, with AMPR weight as the cost related variable. Costs are underestimated for modern aircraft on the basis of number of dissimilar parts. For these reasons AMPR weight has been considered as the best predictor. A plot against AMPR weight is shown in Figure 14. AMPR weight also has an advantage in that it can be determined for individual hardware subcomponents.

Two CERs have been created from the data: one for subsonic and the other for supersonic aircraft. The method used is the same as for engineering direct labor hours.

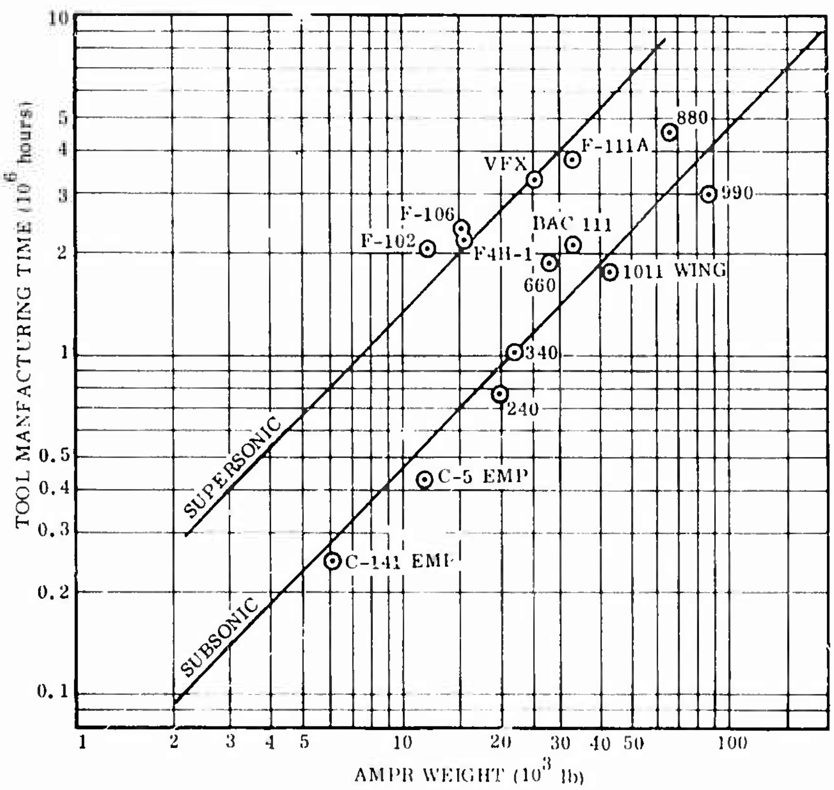


Figure 14. Tool Manufacturing Hours versus AMPR Weight

The CER is expressed in equation form by transformation of the logarithmic linear equation of the form

$$\log Y = \log a + b \log X, \tag{3}$$

where

Y = Number of tool manufacturing hours

X = AMPR weight in pounds

a = Intercept value

b = Slope of the curve,

to a power equation of the form

$$Y = aX^b \tag{4}$$

The value of b is assumed to be the same for both equations. Further, the value of b is so close to 1 that it can be arbitrarily set at that value. Substituting in Equation 5 by choosing a set of points along the curve fit line and solving for log a gives:

Subsonic:

$$\log a = 700{,}000 - \log 15{,}000$$

$$= 5.8451 - 4.1761 = 1.6690$$

and

$$a = 46.66; \text{ and the resulting CER is}$$

$$Y = 46.7X^b \tag{5}$$

where

$$b = 1$$

Supersonic:

$$\log a = \log 2{,}000{,}000 - \log 15{,}000$$

$$= 6.3010 - 4.1761 = 2.1249$$

and

$$a = 1.333; \text{ and the resulting CER is}$$

$$Y = 133.3X^b \tag{6}$$

where

$$b = 1$$

Certain of the data points (C-141 and C-5 empennage, and 1011 wing) are for partial airframes. In each case these fall below the estimating curve, which is logical because there is a missing element of tooling associated with final assembly of the complete airframe. The scale of "a" values encompassing the spread from 46.7 to 133.3 is accomplished against variable speeds and/or alternate types of construction using reference to design analogies. A set of values that can be used as reference points is contained in Table 6. Estimating factors in Table 6

Table 6. Tool Manufacturing Hours Input Table - Subtable A

CER Variable	Simplified Design and Follow-on Subsonic	Regular Subsonic	Complex Subsonic	Simplified Design and Follow-on Supersonic	Regular Supersonic	Complex Supersonic
Input Value (CMT)	32.0	47.0	70.0	100.0	133.0	185.0
Scaling Exponent (C)	1.0	1.0	1.0	1.0	1.0	1.0

were based on Figure 14. By extrapolating the subsonic line in Figure 14 to intersect the ordinate line for a one-pound structure, a tool manufacturing hours-per-pound value of 47 is found. This value is entered in Table 6 as a regular subsonic. Similarly, the value of 133 hours per pound is found for entry under regular supersonic. These values are considered statistical averages. The other values in Table 6 are interpolations between these two points based on general consideration of the subject. The distribution of the values in Table 6 is shown in Figure 15.

The values shown are intended for application to a production program involving 50 or more aircraft. Tooling for a prototype program to produce a few aircraft would be expected to be at least a category lower than the input for a production program. Values in Table 6 and Figure 14 are intended as guides to the cost analyst, and are subject to consideration peculiar to the aircraft design under study.

The categories of aircraft tooling are discussed below starting with the simplified design and follow-on subsonic category. This would include aircraft designed to achieve simplicity of manufacture and aircraft that have undergone major modification where prior production has been achieved.

The regular subsonic aircraft is typified by aircraft such as the 880 and C-141. The 747 and C-5 probably lean toward the complex subsonic because of size consideration. The regular supersonic aircraft would include military aircraft such as F-102, F-111, B-58, and VF(X). The simplified design and follow-on supersonic category would be considered relative to these. The complex supersonic category would involve advanced state-of-the-art aircraft such as SR-71. Estimates for this category are uncertain, and this is indicated by the shaded areas of Figure 15.

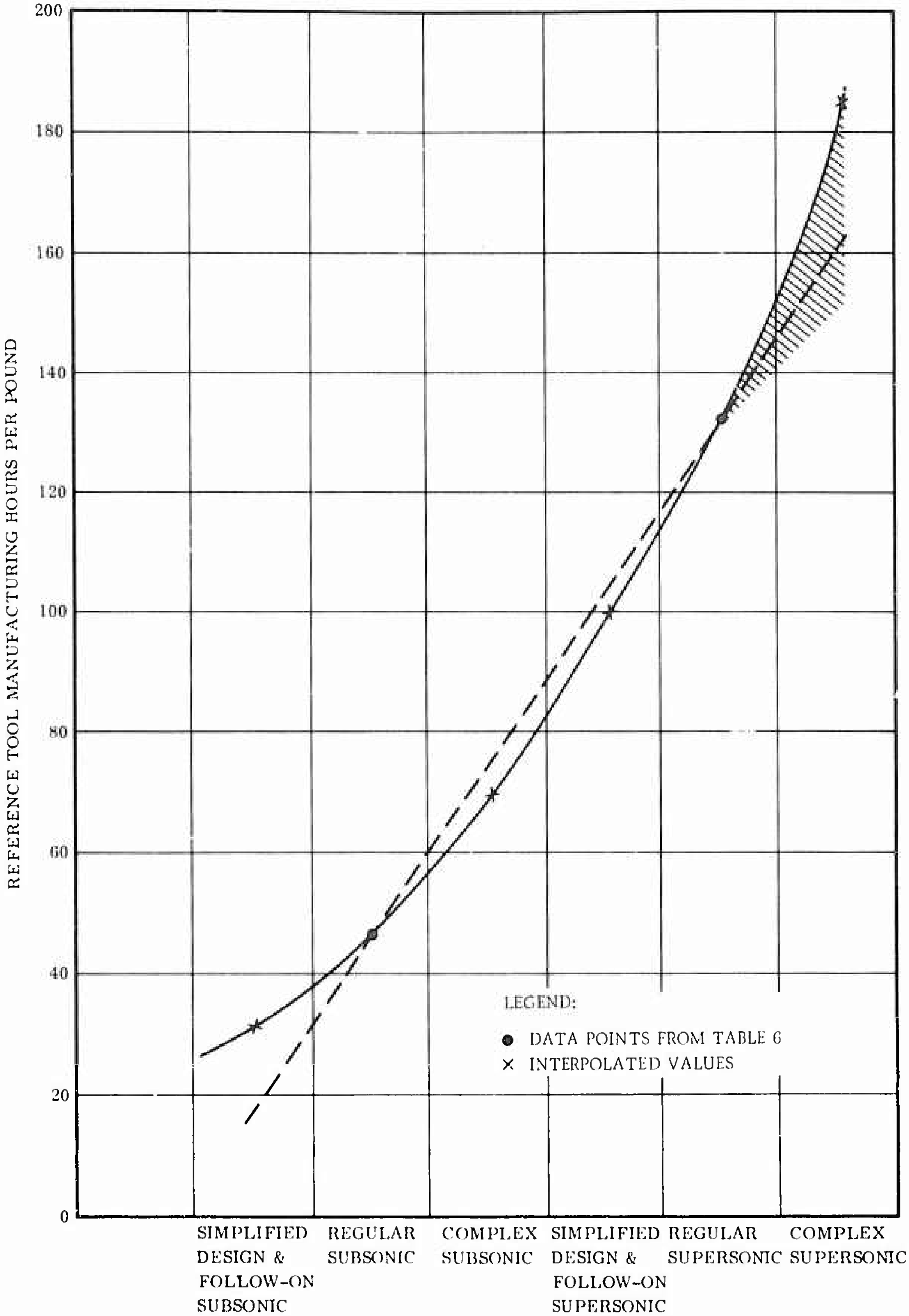


Figure 15. Tool Manufacturing Hours per Pound Complexity Variants

Because the scaling exponent found has a value of 1.0, values from Table 6 or interpolations from Figure 14 may be applied to either whole aircraft structure or portions thereof. It would be appropriate to use different values for different major parts of a structure; i.e., a regular wing might be used with a complex fuselage. Examples of input values from Table 6 for the test cases are shown in Appendix C. The input symbol is CMT.

Total nonrecurring tooling is defined as being made up of the following elements:

a. Tool engineering — basic.

b. Tool engineering — rate.

c. Tool manufacturing — basic.

d. Tool manufacturing — rate.

e. Tool material.

f. Manufacturing aids.

g. Manufacturing development.

h. Material handling and packaging engineering.

Equations 5 and 6 are for basic tool manufacturing. CERs for the remaining elements are developed from them as follows. Supporting data and selection of input values for these CERs, and for engineering development material and quality control hours, is amplified in Volume IV.

Rate Tool Manufacturing. Basic tool manufacturing provides a complete set of manufacturing tools assumed to be capable of supporting a manufacturing rate of approximately three aircraft per month. Rate tooling is defined as the tool provisioning required to increase production capability to a required rate. When expanding tooling capability from an initial base production rate of one per month, industry practice has been to assume that rate tooling increases tooling cost as a function of the square root of the production rate. The exponent shown below in Equation 7 reflects a rate increase from the base of three per month.

$$T_R = T_1 R^{0.3} \qquad (7)$$

where

T_R = Total tooling cost for a given production rate, R, in direct labor hours

T_1 = Basic tool manufacturing direct labor hours for a minimum production rate of three per month

R = Production rate to be estimated

T_1, basic tooling, is obtained by the CERs derived previously. T_{R-1} is defined as the cost increment attributable to the increased rate and is given by:

$$T_{R-1} = T_R - T_1 = T_1 R^{0.3} - T_1 = T_1 (R^{0.3} - 1) \qquad (8)$$

Basic Tool Engineering. Table 5 gives the ratios of basic tool engineering to basic tool manufacture. On the basis of this data, a percentage factor of 40 percent is derived as a factor for estimating T_{EB}, basic tool engineering direct labor hours. That is,

$$T_{EB} = 0.4\ T_1 \qquad (9)$$

where T_{EB} is direct labor hours.

Rate Tool Engineering. Other historical data indicates that rate tool engineering can be estimated at 15 percent of rate tool manufacture (see Volume IV for data). Then,

$$T_{ER} = F_{T1} T_{R-1} \qquad (10)$$

where T_{ER} is direct labor hours and $F_{T1} = 0.15$

Tool Material — Nonrecurring. Historical data indicates that nonrecurring tool material can be estimated at a rate of $1.35 per tool manufacturing hour, or,

$$T_{M_1} = F_{T2} (T_R) \qquad (11)$$

where $F_{T2} = \$1.35$ (In 1970 dollars. Adjust by the term,

$(1 + r)^{y - 1970}$, where r = assumed inflation rate and y = year of the estimate.)

Manufacturing Aids (Plant Engineering). The plant engineering function includes the tasks directly associated with the design, manufacture, and maintenance of special noncapital manufacturing aids such as holding cradle, work platforms, slings, load bars, transportation trailers, handling dollies, and access stands. Experience indicates that on past aircraft programs plant engineering hours have ranged from 8 to 15 percent of tool manufacturing hours. The percentage is affected by assembly requirements and type of construction. For the present phase of the study an average percentage of 12 percent is used. Based on current experience, \$2.00 per plant engineering hour should be applied to cover material cost. The resulting CERs are:

a. Plant Engineering direct labor hours

$$T_{MA} + F_{T3} \cdot T_R \tag{12}$$

where $F_{T3} = 0.12$

b. Plant Engineering dollars

$$T_{MAC} = T_{MA} \times (\text{labor rate} + \text{material factor}) \tag{13}$$

where the material factor is \$2.00/hr

Manufacturing Development. Manufacturing development is estimated as a factor of tool manufacturing hours by the following CER:

$$T_{MD} = F_{T4} \cdot T_R \tag{14}$$

The factor F_{T4} is approximately 2 percent. By the nature of this task it is affected to a considerable extent by the introduction of new types of material and to a lesser extent by new types of construction. Since manufacturing development cost is only a small fraction of total cost, an approximate percentage can be used.

Material Handling and Packaging Engineering. This function includes preparation of handling, packaging, and packing requirements; application of vendor and subcontract packaging instructions; material flow analyses and preparation of charts required to establish handling methods and equipment; and preparation of packaging and packing instructions. This task is such a small fraction of the manufacturing task that it is assumed to be included in that task.

Manufacturing Support Hours and Material. Nonrecurring manufacturing hours represent the effort undertaken to support engineering during the development phase of an aircraft program. This development support cost includes manufacturing labor and material for such items as development test parts, test fixtures, mockup and models, test articles, less than complete test airframes, and other support activities. It also includes manufacturing material and other costs made up primarily of vendor costs for development, test and production startup. In the original structuring of CERs it was intended to have two separate CERs: one for direct labor hours, and a second for material and other. Insufficient data was available, however, for the CER derivation, and Rand's CER for a comparable category of cost described as development support was adopted. The Rand approach has since been revised, Reference 13, and accordingly this CER becomes:

$$E_S = 0.008325\,(W_A)^{0.873}\,(S)^{1.890}\,(Q_D)^{0.346} \quad (15)$$

where

E_S = Development support cost in 1970 constant dollars

W_A = AMPR weight (lb)

S = Maximum speed (kt) at best altitude

Q_D = Development quantity (number of flight test airframes)

Cost-On-Cost Relationships. The remaining cost-on-cost relationships consisting of engineering material and other, quality control direct labor hours, and other costs, are derived in the manner described below.

Engineering Material and Other. Based on historical data, this task can be estimated on the basis of the following CER:

$$\text{(Engrg. Matl. and Other)} = \text{(Engrg. D. L. Hrs.) (Engrg. Labor Rate)}\,(F_{e2}) \quad (16)$$

where

F_{e2}, a percentage factor = 0.1

This cost may not be significant in trade study costing, since no cost variation attributable to type of material or type of construction was noted. However, the percentage might increase for exotic materials, although additional data would be needed to develop an appropriate relationship.

Quality Control Direct Labor Hours. This item is negligible in the nonrecurring category. Support of manufacturing and tool inspection are both involved. The following CER is used:

$$\text{QC hrs} = (\text{Engrg. D.L. Hrs.})(F_{q1}) + (\text{Tool Mfg. D.L. Hrs.})(F_{q2}) \quad (17)$$

where

F_{q1} = percentage of Engrg. D.L. Hrs. = 0.01

F_{q2} = percentage of Tool Mfg. D.L. Hrs. = 0.06

Other Costs. For trade cost purposes it is planned to ignore this cost category. Its consideration will be required for system costing.

Fee/Profit. This category will not be considered for trade cost purposes, and will be optional for system costing.

Direct Labor Costs. These costs are estimated simply by the application of the appropriate composite labor rate and burden to the labor hours as shown below:

$$\text{Engineering Direct Labor Cost} = (\text{Engrg. D.L. Hrs.}) \times (\text{Engrg. Composite rate}) \quad (18)$$

$$\text{Tool Engrg. \& Tool Mfg. D.L. Cost} = (\text{Tool Engrg. Hrs.} + \text{Tool Mfg. Hrs.}) \times (\text{Tooling composite rate}) \quad (19)$$

$$\text{QC Direct Labor Cost} = (\text{QC D.L. Hrs.}) \times (\text{QC composite rate}) \quad (20)$$

$$\text{Mfg. Direct Labor Cost} = (\text{Mfg. D.L. Hrs.}) \times (\text{Mfg. composite rate}) \quad (21)$$

Tooling composite rate is an average rate taking into account both tool engineering and tool manufacturing. The QC composite rate takes into account the item of other direct charges when the rate is applied to production aircraft, but this will be disregarded in the nonrecurring category.

As shown in Figure 6, an attempt has been made to categorize input sources. The factors and various labor rates used in the above relationships for nonrecurring costs are categorized as "other inputs". The discussion of the source of these inputs is deferred to Volume IV, where it simultaneously serves as a part of the estimating handbook. The category "other inputs" is associated almost entirely with nonrecurring costs.

2.2.4.2 Estimating First Unit Cost. The estimates of first-unit hardware cost, as shown in Figure 4, are a means of estimating recurring hardware cost, both development and production. Recurring costs are based on a cost-quantity projection of these first unit costs. The trade study method currently consists of projecting the summary level of data shown on page 3 of Figure 4; however, consideration is being given to projecting each individual cost shown on page 2. The system costing method uses the same first-unit cost convention with its own set of options as to level of detail. It will be noted on page 2 of Figure 4 that detailed fabrication labor, assembly labor, and manufacturing material are estimated separately. Cost-quantity projections can be much more precisely made with this as a minimum breakout as opposed to an aggregation resulting in total manufacturing dollars.

The set of CERs used for aerodynamic surfaces, as shown in Appendix B, is comparable to those developed under the previous contract for the horizontal stabilizer except for the following revisions:

a. The CERs for rib, spar, and cover subassembly have been reduced to one CER each. That is, center assembly and center-to-cap assembly have been combined in estimating rib and spar subassembly costs. In the case of covers, stringer and doubler installation have been combined into a single cover subassembly CER.

b. Separate CERs have been created for detailed fabrication hours and subassembly hours for items of secondary structure.

c. Separate CERs have been created for manufacturing material costs for ribs, spars, covers, and items of secondary structure, and the breakout of material into structural and assembly material has been eliminated for these items.

d. The cost of subassembly for primary structure elements is now estimated using weight as the primary cost-related variable instead of the parameters previously used: area, perimeter, stringer frequency, thicknesses, and fastener types. These parameters are considered in the development of complexity factors. Detailed fabrication hours and manufacturing material continue to be estimated on the basis of weight.

In the estimating method developed initially and tested for horizontal stabilizer structure, assembly hours were estimated using a series of equations that represented a model of the activities occurring during manufacturing assembly. Significant factors affecting assembly costs were analyzed and combined into recommended CERs. The model of the manufacturing process assumed that these elements were assembled as complete structures in two steps. It was pointed out that a wide variety of assembly tasks could be involved in aircraft structure, depending upon the construction type. There can be a series of trusses to assemble to rails in the case of built-up truss construction, or buildup of sheet metal in the sheet web case, or almost no assembly at all in the case of integrally machined parts. Therefore, it was clear that a CER for these assembly costs should have a cost factor reflecting construction-type cost influences. Ribs and spars were considered as being of fairly similar structure consisting of caps attached to a rib or spar center, and the rib and spar assembly task was divided into two parts, including assembly of the rib center and the attachment of the rib center to the caps. The descriptor rib center includes all kinds of centers such as built-up, truss, etc. Two assumptions were made leading to the result that no assembly costs were estimated for rib or spar caps: The first assumption that, while occasionally a clip or a doubler may be attached to a cap, these assembly costs on the average would be negligible and could be considered as part of rib center assembly cost, or rib center-to-cap assembly cost if there is no rib center assembly; the second that there would be no splices in the cap. While spar cap splices were used in the design of older aircraft, none are expected in new designs of C-5A or smaller size horizontal stabilizers. Therefore, spar or rib cap assembly costs were considered negligible.

The following two CERs for rib assembly tasks illustrate the method used:

Rib Center Assembly Hours:

$$H_1 = (\text{Rib Area})^b\ (\text{Hours per unit area})\ (F_1)(F_2)(\text{No. of ribs})^c \times (F_3)$$

where

b = Size scaling exponent

F_1 = Factor for material selection

F_2 = Factor for fastener selection

c = Commonality factor for quantity of ribs

F_3 = Spar type adjustment factor $= \dfrac{\text{number of spars}}{2}^{c}$

Area was chosen to represent the size function but required an exponent to change the rate of numerical increase because area is a square function, and costs would not be expected to increase at that rate. Hours per unit area provided hours as a function of construction type. The material factor takes into account material type.

Fastener-type factors are needed to denote cost effects due to choice of fasteners. The number of ribs is modified by an exponential function to take account of a commonality effect. This effect indicates that a reduction in cost can be expected if there are a number of similar items to be manufactured as compared to the situation where all items are widely different. The number of spars, as modified by the exponent, is required only for the multispar case. In a multispar design, ribs are divided into segments between the spars, thus increasing cost per rib. The more spars, the more rib segments; therefore the more cost. With only two spars, this factor equals 1.0.

Rib center-to-rib cap assembly cost was assumed to be related to installing a series of fasteners around the perimeter of the rib center sections to attach the web to the cap. The suggested CER was:

Rib Center-to-Cap Assembly Hours:

$$H_2 = (\text{Rib perimeter})^b \ (\text{Hours per unit length}) \ (F_1)(F_2)(\text{No. of ribs})^c$$

Here the perimeter of the center provides the size parameter, and in this case the exponent is provided to permit a change of slope as indicated from available data. Construction type has a similar impact as before, although the values associated with construction are different than those for rib center. Material and fastener type factors were developed from available data. The number of ribs has the same commonality cost improvement prediction function as before.

The complete rib assembly cost was:

$$\text{Rib assembly total} = H_1 + H_2.$$

Two problems appear with this approach: (1) With the CER being an attempt to model the manufacturing process, it was subject to the vagaries of this process, and (2) Estimating factors such as hours per unit area and hours per unit length were without precedent, and insufficient detailed cost data was available for their development.

The revised methodology that has been developed is illustrated by the following CER for rib assembly:

$$WH_4 = \frac{WW_1\,CM_1 + WW_2\,CM_2 + WW_3\,CM_3}{WW_T}(WH_{F4})(WW_T)^{E_{10}} \qquad (22)$$

where

WH_4 = Subassembly direct labor hours for wing ribs

WW_i = Weight of wing ribs with complexity CM_i

CM_i = Complexity factor related to a given material and construction technique

$WW_T = WW_1 + WW_2 + WW_3$

WH_{F4} = Subassembly hours per pound for baseline wing ribs

E_{10} = Weight scaling exponent

The development of complexity factors and the derivation of baseline CER coefficients used in first-unit cost CERs will be covered in the two following sections. The complexity factor is based on an assessment of the relative difference in cost due to differences in type of construction or material. It takes into account the differences in manufacturing costs attributable to the various physical characteristics previously incorporated in the CER formulation. It thereby provides a way of directly incorporating the findings of industrial engineering, manufacturing development, value engineering, tooling, and producibility analyses of alternative manufacturing approaches without requiring a change in the form of the CER.

These same types of analyses can be applied to composite materials and advanced structural concepts to evaluate their impact on cost.

The baseline CER coefficients are derived from historical cost data to provide a reference for the complexity factor, relativistic structure. A minimum need for cost data (one data point per CER) results from this approach. Additional data affords improvement, however, in both the choice of reference point and in the added possibility for verification of the complexity factor structure.

In the initial estimating method, detailed fabrication and subassembly hours were combined for items of secondary structure. Separate CERs have now been created. The principal reason for the separation is to permit the use of individual cost-quantity projections in each case. Weight is used as the basic parameter in both cases, and there is no significant difference between the present and previous form of the CER. The previous CER is illustrated below and can be compared to those in Appendix B:

$$H_i = (CM_S)(H_{WW_i})(WW_i)^E \qquad (23)$$

where

H_i = Fabrication and assembly hours per pound for structural component

CM_s = Complexity factor for type of material and type of construction

WW_i = Weight of the structural element

H_{WW_i} = Hours per pound for a baseline case

E = Weight scaling exponent

Separate CERs have been created for manufacturing material costs for each structural element. The past and present manufacturing material cost breakdown is listed below:

Previous breakdown

Primary box structural material cost

Primary box assembly material cost

Secondary box structural material cost

Secondary box assembly material cost

Other structure material cost

Horizontal stablizer assembly material cost

Present breakdown

Primary box structural material cost by element: ribs, spars, covers

Secondary structure material cost by element: leading edge, trailing edge, tip, etc.

Primary box assembly material cost: wing, stabilizer, etc.

Component assembly material cost: wing, stabilizer, etc.

This treatment provides visibility for each individual structural element and permits trade study consideration of variation in the material used in these elements.

The basic CER forms presently used are illustrated below:

Element structural material

$$WM_i = WW_i (RMC_i)(SF_i) \tag{24}$$

where

WM_i = Material cost for primary and secondary structural element

WW_i = Weight of finished structure

RMC_i = Raw material cost per pound

SF_i = Scrappage factor

Primary box assembly material cost

$$WA_1 = WH_1 (AMF_1)(FM_1) \tag{25}$$

where

WA_1 = Primary box assembly material cost

WH_1 = Total assembly labor hours for primary box

AMF_1 = Assembly material per labor hour

FM_1 = Fastener type complexity factor

Component assembly material cost

$$WA_2 = WH_2 (AMF_2) (FM_2) \tag{26}$$

where

WA_2 = Component assembly material cost

WH_2 = Total assembly hours for component (wing, etc.)

AMF_2 = Assembly material per labor hour

FM_2 = Fastener type complexity factor

The discussion above also illustrates the elimination of the breakout of material into structural and assembly categories for detailed hardware elements. Assembly material is, however, separately estimated for primary box and component-level assembly.

The use of weight for estimating the cost of subassembly for primary structure elements was discussed above in describing the first revisions to the method. CERs have been formulated for detailed fabrication hours, assembly hours, and manufacturing material for each of the elements of primary structure for wings, horizontal stabilizers, and vertical stabilitizers. The complete set of CERs appears in Appendix B, numbered for correlation to the cost breakout. A summary list of the first-unit cost CERs is given on page 50.

In addition to the above revisions, the following changes are being evaluated for possible incorporation into the final method:

a. Provision of capability for estimating alternative production quantities to the first-unit cost format and level of detail (shown by the first-unit cost printout in Figure 4).

b. Use of discrete cost-quantity projections by structural elements within the fabrication, subassembly, material cost categories.

c. Inclusion of an additional term in certain CERs to give consideration to internal structural commonality.

d. Consideration of taper in the machining of parts in the development of complexity factors.

The desirability of these features must be weighed against their cost in relation to other required tasks. Each would add to the flexibility, responsiveness, and accuracy of the estimating method.

Summary of First-Unit Cost CERs

Wing CER Formulation

Box Detail Fabrication

- Ribs
- Spars
- Covers

Subassembly

- Ribs
- Spars
- Covers

Box Assembly

Secondary Structure Detail Fabrication and Subassembly

- Leading Edge
- Trailing Edge
- Ailerons
- Fairings
- Tips
- Spoilers
- Flaps and Flaperons
- Attachment Structure
- Access Doors, Frames and Landing Gear Doors
- Air Induction
- Wing Mounted Air Induction
- High Lift Ducting
- Slots
- Hinges, Brackets and Seals
- Pivots and Folds
- Center Section
- Other

Wing Assembly

Horizontal Stabilizer CER Formulation

Box Detail Fabrication

- Ribs
- Spars
- Covers

Subassembly

- Ribs
- Spars
- Covers

Box Assembly

Secondary Structure Detail Fabrication and Assembly

- Leading Edges
- Trailing Edge Assemblies
- Fairings
- Elevators
- Balance Weight
- Tips
- Hinges, Brackets and Seals
- Attachment Structure
- Pivots and Folds
- Center Section
- Other

Horizontal Stabilizer Assembly

Vertical Stabilizer CER Formulation

Box Detail Fabrication

- Ribs
- Spars
- Covers

Subassembly

- Ribs
- Spars
- Covers

Box Assembly

Secondary Structure Detail Fabrication and Assembly

- Leading Edge
- Trailing Edge
- Fairings
- Rudder
- Balance Weight
- Tips
- Hinges, Brackets and Seals
- Access Door and Frames
- Attachment Structure
- Other

Vertical Stabilizer Assembly

2.2.4.3 Development of Complexity Factors. Complexity factors are used in the current methodology as a segment of an overall costing process. The costing process can be thought of as having basically three inputs; viz., historical costs, projected costs, and some type of hardware definition. These inputs interact within the costing methodology to produce a cost estimate. Definition of the hardware has the element of size and complexity. Defining these two elements is sufficient to provide a suitably unambiguous specification of the hardware. The complexity of any piece of structure can be thought of as caused by the material and the type of construction used. This complexity associated with a given material and construction technique can be symbolized by a numerical complexity factor. The flow of this costing process and the interrelationships are shown in Figure 16.

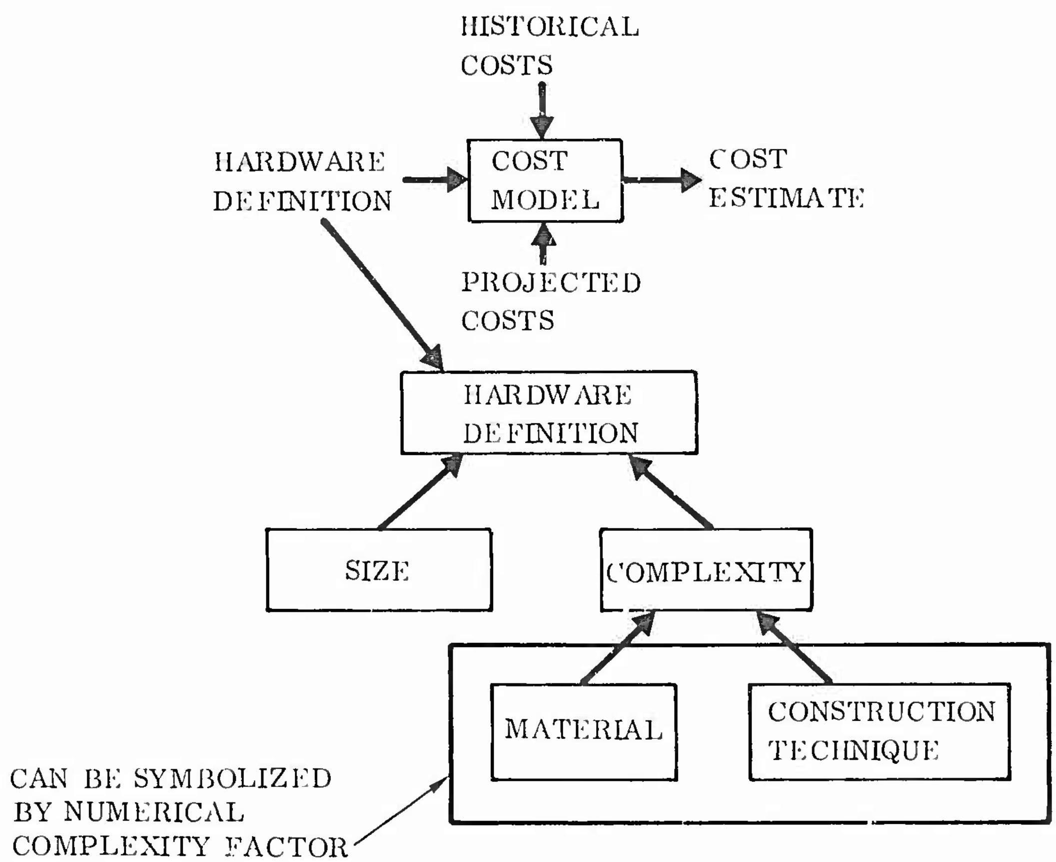


Figure 16. Costing Process

The numerical complexity factors are developed from a detailed analysis of the candidate structures and materials. The first step in this process is the selection of a nominal structural element that provides a structural model of the manufacturing approaches.

A baseline with a reference complexity of one is then defined. Other structural approaches using different materials and construction techniques are defined. The manufacturing processes for both the baseline and alternate structures are then identified and listed. From both historical and projected labor data, hours can then be assigned to the various manufacturing processes. This results in a number of hours being associated with each specific type of material and construction technique for the given nominal structural element.

By dividing the number of hours for each material construction technique combination by the number of hours required for the baseline, we arrive at a complexity factor for each box of the material-construction technique matrix. The flow of this process is shown in Figure 17. An example of the completed material-construction technique matrix for rib detail fabrication is shown in Table 7. A sample of the detailed estimates used to generate hour requirements for the different types of construction and material appears in Figure 18.

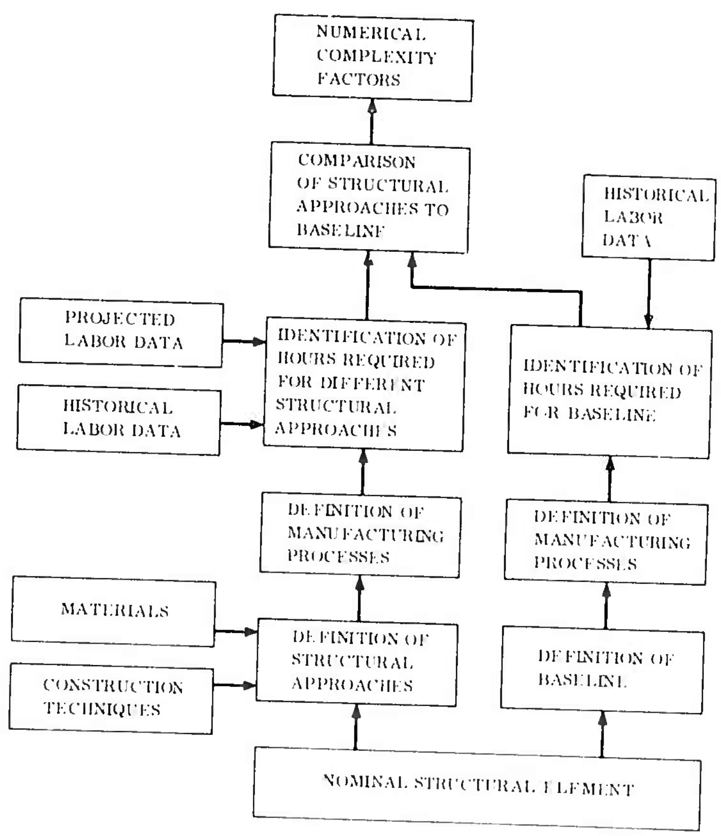


Figure 17. Development of Complexity Factors

Table 7. Complexity Factors for Rib

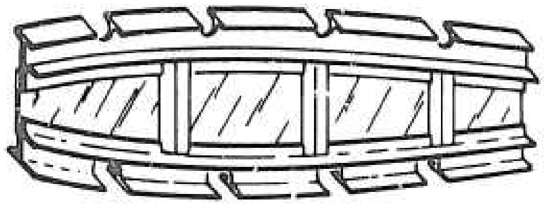
Structural Element / CER Input Symbol	Material Type	Construction Type					
		Built-Up Web Stiffener	Build-Up Truss	Sheet Web	Corregated Web	Integral Web Stiffener	Integral Truss
Ribs Detail Fabrication CF_i	Aluminum	1.00	0.70	0.52	0.51	0.99	0.96
	Titanium	1.31	0.95	0.59	0.57	1.82	1.86
	Low Carbon Steel	1.05	0.77	0.54	0.53	1.21	1.24
	Stainless Steel	1.56	1.15	0.64	0.62	2.48	2.54

The complete set of material-construction complexity factors developed for ribs, spars, and covers at the detail fabrication and subassembly level can be found in Volume IV.

The ribs complexity factors are divided into twenty-four categories based on construction type and material. The construction types covered are built-up web stiffener, built-up truss, sheet web, corregated web, integral web stiffener, and integral truss. The types of material covered are aluminum, titanium, low-carbon steel, and stainless steel.

The spars complexity factors were also divided into the same twenty-four categories, based on construction type and material. Covers were divided into sixteen different categories, based on construction type and material type. The types of construction covered are built-up skin stringer, integral skin stringer, machined plate, and sheet. The types of material covered are aluminum, titanium, low carbon steel and stainless steel.

For each type of construction, a sketch defined the specifics, such as number of rails web parts, number of machined surfaces, number of stiffeners, etc. A nominal size was defined to make the different design approaches to ribs, spars, and covers comparable on a complexity factor basis. For each piece of detail structure, the manufacturing operations were identified that are required to manufacture each piece. These included such operations as those shown in Figure 18: saw set up, edge burring, router set up, routing of cutouts, processing to specifications, identifying and inspecting, etc. Where assembly was required, these operations were identified and included clamping in place, hole drilling, riveting, welding, identifying and inspecting, etc.



RIB BUILT-UP
WEB STIFFENER

	Low-C Non-Hard. Steel	Ti	SS	Al	1
Rib size = 48 x 12 x 2 in.					
Detail parts are rails (2), web (1), stiffeners (2) & intercostals (3)					
Fabrication of rails (2)					
Setup saw	0.50	0.50	0.50	0.5	
Saw extrusion to length (2)		0.75	1.11	0.3	
Burr edges	0.42	0.75	1.11	0.3	
Setup router	0.50	0.50	0.50	0.5	
Route stringer cutouts	0.98	1.75	2.59	0.7	
Burr	0.42	0.75	1.11	0.3	
Set up rolls	0.50	0.50	0.50	0.5	
Roll form to contour	0.30	0.30	0.30	0.3	
Process to spec. (alodine)	4.00	4.00	4.00	4.0	
Prime surfaces	0.50	0.50	0.50	0.5	
Identify & inspect	0.50	0.50	0.50	0.5	
Fabrication of web (1)					
Setup shear	0.50	0.50	0.50	0.5	
Shear part to width & length (12 in x 48 in.)	0.30	0.30	0.30	0.3	
Burr	0.50	0.50	0.50	0.5	
Route web to shear	0.70	1.25	1.85	0.5	
Burr	0.28	0.50	1.74	0.2	
Process to spec. (alodine)	4.00	4.00	4.00	4.0	
Prime surfaces	0.50	0.50	0.50	0.5	
Identify & inspect fabrication of stiffeners (2)					
Setup saw	0.50	0.50	0.50	0.5	
Saw extrusion (2)	0.42	0.75	1.11	0.3	
Burr	0.28	0.50	0.74	0.6	
Setup rolls	0.50	0.50	0.50	0.5	
Roll form to contour	0.50	0.50	0.50	0.5	
Process to spec. (alodine)	4.00	4.00	4.00	4.0	
Prime surfaces	0.50	0.50	0.50	0.5	
Identify & inspect	0.50	0.50	0.50	0.5	
Fabrication of intercostals (3)					
Setup saw	0.50	0.50	0.50	0.5	
Saw extrusion (3)	0.42	0.75	1.11	0.3	
Burr	0.42	0.75	1.11	0.3	
Process to spec. (alodine)	4.00	4.00	4.00	4.0	
Prime surfaces	0.50	0.50	0.50	0.5	
Identify & inspect	0.50	0.50	0.50	0.5	
Total detail Fabrication	29.24	33.40	37.48	28.3	

Figure 18. Detailed Industrial Engineering Estimates for Complexity Factor Derivation

Complexity factors for the secondary structure are in the process of development. A somewhat different procedure is being used. The major difference is that costs, as measured by hours, will be grouped into four major cost-driving categories; viz., fabrication, assembly, hole drilling and fastening. Relative costs for these different categories, when different materials are used, will be determined and this data used to generate top-level complexity factors. The types of material and types of structure to be explored for the various pieces of secondary structure are summarized as follows:

Complexity Factor Matrices for Secondary Structure

Leading Edge

Material	Type of Construction	
	Built Up Sheet	Layup
Aluminum	X	
Fiberglas		X
Boron Aluminum	X	

Trailing Edge

Material	Type of Construction		
	Built Up Sheet	Layup	Honeycomb Sandwich
Aluminum	X		X
Fiberglas		X	
Boron Aluminum	X		
Graphite Epoxy			X

Ailerons

Material	Type of Construction		
	Built Up Sheet	Honeycomb	Machined
Aluminum	X	X	X
Boron Aluminum	X		
Graphite Epoxy		X	

Fairings

Material	Type of Construction: Built Up Sheet	Layup
Aluminum	X	
Fiberglas		X
Boron Aluminum	X	

Tips

Material	Type of Construction: Built Up Sheet	Layup
Aluminum	X	
Fiberglas		X
Boron Aluminum	X	

Spoilers

Material	Type of Construction: Built Up Sheet	Honeycomb Sandwich	Machined
Aluminum	X	X	X
Boron Aluminum	X		
Graphite Epoxy		X	

Wing Mounted Air Induction

Material	Type of Construction: Built Up Sheet	Machined
Aluminum	X	X
Stainless Steel	X	X
Boron Aluminum	X	

High Lift Ducting

Material	Type of Construction: Formed Tubing
Steel	X
Titanium	X

Slats

Material	Type of Construction: Built Up Sheet	Honeycomb Sandwich	Machined
Aluminum	X	X	X
Boron Aluminum	X		
Graphite Epoxy		X	

Hinges and Brackets

Material	Type of Construction: Machined
Aluminum	X
Steel	X

Pivots and Folds

Material	Type of Construction: Machined
Steel	X
Titanium	X

Center Section

Material	Type of Construction: Built Up Sheet	Machined
Aluminum	X	X
Boron Aluminum	X	

Other

Material	Type of Construction: Built Up Sheet	Machined
Aluminum	X	X
Titanium	X	X
Steel	X	X
Boron Aluminum	X	X

Flaps and Flaperons

Material	Type of Construction: Built Up Sheet	Honeycomb Sandwich	Machined
Aluminum	X	X	X
Boron Aluminum	X		
Graphite Epoxy		X	

Attachment Structure

Material	Type of Construction: Machined
Aluminum	X
Titanium	X
Steel	X

Access Doors, Frames and Landing Gear Doors

Material	Type of Construction: Built Up Sheet	Layup
Aluminum	X	
Fiberglas		X
Boron Aluminum	X	

Elevators

Material	Type of Construction: Built Up Sheet	Layup
Aluminum	X	
Fiberglas		X
Boron Aluminum	X	

Rudder

	Type of Construction: Built Up Sheet	Layup
Aluminum	X	
Fiberglas		X
Boron Aluminum	X	

2.2.4.4 Derivation of Baseline CER Coefficients. A summary of cost elements for which baseline coefficients were developed is shown in Figure 19. Historical cost data

FIRST UNIT COST	DETAIL FABRICATION	SUBASSEMBLY
STRUCTURAL BOX		
RIBS	X	X
SPARS	X	X
COVERS	X	X
SECONDARY STRUCTURE		
LEADING EDGE	X	X
TRAILING EDGE	X	X
AILERONS	X	X
FAIRINGS	X	X
TIPS	X	X
SPOILERS	X	X
FLAPS + FLAPERONS	X	X
ATTACHMENT STRUCTURE	X	X
ACCESS + OTHER DOORS	X	X
AIR INDUCTION	X	X
HIGH LIFT DUCTING	X	X
SLATS	X	X
HINGES, BRACKETS, SEALS	X	X
PIVOTS + FOLDS	X	X
CENTER SECTION	X	X
ELEVATORS	X	X
BALANCE WEIGHTS	X	X
RUDDER	X	X
OTHER	X	X

Figure 19. Summary of CER Coefficients.

was collected for each of the cost elements of the matrix. This basic cost data was normalized, where appropriate, by making use of the complexity factors. The construction and material type for each of the cost elements was identified and the appropriate complexity factor divided into the baseline cost. The effect of this procedure is to reduce all the data points to a common basis to which a complexity factor of one can be applied.

Once the normalized data for the cost elements has been plotted on log-log paper, the problem becomes one of simply determining the line that can best represent the adjusted data. The two basic parameters define the CER line: the slope of the line and the intercept of the y axis where the value of the x axis (weight) is one pound. Based on a composite plot of all cost data and the results of previous research, in particular

References 17, 18, and 19, it was decided to use the equivalent of an 80 percent learning curve as a constant slope (i.e., with slope defined in a cost-quantity progress context). With the slope of the curves specified, each y intercept was determined by fitting the fixed slope line to the data available for each cost element. A cost plot showing the technique for the rib detail fabrication is shown in Figure 20. Back-up data charts for each of the CERs appear in Volume III.

2.2.4.5 Recurring Costs. Recurring costs related to airframe production are estimated in essentially the same manner for aerodynamic surfaces as that used for the horizontal stabilizer. The two main subcategories previously used are retained:

a. RDT&E recurring production.

b. Procurement recurring production.

For purposes of the estimating method, these are assumed to be continuous production lots, irrespective of procurement policies. Specific program data would be needed to define the exact sequence of production for any other assumption. For trade study relative costs, however, more exact treatment is not required. The matrix of CERs used for both subcategories is shown in Table 8. The individual CERs are described in the following discussion.

Sustaining Engineering Hours. The CER recommended for sustaining engineering hours has the following form:

$$E_{SUST} = EH \left[N_i^{ES} - 1 \right] \quad (27)$$

where

EH = Nonrecurring engineering direct labor hours

N_1 = Number of airframes

ES = Scaling of sustaining engineering with quantity

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17. R.E. Kenyon and R.J. Reid, "Aircraft Cost Estimating Relationship Improvements, Construction and Material Effect and New Data," GDC-ERR-1633, Convair Aerospace Division of General Dynamics, January 1972.

18. Indices of Airplane Production Efficiency, Aircraft Resources Control Office, November, 1943.

19. Space Transport System Cost Methodology, System Cost Office, The Aerospace Corporation, Contract No. FO4701-70-C-0059, August, 1970

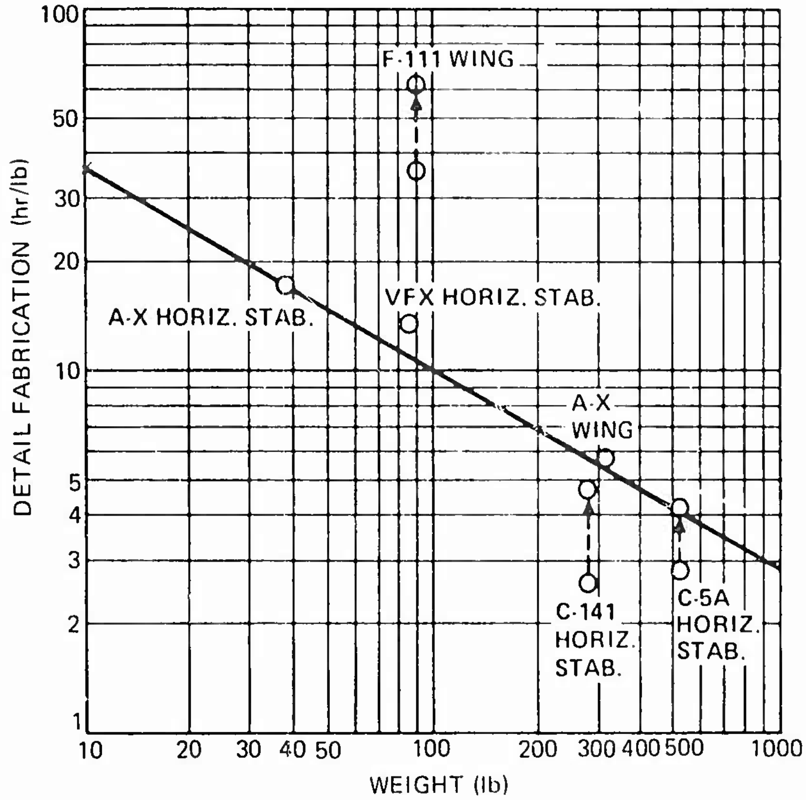

Figure 20. Detail Fabrication Hours Versus Weight for Ribs with Complexity Factor normalized

Table 8. Recurring Airframe Production Costs

						Hours	Dollars
RDT&E Articles (Qty)							
Sustaining Engineering						$E_{SUST\ 1}$	$E_{SC\ 1}$
Sustaining Tooling						$T_{SUST\ 1}$	$T_{SC\ 1}$
Manufacturing:	Horiz. Stab.	Vertical Stab.	Wing	Fuselage	Nacelle		
Detail Fab Hours	H_{DF1}	H_{DF2}	H_{DF3}	H_{DF4}	H_{DF5}	H_{DFS}	H_{DFC}
Assembly Hours	H_{AS1}	H_{AS2}	H_{AS3}	H_{AS4}	H_{AS5}	H_{ASS}	H_{ASC}
Quality Control Hours	-	-	-	-	-	H_{QC1}	QC_{C1}
Material and Other	MM_{C1}	MM_{C2}	MM_{C3}	MM_{C4}	MM_{C5}	-	MM_{CS}
Procurement Articles (Qty)							
Sustaining Engineering						$E_{SUST\ 2}$	$E_{SC\ 2}$
Sustaining Tooling						$T_{SUST\ 2}$	$T_{SC\ 2}$
Manufacturing:	Horiz. Stab.	Vertical Stab.	Wing	Fuselage	Nacelle		
Detail Fab Hours	H_{DF11}	H_{DF12}	H_{DF13}	H_{DF14}	H_{DF15}	H_{DFSP}	H_{DFCP}
Assembly Hours	H_{AS11}	H_{AS12}	H_{AS13}	H_{AS14}	H_{AS15}	H_{ASSP}	H_{ASCP}
Quality Control Hours	-	-	-	-	-	H_{QC2}	QC_{C2}
Material and Other	MM_{C11}	MM_{C12}	MM_{C13}	MM_{C14}	MM_{C15}	-	MM_{CSP}

Where previously the scaling of hours with quantity was a constant, it is now treated as a variable, thus allowing consideration of individual experiences.

Sustaining engineering hours by RDT&E and procurement are obtained by apportioning hours to the corresponding production quantities as follows.

RDT&E Sustaining Engineering Hours. Sustaining engineering hours for airframes 1 through N_1, where N_1 is the cumulative number of prototype, static and fatigue test, and flight test airframes in the RDT&E program, is given by:

$$E_{SUST\ 1} = EH\left[N_1^{ES} - 1\right] \tag{28}$$

where

EH = Nonrecurring engineering direct labor hours

N_1 = Number of RDT&E airframes

ES = Scaling of sustaining engineering with quantity

Procurement Sustaining Engineering Hours. Sustaining engineering hours for airframes beyond N_1 through production quantity N_2, where N_2 includes N_1, is given by:

$$E_{SUST\ 2} = EH\left(N_2^{ES} - N_1^{ES}\right) \tag{29}$$

where

N_2 = Sum of RDT&E and procurement production quantities

Sustaining Engineering Labor Costs. Labor cost for each of the two categories of sustaining engineering are obtained simply by the application of the appropriate labor rate.

Sustaining Tooling Hours. An approach similar to sustaining engineering is used for estimating sustaining tooling hours. The form of the CER is:

$$T_{SUST} = T_S\left[N_i^{TU} - 1\right] \tag{30}$$

where

$TS = T_R + T_{ET} + T_{MD}$

TU = Scaling of sustaining tooling with quantity. (Use $TU = .14$)

Sustaining tooling hours by RDT&E and procurement are given by apportioning hours to the corresponding production quantities as follows:

RDT&E Sustaining Tooling Hours. Sustaining tooling hours for airframes 1 through N_1 where N_1 is the number of airframes produced for the RDT&E program, is given by:

$$T_{SUST\ 1} = T_S \left[N_1^{TU} - 1 \right] \tag{31}$$

Procurement Sustaining Engineering Hours. Sustaining tooling hours for airframes beyond N_1 through productions quantity N_2 is given by:

$$T_{SUST\ 2} = T_S \left[N_2^{TU} - N_1^{TU} \right] \tag{32}$$

Sustaining Tooling Labor Costs. Labor cost for each of the two categories of sustaining tooling are obtained by the application of the appropriate labor rate.

Manufacturing Hours. Manufacturing hours associated with airframe production are estimated by means of standard learning curve theory using a log-linear unit curve application such as shown in Reference 20. Thus, costs for any given unit are given by:

$$Y_u = a x^b \tag{33}$$

where

Y_u = Cost of a given unit x

a = Cost of the first unit

x = Number of units

$b = \frac{\log s}{\log 2}$, where s = learning curve percentage expressed as a fraction

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20. C.A. Batchelder, et al., "An Introduction to Equipment Cost Estimating," RM-6103-SA, Rand Corp., December 1969.

The total cost for a given production quantity x is given by

$$T_n = a \sum_{x=1}^{n} x^b, \tag{34}$$

and the cumulative average cost Y_c of producing the first n units is given by $Y_c = T_n/n$.

The number one unit is considered to be the first RDT&E airframe, which may be a prototype. The series of x units is counted from this unit, and RDT&E and procurement costs are identified by using the appropriate segments of the total cost summations. These CERs are:

RDT&E Manufacturing Hours

$$H_{DFi} = (FU_{DFi}) \left(\sum_{i=1}^{N_1} N_i^{K} \right) \tag{35}$$

where

H_{DFi} = Total detailed fabrication hours for a quantity N_1 of a given basic structure component for RDT&E test hardware. i = 1 for horizontal stabilizer, i = 2 for vertical stabilizer, etc.

FU_{DF} = Total detailed fabrication first unit hours for a given basic structure components, i.e., horizontal stabilizer, vertical stabilizer, wing, fuselage, nacelle.

This summation is accomplished twice: once for detailed fabrication hours and once for assembly hours. H_{ASi} = Total assembly hours for the quantity N_1. FU_{AS} represents first unit assembly hours for basic structure components. FU_{DF} and FU_{AS} are obtained by summing the respective first unit labor estimating equations in Appendix B. Using the wing as an example,

FU_{DF} = The sum of Appendix B equations 1, 4, 7, 40, 42, 44, 46, 48, 50, 52, 54, 56, 58, 60, 62, 64, 66, 68 and 70.

$\sum_{i=1}^{N_1} N_i^K$ = Production quantity with a learning function

$K = \frac{\log PC_i}{\log 2}$, where PC_i = learning curve expressed as a decimal fraction, and

PC_1 = Learning curve decimal fraction for detailed fabrication hours.

PC_2 = Learning curve decimal fraction for assembly hours.

Procurement Manufacturing Hours

$$H_{DF1i} = (FU_{DFi}) \left(\sum_{i=N_1+1}^{N_2} N_1^K \right) \quad = \text{Detail fab hours for } N_2 - N_1 \text{ quantity} \quad (36)$$

$$H_{AS1i} = (FU_{ASi}) \left(\sum_{i=N_1+1}^{N_2} N_i^K \right) \quad = \text{Assembly hours for } N_2 - N_1 \text{ quantity.} \quad (37)$$

Manufacturing Labor Costs. Labor costs for each of the two categories of manufacturing are obtained by the application of the appropriate labor rate as follows:

RDT&E Manufacturing Labor Costs

$$H_{DFC} = H_{DFS} \times (\text{Mfg. labor rate}) = \text{Detailed fab labor cost for RDT\&E articles} \quad (38)$$

where

$$H_{DFS} = H_{DF1} + H_{DF2} + H_{DF3} + H_{DF4} + H_{DF5} \quad (39)$$

(i.e., summation of horizontal, vertical, wing, fuselage and nacelle)

and

$$H_{ASC} = H_{ASS} \times (\text{Mfg. labor rate}) = \text{Assembly labor cost for RDT\&E articles} \quad (40)$$

where

$$H_{ASS} = H_{AS1} + H_{AS2} + H_{AS3} + H_{AS4} + H_{AS5} \quad (41)$$

Procurement Manufacturing Labor Costs

$$H_{DFCP} = H_{DFSP} \times (\text{Mfg. labor rate}) = \text{Detailed fab labor cost for procurement articles} \quad (42)$$

where

$$H_{DFSP} = H_{DF11} + H_{DF12} + H_{DF13} + H_{DF14} + H_{DF15} \quad (43)$$

and

$$H_{ASCP} = H_{ASSP} \times (\text{Mfg. labor rate}) = \text{Assembly labor cost for procurement articles} \quad (44)$$

where

$$H_{ASSP} + H_{AS11} + H_{AS12} + H_{AS13} + H_{AS14} + H_{AS15} \quad (45)$$

Manufacturing Materials and Other. These elements are estimated on the basis of the application of a learning curve to the estimated first unit cost in a manner similar to manufacturing using values for manufacturing material cost.

RDT&E Manufacturing Materials and Other Costs

$$MM_{Ci} = (HS_M^{*}) \sum_{i=1}^{N_1} N_i^{K} \quad (46)$$

*VS_M, W_M, Fm, and N_M in turn for each of the major components.

where

MM_{Ci} = Dollar cost of manufacturing materials for the various structural components for RDT&E hardware

MM_{C1} = Horizontal stabilizer cost

MM_{C2} = Vertical stabilizer cost

MM_{C3} = Wing cost

MM_{C4} = Fuselage cost

MM_{C5} = Nacelle cost

HS_M = First unit material cost for horizontal stabilizer

VS_M = First unit material cost for vertical stabilizer

W_M = First unit material cost for wing

F_M = First unit material cost for fuselage

N_M = First unit material cost for nacelle

K = Material learning curve factor

$$= \frac{\log pc_3}{\log 2}$$

and

MM_{CS} = Total manufacturing material cost

$$= MM_{C1} + MM_{C2} + MM_{C3} + MM_{C4} + MM_{C5}$$

Procurement Manufacturing Materials and Other Costs

$$MM_{C1i} = (HS_M^*) \left(\sum_{i=N_1}^{N_2} N_i^K \right) \qquad (47)$$

and

MM_{CSP} = Total manufacturing material cost for procurement production articles

$$= MM_{C11} + MM_{C12} + MM_{C13} + MM_{C14} + MM_{C15}$$

Quality Control Hours. Quality control hours are estimated for both RDT&E and procurement on the basis of a ratio between quality control and manufacturing hours for procurement production. A separate ratio can be used for each.

RDT&E Quality Control Hours

$$H_{QC1} = (H_{DFS} + H_{ASS}) F_{10} \tag{48}$$

where

H_{QC1} = Quality control hours for RDT&E production units

F_{10} = Ratio between quality control and manufacturing hours

Procurement Quality Control Hours

$$H_{QC2} = (H_{DFSP} + H_{ASSP}) F_{11} \tag{49}$$

where

H_{QC2} = Quality control hours for procurement production units

F_{11} = Ratio between quality control and manufacturing hours for procurement production

Quality Control Labor Costs. Labor costs for each of the two categories of quality control are obtained by the application of appropriate labor rates.

2.2.5 COST ESTIMATING INPUTS. The inputs required to generate first-unit costs for the exploratory wing, horizontal and vertical cases have been tabulated and appear in Appendix C. These inputs cover the assessment of complexity factors for structure/material types, baseline hours per pound costs for various pieces of structure, weight scaling exponents, weights of specific structural components, detailed sizes and quantities determined by the structural synthesis program, and various detailed manufacturing parameters.

The inputs required to generate nonrecurring and recurring costs for the demonstration cases have been tabulated and appear in the same Appendix. These inputs cover design engineering, tool manufacturing, tool engineering, support, quality control, sustaining engineering, sustaining tooling, and manufacturing.

The supporting data for the generation of the required inputs appears in Volume IV, where the identification, source, and determination of required inputs are covered.

2.2.6 TEST CASES. Exploratory cases were run for the F-111 wing box, C-5A horizontal, F-111 vertical, AX wing, C-141 horizontal, and C-5 vertical box. The results of these runs were compared with actual historical data, percentage differences computed, and the results tabulated in Table 9. These cost comparisons include both manufacturing hours and material dollars.

Table 9. Exploratory Cases, First Unit Costs

	Manufact. Time			Material Cost		
	Actual (hr)	Estimated (hr)	% Diff.	Actual ($)	Estimated ($)	% Diff.
F-111 Wing Box	44,545	46,041	+3	52,749	45,814	-15
C-5A Hor.	47,221	62,761	+33	83,473	101,489	+22
F-111 Vert.	12,300	14,217	+16	24,000	20,976	-12.7
AX Wing	49,833	42,305	-15	76,660	32,904	-57
C-141 Hor.	27,839	34,380	+24	42,972	47,206	+10
C-5 Vert. Box	16,152	27,614	+71	85,500	60,902	-28.8

Nonrecurring costs for the F-111 wing, F-111 vertical, C-5 horizontal, and C-5 vertical were estimated. The cost elements covered were engineering design, tool engineering and manufacturing, materials, support, and quality control. Where appropriate, both hour and dollar values were developed. The results of these runs appear in Table 10.

Table 10. Exploratory Cases, Nonrecurring Cost ($ Millions)

Cost Element	F-111 Wing		F-111 Vertical		C-5 Horizontal		C-5 Vertical	
	Hours	$	Hours	$	Hours	$	Hours	$
Engineering Direct Labor Hours	242,997	4.859	37,694	0.753	291,943	5.838	259,260	5.185
Engineering Material	-	0.486	-	0.075	-	0.583	-	0.518
Tool Manufacturing Hours	1,981,676	30.914	176,268	2.749	572,580	8.932	505,313	7.882
Tool Engineering Hours	623,970	11.181	55,502	0.994	206,443	3.699	182,190	3.264
Mfg. Devel. & Plant Engr. Hours	39,634	0.566	3,525	0.050	11,452	0.163	10,106	0.144
Tooling Material & Other Dollars	-	1.981	-	0.176	-	0.572	-	0.505
Manufacturing Support Dollars	-	0.486	-	0.075	-	0.583	-	0.518
Quality Control Hours	2,430	0.035	377	0.005	37,274	0.540	32,911	0.477

2.2.7 ESTIMATING SPECIAL STRUCTURES AND PROCESSES. The estimating framework previously discussed provides for estimating within the categories of construction and material types described thereby. In actual practice, exceptions are considered to be accounted for in the estimating factors used. However, major exceptions need to be separately analyzed; and because they are exceptions, generalized methods of estimating their cost are not necessarily available. Such an exception may thus require its own separate approach, although estimating by analogy may offer a solution.

The discussion in this section is a summarization of estimates made for the horizontal stabilizer. An estimate made in conjunction with the Fort Worth Operations study of an advanced fighter wing box for AFFDL is a further illustration that is discussed in Section 2.4 on advanced structures.

2.2.7.1 Full Depth Honeycomb Construction. The method for estimating costs of those horizontal stabilizer parts that are of full depth honeycomb construction is to use a set of supplementary equations in addition to the basic set of equations for metal structures already described. This approach is based on the idea that the cost of the hardware described by inputs to the basic equations is predicted properly, but when full depth honeycomb is used in part or in all of the structure, the additional costs must be predicted, and the use of supplementary equations is required. Full depth honeycomb, in this example, appears as a partial substitute for stringers and ribs, but a framework of conventional structure remains. The basic equations predict an incomplete structural cost that must be augmented by the honeycomb-peculiar costs predicted by the supplementary equations. The set of equations used covers the following items:

a. Added Structural Box Cost:

Detailed fabrication hours.

Material cost.

Assembly costs.

b. Added Cost in Other Structure:

Labor hours.

Material.

Multiple equations are used in some cases. In each case costs are additive to those obtained from the basic equation set.

Added Structural Box Cost, Detailed Fabrication Hours. This task consists of cutting the honeycomb core material to contour. The equation is:

$$\text{Hours} = (\text{No. of surfaces}) \left[(\text{fraction of box area using honeycomb}) (\text{box area})\right]^{P} (\text{machining labor factor}) (\text{material type factor}) \quad (50)$$

Box area is available from an analysis of the output of the multistation structural synthesis program. The fraction using honeycomb must be obtained from design information. The machining labor factor and the material type factor are obtained from Table 11. Area is scaled with the scaling exponent based on engineering judgment.

Derivation of the machining labor hours per square foot factors in Table 11 is based on data from standard hour tables. Consider first the machining of a single plane cut on full depth aluminum honeycomb material. A flat plane cut could be parallel to an existing surface or a bevel plane cut. The factors to be considered are as follows:

The original honeycomb raw stock must be stabilized before machining. This can be accomplished by freezing into a block of ice. This process plus setup on a milling machine and an allowance for checking is determined to be 0.0063 hour per square

Table 11. Honeycomb Detail Fabrication Labor Factors

Material Type Factor	Machining Labor: Single Plane (hr/ft^2)	Multi Lands or Planes (hr/ft^2)	Contour to Compound Curve (hr/ft^2)
	2.335	4.5	8.56
Aluminum	1.0		
Titanium	2.2		
Steel	1.8		
Fibre Glass	1.3		

Note: If only one side of the core requires cutting, the machining labor factor is divided by two.

inch. The milling run factor is 0.0006 hour per square inch. Thus (0.0003 + 0.0006) times 144 square inches per square foot, times 18 for first unit, yields 2.335 hours per square foot, which is the value in the first column of Table 11.

In the same manner, a machining hours-per-square-foot factor is determined for a compound contour such as an aerodynamic surface. This would normally imply an electronically controlled mill. Cutting is slower because of smaller cutting tools and the frequent passes required to machine a smooth contour. From standard hour tables, values of 0.0006 hour per square inch for setup, and 0.0027 hour per square inch for run time are found. Thus (0.0006 + 0.0027) times 144, times 18, yields 8.56 hours per square inch. The 4.5 hour factor for multi-lands or planes is a judgment factor.

The material type factor values of Table 11 are largely judgment values based on the ratios for regular machining of these materials. The resulting labor estimate is for one aerodynamic surface only and must be multiplied by two for a complete ship set.

Material Cost. The weight of honeycomb material is excluded from the calculations of the basic method, and the following equation is used to predict honeycomb material costs:

$$\text{Material cost} = \left[(\text{Structural box area})\ (\text{average structural box thickness})\right]^{G} (\text{Base cost per cubic ft.})\ (\text{Material type factor}) \qquad (51)$$

Base costs differ from catalog quotations due to inclusion of shipping, receiving, receiving inspection, and an allocation of inventory and material control costs. Volume is scaled by the exponent used in the basic method. Average structural box thickness is assumed to equal average spar height times 1.2. The base cost for a one-cubic-foot aluminum core is taken at $127.00. Factors for material type are shown in Table 12.

Table 12. Material Cost Factors for Different Honeycomb Core Materials

Material	Aluminum	Titanium	Steel	Fibre Glass
Material Type Factor	1.0	7.5	3.75	2.5

Note: Welded titanium and stainless steel honeycomb core materials are currently available only to about 2 inches in depth.

Table 12 contains cost ratios for four types of materials. These ratios are related to the base costs of aluminum core material at $127 per cubic foot. The basis for this value is shown in Figure 21. From a catalog of honeycomb prices, an average value of $1.80 per inch foot is found, which includes a cutting and expanding charge. This value, multiplied by 12 inches per cubic foot, yields an average vendor price of $22 per cubic foot. To this is added a receiving and inventory cost of $4 per pound, which is a value comparable to that used for other aluminum construction material. Using an average of 5.0 pounds per cubic foot gives an additional $20 per cubic foot. Thus $42 per cubic foot at the 100 cubic foot quantity becomes the reference value in Figure 21. The exponential slope of the line shown is -.23. This corresponds to the slope used for all first-unit quantity effects on other materials except the composite fabric materials.

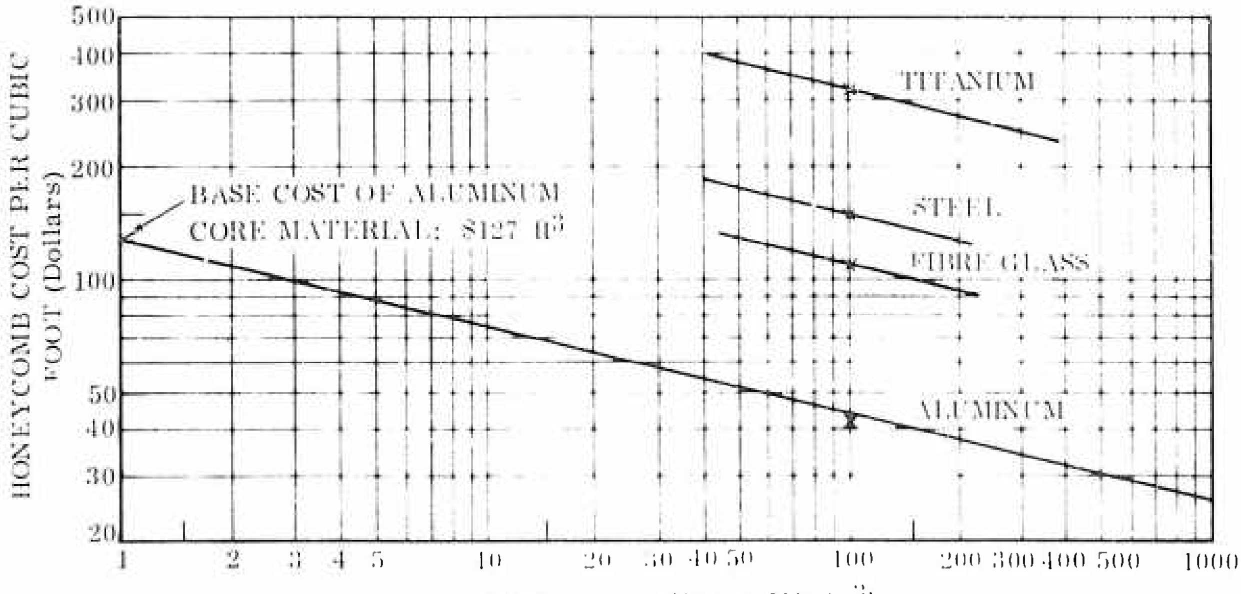


Figure 21. Aluminum Honeycomb Costs per Cubic Foot

Assembly Costs. This task is estimated in two steps. First is the task of cleaning the covers and applying the adhesive over the honeycomb areas, which is considered to be a function of the area involved. Next is the task of providing bonding at all of the perimeter butt and lap joints.

Step 1. Estimating added assembly labor as a function of area is accomplished as follows:

$$\text{Hours} = (\text{No. of surfaces}) \left[(\text{fraction of box area using full depth honeycomb})(\text{structural box plan view area})\right]^{P} (\text{assembly labor per sq. ft.})(\text{Material type factor}). \quad (52)$$

Assembly is accomplished by bonding in the case of honeycomb, and value for cost per square foot is determined by accumulating standard hours for the surface bonding labor and multiplying by 144 sq. inches per sq. ft. and by 18 to convert to first unit cost.

First unit check and cleaning	0.0005 hr/sq. in.
Pre fit	0.0002 hr/sq. in.
Apply adhesive	0.0008 hr/sq. in.
Assemble	0.0002 hr/sq. in.
Bag and press	0.0002 hr/sq. in.
Cure and removal	0.0002 hr/sq. in.
Total	0.0021 hr/sq. in.

Bonding labor factor per square foot = 0.0021 x 144 x 18 = 5.44 hr/sq. ft.

Bonding labor changes when different materials are used. Factors for some materials are shown in Table 13.

Table 13. Material Type Factor for Bonding Labor

	Aluminum	Titanium	Steel	Fibre Glass
Bonding Labor Factor	1.0	1.3	1.3	1.0

Step 2. Estimating added assembly labor as a function of perimeter is accomplished as follows:

Hours = (Box perimeter) (fraction of box area using full depth honeycomb) (labor cost per lineal foot) (material type factor). (53)

A value for additional labor per foot of perimeter is determined by accumulating standard hours for bonding labor per inch, and multiplying by 12 inches per foot, and by 18 to convert to first unit cost.

First unit check and cleaning	0.0005 hr/inch
Apply double sided bonding tape or adhesive past	0.0008 hr/inch
Trim excess adhesive after cure	0.0006 hr/inch
Total	0.0019

The added labor factor per lineal foot = 0.0019 x 12 x 18 = 0.41 hour/foot. Values for material type factor are taken from Table 13.

Added Cost in Other Structure. The basic equation set predicts a standard cost for these components based on weight and kind of material. No differentiation is made for construction type in the basic equation set. Furthermore, detail fabrication, subassembly, and assembly labor are not differentiated. Two equations are described below to be used to estimate the labor and material cost differential due to use of honeycomb. These two equations are recalculated each time for each component using full depth honeycomb construction.

Labor Costs. Hours = (square feet of honeycomb used)^{P_1} (No. of sides) (3.44 hours/sq. ft + machining value from Table 10) (Material type factor). (54)

The material type factor values are taken from Table 14.

Table 14. Material-Type Labor Factors for Other Structure

	Aluminum	Titanium	Steel	Fibre Glass
Other Structure Labor Factor	1.0	1.7	1.6	1.2

Material Costs. Added material dollars = [(square feet of honeycomb) (widest depth)] ^{G} ($75.0 per cu. ft.) (material type factor).

The material cost per cubic ft factor has been reduced by $52 per pound because this equation adds to previous partially computed costs. Material type factors are selected from Table 12.

2.2.7.2 Other Special Structure. Other items of structure to be investigated that might be treated in a manner similar to the above are:

a. Fuel tanks.

b. Sandwich skins.

c. Ducting.

d. Air induction.

e. Landing gear provisioning.

In the case of fuel tanks, an equation is needed to estimate the cost of those portions of the fuel tank that double as basic structure but that would not be required if fuel tanks were not located within the wing. Sandwich skins, upon determination of suitable factors, can be handled in a manner analagous to honeycomb core. Ducting would be separately costed but as a part of the subsystem with which it is associated: propulsion, flight control, environmental control, etc. Wing-mounted air induction interacts with the basic structure and must be analyzed in terms of the additional structural complexity that it introduces. A wing-mounted landing gear is treated as a penalty reflected as added cost to the basic structure. Estimating equations and the supporting estimating factors must be developed to support the above techniques.

2.3 THE TRADE STUDY COST ESTIMATING METHOD FOR FUSELAGE AND OTHER BASIC STRUCTURE

The next phase of the study deals with extending the trade study cost estimating method to the fuselage, nacelle, and landing gear. This section describes that extension in terms of progress to date and remaining work. The significant tasks include the following:

a. Development of adequate cost data.

b. Derivation of first-unit CER.

c. Development of complexity factors.

d. Development of baseline estimating coefficients.

e. Development of fuselage structural synthesis program.

f. Development of weight estimating subroutines.

g. Development of cost estimating methodology for other basic structure: nacelles and landing gears.

h. Computer programming.

i. Estimating test cases.

Current plans are to base the fuselage estimating method on use of the APAS multistation structural synthesis program. An alternative would be the use of both APAS and a finite element synthesis program. Use of the APAS program by itself limits the structural analysis capability to simple fuselages and wings, which means that a fuselage such as the F-111 or a delta wing such as the B-58 cannot be treated. Using both synthesis programs interfaced to permit alternative modes of analysis would require repeating a substantial portion of each of the above steps for both the fuselage and the wing. Using the finite element capability alone is not warranted in view of the advanced state of development of the APAS program, per se, and considering the fact of its present substantial integration into the costing methodology.

Figure 22 illustrates the activity involved in the extension of the trade study cost estimating method to the fuselage. This figure includes data organization features not listed but implicit in the above list of tasks. The focus of the effort is the test case runs and the analysis of estimating results. Also, special features synthesis is not included in the weight estimating method. Results to date and expected future results are discussed below. It should be noted that the structural synthesis program development is being accomplished under independent research sponsorship. The selection of a transport test case is under study.

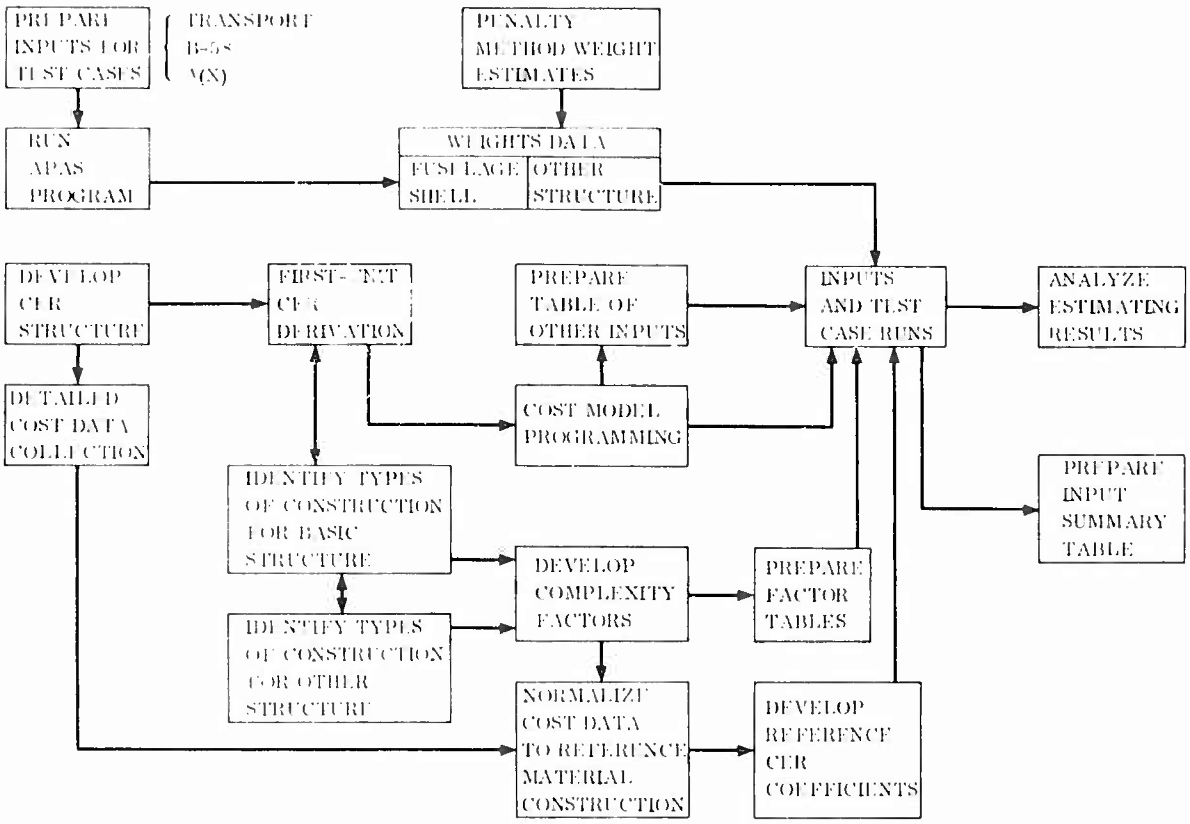


Figure 22. Development of Trade Study Cost Estimating Method for Simple Fuselage

2.3.1 COST DATA COLLECTION. The total data sample from which fuselage cost data was to be collected and analyzed consisted of the following aircraft:

F-111A	DC-10
B-58	747
AX	F-5E
F-106	B-1
F-102	A-5A
VSX	T-2A

Action on F-111 data is being delayed pending a decision in October on the use of the finite element structural synthesis mode of analysis. B-58 fuselage data is available only at the total fuselage level of detail. The AX, VSX, and B-1 are being researched from proposal data. F-106 and F-102 historical cost data is not readily available, and it is felt that the cost of its acquisition for this study would be prohibitive. A-5A and T-2A fuselage data are available in the detail illustrated below:

Total Body Structure

Total Forward Fuselage Structure

Structure

Windshield

Canopy

Auxiliary landing gear door

Inflight refueling probe dome

Radome

Equipment bay access door

Total Intermediate Fuselage Structure

Structure

Main landing gear door

Total Aft Fuselage Structure

Structure

Engine access doors

Weights, first-unit hours per pound, and cost quantity slopes are available at this level of detail. DC-10 data is under study. The 747 and F-5E data are expected to be made available from AFFDL ADP results. The possibility of obtaining C-141 and C-5 fuselage cost data from Air Force sources is also being investigated.

2.3.2 DERIVATION OF FIRST UNIT CER. A set of CERs similar in form to that use for aerodynamic surfaces is being developed for the fuselage. The structural synthesis program, at this stage of development, provides data for the calculation of weights and dimensions of the primary structure: namely skin panels, stringers, longerons, and frames. Weight data for secondary structure, which in the case of aerodynamic surfaces was synthesized by means of a special secondary structure synthesis procedure, will be estimated by means of the penalty method, Reference 21. Dimensional data will be available to the extent that it is generated as inputs necessary for the penalty method.

The hardware breakout afforded by the APAS program is less detailed for fuselages than for aerodynamic surfaces. It is expected to be somewhat as follows:

Primary Structure

Skins

Frames

Longerons (stringer)

---

21. H. L. Roland and R. E. Heben, "Aircraft Structural Weight-Estimating Methods," ERR-FW-242, General Dynamics/Fort Worth, 15 September 1966.

Secondary Structure

- Windows (including frames)
- Doors (including frames)
- Floors
- Other

The penalty effects to be considered will be:

- Cockpit pr[illegible]sions
- Nose landing gear door
- Nose landing gear load introduction
- Wing reaction body tie
- Tail provisions
- Windshield and canopy
- Main landing gear doors
- Main landing gear c/o load introduction
- Fuel provisions
- Engine provisions
- Duct provisions
- External stores provisions
- Speed brakes
- Cabin flooring and supports
- Cabin windows
- Doors

A breakout of detail fabrication, subassembly, and material cost will be accomplished. In the case of subassembly labor, consideration will be given to both weight and dimensional data as the cost-related variable.

2.3.3 <u>DEVELOPMENT OF COMPLEXITY FACTORS.</u> Complexity factor development will follow the same procedures as used for aerodynamic surfaces. A set of complexity factor tables is being developed, consisting of a table for each of the elements of primary and secondary structure called out above.

2.3.4 DEVELOPMENT OF BASELINE ESTIMATING COEFFICIENTS. Again, the aerodynamic surfaces procedures are applicable. One set of coefficients is required for each CER.

2.3.5 DEVELOPMENT OF FUSELAGE STRUCTURAL SYNTHESIS PROGRAM. This work has been completed in the form of the APAS program for multistation analysis. A finite element structural synthesis program is under independent development, but its use in the program will depend on a subsequent decision as to the improvement in method that it would offer against the cost of its adaption. Multistation approaches can be used to advantage in those structures that are relatively "clean" (i.e., smoothly varying cross sections with minor cutouts), typical of transport aircraft. In these cases, each of various fuselage stations are sized independently for various loading conditions with common geometric and manufacturing constraints. Programs with this procedure are usually very economical with simple input. The finite element approach is more adaptable to the sizing of structures having abrupt cross-sectional variations and large cutouts, such as occur in complex fighter, bomber, and cargo aircraft designs.

2.3.6 DEVELOPMENT OF WEIGHT ESTIMATING SUBROUTINES. Two separate subroutines for fuselage weight estimating are required. One is designed to use the output of the structural synthesis program to provide dimensional data for estimating the theoretical weight of the primary structure. The second is a subroutine to predict the weight associated with the body penalties as listed in section 2.3.2. Weight correlation factors are applied to the output of the first subroutine to arrive at an adjusted actual weight estimate. The second subroutine encompasses an empirical approach in which the correlation factor adjustment is not required.

A standard Convair Aerospace vehicle synthesis program is used as a driver for the structural synthesis program. The vehicle synthesis, or weight sizing, procedure enables the preliminary design analyst to define the general size and weight of an aerospace vehicle at the conceptual design stage using only generalized mission and performance requirements as inputs, and as more detailed design data becomes available, it allows the option of direct input with a resulting override of the internally generated data.

2.3.7 DEVELOPMENT OF COST ESTIMATING METHODOLOGY FOR NACELLES AND LANDING GEARS. These items are estimated using weight as the primary cost driver. First unit costs are estimated in the categories of detailed labor, subassembly labor, material cost, and quality control for the following structural elements:

Nacelles

Cowling

Pylon

Main landing gear door

Landing Gear

Brakes

Brake controls

Wheels

Tires

Oleos

Axles, trunnions, and fittings

Drag braces

Subroutines to predict the weight of the above elements are required. Cost estimating relationships will be developed in the following steps:

a. Collection of cost data.

b. Derivation of weight-related cost estimating relationships.

c. Development of factors to assess special features and requirements.

2.3.8 COMPUTER PROGRAMMING. The computer program will be extended to add the fuselage module. This requires integration with the structural synthesis program and the weight estimating subroutines and a simple modification of the cost program to fill in the details of the equations already blocked out in the existing cost program.

2.3.9 ESTIMATING TEST CASES. Three different fuselages will be run through the estimating procedure as preliminary demonstration cases: the B-58 representing a bomber, the AX as a fighter type, and a yet-to-be-selected transport fuselage. The latter selection is between the DC-10, C-141, and C-5A and is dependent primarily on data availability. Each of the test cases will be estimated in the categories shown in Figure 4. Estimates will be compared to actuals and the results analyzed.

2.4 TECHNIQUE UPDATE FOR CONSIDERATION OF COMPOSITES AND ADVANCED STRUCTURES

This phase of the study is scheduled to follow completion of the aerodynamic surface estimating techniques development. However, some work has been accomplished in advance of the schedule: Investigation of raw material and formed-parts cost of boron aluminum and boron epoxy, investigation of in-plant experimental hardware costs; and the estimation of the cost of an advanced fighter wing box in connection with AFFDL's Advanced Development Program.

The tasks to be performed as part of this activity consist of: (1) Development of cost estimating relationships to handle the added cost of selective reinforcements to basically metallic structures, (2) Development of complexity factors to handle advanced material and construction techniques, and (3) study to furnish projections of raw material costs for composite materials such as boron-aluminum, boron-epoxy, carbon and graphite-epoxy, and carbon and graphite-polyimide.

The trade study cost estimating method provides a means for handling the first two items above. The added cost of selective reinforcement is handled in the same way as the estimating of special structures and processes. The method is described in Reference 1, page 169, and is illustrated in appendix V of this same reference using the F-111 boron epoxy, experimental horizontal stabilizer as an example. The development of complexity factors to handle advanced materials and construction techniques can be accomplished within the existing CER framework. The steps outlined in Section 2.2.4.3 must be performed for each new material or structural concept, having conceptualized and depicted an adequate experimental hardware representation to support the analysis.

The third task has as its objective the development of a basis for projecting material costs of composite structure. The economics of composite material production will be briefly analyzed, and the opinions of experts in the field will be solicited to arrive at an updated projection of raw material and material processing costs. Reporting on the results of the boron aluminum and boron epoxy material cost investigation and the in-plant experimental hardware cost investigation will be deferred until the remainder of the study is completed. However, the third item of accomplishment, the estimation of cost for the referenced advanced fighter wing box, is of current interest in evaluating the capability of the trade-study cost estimating method.

Estimate for Advanced Fighter Wing Box. A cost estimate was completed and submitted to the Convair Aerospace Forth Worth operation for the upper and lower adhesive bonded honeycomb panel wing box structural design concept as defined by Convair Aerospace drawing No. 610 RW 004 "A". The estimating approach was based on the AFFDL cost estimating method for aerodynamic surfaces augmented by special processes supplementary CERs for adhesive bonding, for spar subassembly involving honeycomb spar webs, and for cover subassembly involving honeycomb skins. First-unit cost estimates were made in the following categories:

Manufacturing labor

- Detail fabrication
- Subassembly
- Box assembly

Material

- Structural
- Assembly

Quality Control

Cost-quantity progress curves based on Convair Aerospace Fort Worth operation experience on the F-111 were applied to first-unit costs to estimate recurring costs at the 506th unit. The same estimates were made by the Forth Worth operation using "grass-roots" estimating techniques. A comparison of the results of the two estimating processes is shown below:

	AFFDL Trade Study Estimating Technique	FWO Grass Roots Estimates
Manufacturing and QC labor	2,875 hrs	2,907 hrs
Material	$10,400	$11,284

2.5 DERIVATION OF OPERATING COST FIGURES-OF-MERIT RELATED TO BASIC STRUCTURE DESIGN

The previous study sought to identify interrelationships between alternative materials and/or types of construction, and certain operation and maintenance costs occurring during the life cycle of the weapon system. An analysis of operations and maintenance costs associated with total system or life cycle costs concluded that the following elements could be expected to vary with structural design changes:

Cost	Definition
Airframe Replenishment Spares	The continuing replenishment of spare parts for repair of aircraft structural components. Includes spare parts used for both base and depot maintenance activities.
POL	Petroleum, oil, and lubricants used for operational purposes during the operational life of a given aircraft weapon system.
Pay and Allowances	The cost of military and civilian personnel involved in base-level airframe maintenance activities. Excludes base operating support, squadron administrative personnel, and depot maintenance labor.
Depot Maintenance	The cost of depot maintenance labor involving aircraft structural components.

Each of these elements of cost if affected to some extend by structural design, and it would be desirable to have a way to measure the cost impact of design change. Items such as aircraft modifications, special kinds of maintenance, new item inventory cost, AGE, training equipment, and technical data are excluded because they must be individually analyzed for each weapon system.

The portion of spare and repair parts that relates to airframe structure is not large, but the cost is affected by the selection of materials and type of construction.

This effect shows up in the original cost of the spare part. Aggregate spare part cost is also affected by frequency of repair. Therefore, the measurement of relative costs for use in trade costing should include a measurement of changes in initial cost and removal rates.

Petroleum, oil, and lubricants used for operational purposes during the operational life of a given aircraft weapon system are affected by structural design. Improvements in structural efficiency that reduce the structural weight with a given range/ payload, and result in reduced gross takeoff weight, can be translated into reduced POL cost.

Pay and allowances constituting the cost of military and civilian personnel involved in base-level maintenance activities are reduced by reductions in maintenance requirements. Such savings should theoretically show up as reduced maintenance manhours per flight hour attributable to the structural subsystems of the aircraft through a reduced number of removals for repair.

Depot maintenance theoretically can be reduced by improvements to aircraft basic structure. Less frequent IRAN, less expensive parts, or less frequent removal for repairs are factors that could produce cost reductions.

To include these considerations in the trade costing methodology and to develop an estimating technique for these operating costs requires the derivation of appropriate CERs. This derivation proved to be beyond the scope of the previous study due to the lack of a detailed operating cost data breakdown. This lack means that the development of relationships is generally limited to an aggregate level of hardware indenture (generally the total aircraft).

For the effort proposed in the next phase of study, a restructuring of these costs into the following categories is proposed:

a. Airframe replenishment spares.
b. POL.
c. On-equipment maintenance.
d. Off-equipment maintenance.

These categories cover the same activities, but instead of distinguishing between depot and base maintenance, they distinguish between on-equipment and off-equipment maintenance. The revision provides a better basis for costing relationships.

For spares and off-equipment maintenance, which might be accomplished at either base or depot level, a relationship is to be developed between structural concept and structural element removal rate. Cost of the individual part removed is proportional to the production cost of the element. Removal rates will be in terms of removals per flight hour. Separate conversion factors will be developed for a fighter, a bomber, and a cargo example as an estimating analog.

For on-equipment maintenance, which is accomplished at the base level, a relationship will be developed between structural concept and maintenance manhours per flight hour. Individual maintenance factors will be developed for fighter, bomber, and cargo aircraft examples.

The fuel requirements for an aircraft are primarily a function of the type of mission flown, the characteristics of the propulsion system, the frequency of missions over the operating life, aerodynamic design, and structural efficiency; i.e., the ratio of structural weight to payload. An example of a trade effect might be a tradeoff between use of composites or other material to lighten and strengthen basic structure, which would result in a savings in basic structural weight for a constant range/payload, and which would in turn, result in a savings in POL.

The savings in weight may be translated to benefit or utility in a number of different ways. Therefore evaluation of the effects must be treated within the context of a tradeoff study. The contribution of cost estimation, together with structural sizing and weight estimation, is the costing of the alternative design concepts by the trade cost estimating method, augmented by system costing to measure and aggregate the impact of the smaller subsystems reflecting reduced structural weight.

The treatment of the above problems is scheduled for the phase of the study following the Interim Report. Limited study resources are to be applied so that figures of merit are available to give some consideration to this element in trade studies.

2.6 DEVELOPMENT OF THE AIRFRAME SYSTEM COST ESTIMATING METHOD

The system cost estimating method development is to be undertaken during the second phase of this study. Limited study resources have been assigned to this task, since it is planned to use cost estimating relationships and other results obtained from separately funded independent research.

Although primary emphasis is being given to trade study methodology development, the system costing method represents a significant capability.

The purpose of the system study cost estimating method is to accurately estimate total airframe costs for chosen designs, with airframe defined as including basic structure plus aircraft subsystems, as shown in Figure 23. It is designed to be complementary to the trade cost method. The maximum realization of this will occur when the trade cost method is fully developed. The complementation is achieved by means of a modular relationship between the methods. The system study method is designed as an estimating framework into which the available detailed trade study cost estimating modules are introduced as they are needed for a particular cost analysis.

Alternative sets of CERs will be available to provide estimating at optional levels of detail. These occur both within the context of the system costing method itself and by virtue of the modular relationship with the trade study method that provides the option of substituting its detailed procedures in the system costing framework. The system costing method is thus designed to achieve the following objectives:

a. By opting for the more aggregate CERs, which in turn require less detailed inputs, to provide an earlier (in relation to the predesign cycle) capability for cost estimating.

b. By including the aircraft subsystem estimating capability and providing for the option of including trade study modules to provide a more comprehensive costing capability.

c. By estimating at the airframe level to accomplish a more comprehensive comparison of estimates to actuals.

d. By providing an estimating capability in the absence of operational design synthesis programs, assuming alternative means of weight estimating is available, to provide an alternative mode of estimating.

2.7 TRADE STUDY APPLICATIONS

A series of brief studies is planned for the latter part of the program to accomplish the following objectives:

a. Interrelate the various computer programs used in the estimating methods so that the data transfer between each is identified, organized, and documented for the user's convenience.

b. Provide an outline describing the application of trade study procedure to preliminary design studies.

c. Develop a recommendation regarding the feasibility of applying interactive graphics to the cost-estimating method.

WORK BREAKDOWN STRUCTURE	TRADE STUDY COSTING	SYSTEM COSTING
AIRFRAME		
Wing	X	X
Horizontal Stabilizer	X	X
Vertical Stabilizer	X	X
Fuselage	X	X
Nacelles	X	X
Landing Gear	X	X
Surface Controls		X
Fuel System		X
Furnishings & Equipment		X
Environmental Control		X
Hydraulics/Pneumatics		X
Electrical/Electronics		X
Instruments		X
Auxiliary Power		X
Engine-Associated Equipment		X
Avionics Installation		X
Airframe Assembly	X	X

Figure 23. Trade Study versus Systems Costing WBS Inclusions

Integrated Computer Programming. A CDC 6400/6600 digital computer program written in Fortran IV has been developed for the aerodynamic surfaces cost estimating module. A minor modification will be required to include the fuselage module.

The APAS (Automated Program for Aerospace Vehicle Synthesis) program has been modified to include a weight estimating capability for both wings (except delta wings) and simple fuselages. The principal inputs to the APAS program are loads and geometry data. Figure 9 illustrates the main features of the APAS operational environment looked at from the standpoint of input sources. In defining supporting programs, it is necessary to apply an arbitrary cutoff; otherwise, the total design procedure is pulled into the picture.

A computer program for the synthesis of aerodynamic surfaces secondary structure has been developed. The initial program, which was used in the test cases, is being modified by the incorporation of geometry subroutines and by the incorporation of overlay procedures to reduce the program run time.

The relevant supporting programs will be operated in test cases and preliminary demonstrations and will be furnished to AFFDL in the form of Fortran source decks or tapes together with the user's guide. As stated in the introduction, a more complete description of the supporting programs is given in Volume II.

Outline for Trade Study Application to Preliminary Design Studies. Use of the integrated trade-system cost estimating method will be illustrated in examples of preliminary design study problems. The capability of the method in relation to typical problems will be illustrated as well as the interrelationship between the trade study and system costing methods.

Recommendation on Use of Interactive Graphics. The use of interactive graphics is intended to facilitate design tradeoff studies at the preliminary design level. It provides a way of putting the analyst "on-line" with the computer and may provide a way of simplifying the traditional, drawn-out process of effecting and evaluating input changes when using a computerized program. As part of this study, the feasibility of applying interactive graphics to the trade cost estimating method will be studied and a recommendation will be developed.

2.8 METHOD DEMONSTRATION

The method demonstration has a two-fold purpose: (1) To show the final results of estimating performed by the cost-estimating methods, and (2) To provide instruction and guidance in the use of the estimating program. Two examples will be estimated: a fighter example and either a bomber or a transport example. Test cases will be selected that are not part of the data base used in developing cost estimating relationships. The program will be demonstrated by installing the computer program on ASD's CDC 6600 computer at Wright-Patterson Air Force Base and running the selected test cases. The demonstration will include the instruction of interested AFFDL/ASD personnel in programming and execution. Test case cost estimates will be evaluated against available actuals.

2.9 COST TREND DATA

An addendum to the basic cost methodology research contract to examine available general cost trend data is the subject of this section. The development of cost trend data is divided into four general areas outlined as follows:

a. Plots of whole aircraft and/or AMPR structure costs versus various aeronautical design or performance parameters.

b. Plots of aircraft costs as a function of time or economic factors.

c. Pie-charts of aircraft development program costs as functions of quantity produced and aircraft system complexities.

d. Plots of structural cost versus weight for fuselage, wing and tail sections structures.

Each of these four areas is discussed below.

2.9.1 PARAMETRIC COST TREND CHARTS. The objective is to prepare plots of available parametric data to investigate general aircraft cost trends. Whole aircraft and aircraft structure costs are plotted against parameters such as gross takeoff weight, basic structure weight, speed, range, aircraft structural density, and maximum wing loading. Additional plots may be possible if more data are found describing aircraft "wetted" surface areas and maximum design aerodynamic pressure. Other plots involving combinations of parameters may be of interest.

Two examples of aircraft cost trend charts are presented to illustrate the approach being taken. In Figure 24 complete aircraft costs (including all system costs) per AMPR pounds are plotted against a maximum aircraft range in nautical miles.

AMPR weight is defined in the Aeronautical Manufacturer's Planning Report as "the empty weight of the airplane less (1) wheeels, brakes, tires and tubes, (2) engines, (3) starter, (4) cooling fluid, (5) rubber or nylon fuel cells, (6) instruments, (7) batteries and electrical power supply and conversion equipment, (8) electronic equipment (9) turret mechanism and power operated gun mounts, (10) remote fire mechanism and sighting and scanning equipment, (11) air conditioning units and fluid, (12) auxiliary power plant unit and (13) trapped fuel and oil." This weight concept may be referred to in current sources as "DCPR" weight, after the new Defense Contractor's Planning Report. It is seen that lower speed bomber costs per pound trend downward with increasing range, whereas the tactical (fighter, attack) costs per pound tend to increase with range.

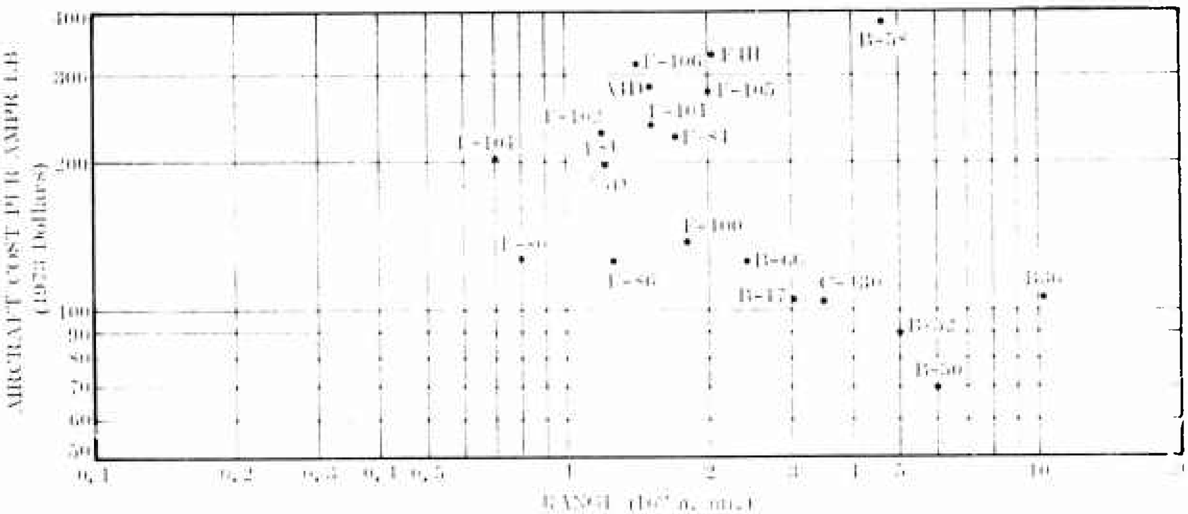


Figure 24. Aircraft Cost per AMPR Pound as a Function of Range

In Figure 25, the aircraft AMPR structure cost per pound trends upward as structural density increases.

2.9.2 <u>ECONOMIC FACTORS COST TREND CHARTS.</u> The objective here is to examine cost trend factors not directly related to aircraft design or performance parameters. These factors include the influence of time/inflation on aircraft costs and the increase in freight or passenger hauling efficiency with larger and faster aircraft.

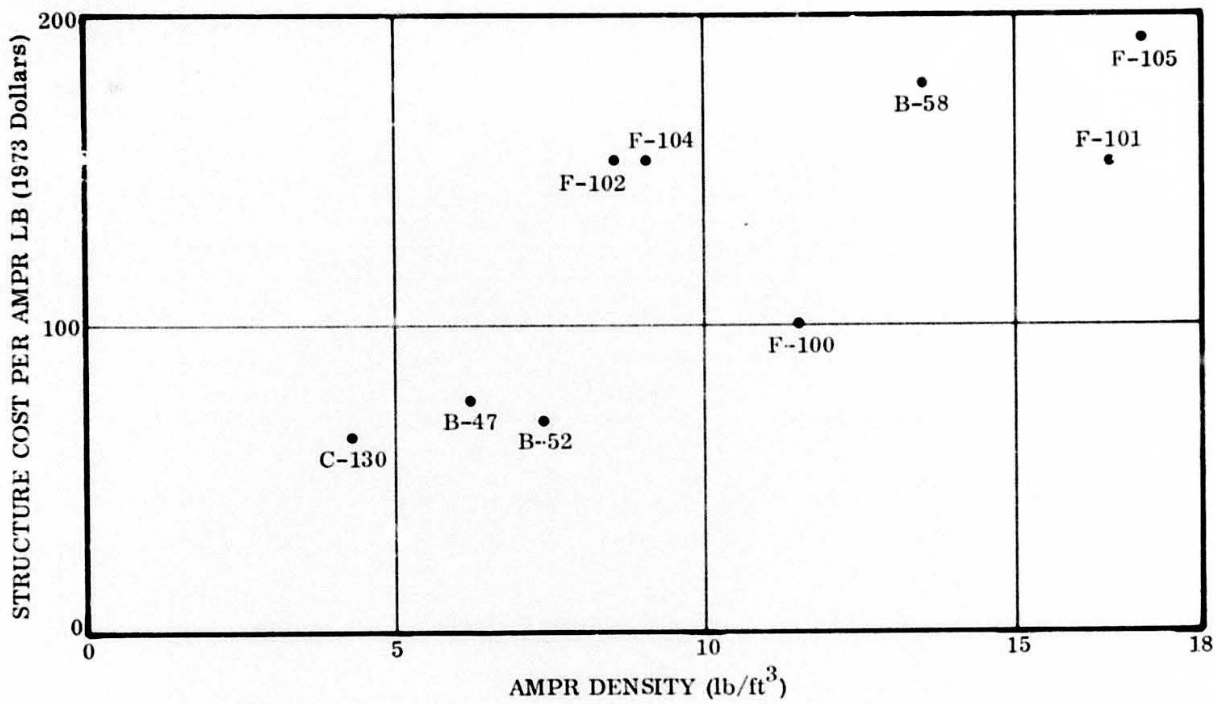


Figure 25. Structure Cost Per Pound Vs. Density

Figure 26 shows increasing aircraft costs since World War II. Overall aircraft costs are increasing due to increasing size, speed, and improved internal avionics and also due to inflation effects.

2.9.3 AIRCRAFT PROGRAM COSTS. Overall aircraft program costs are influenced by requirements to improve the state of the art, system complexities, and aircraft size, as well as the number of aircraft produced. If the development cost is prorated over the number of aircraft produced, development cost allocated to each aircraft is, of course, reduced the more aircraft produced. Secondly, the production cost per aircraft is reduced on a log-linear basis as more aircraft of like design are produced due to production cost/quantity effects.

These cost trend factors will be illustrated by a series of pie-charts for F-102, F-106, and B-58 aircraft. Figure 27 shows a 100 unit B-58 program as an illustration of the type of charts to be presented.

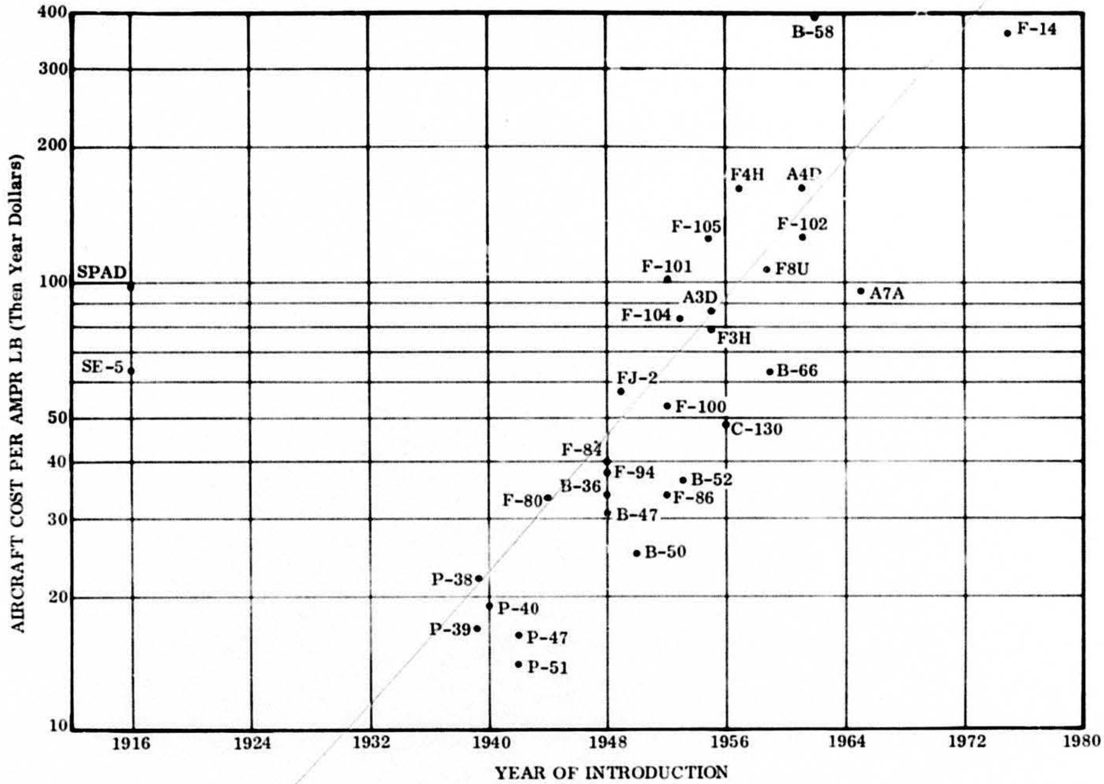
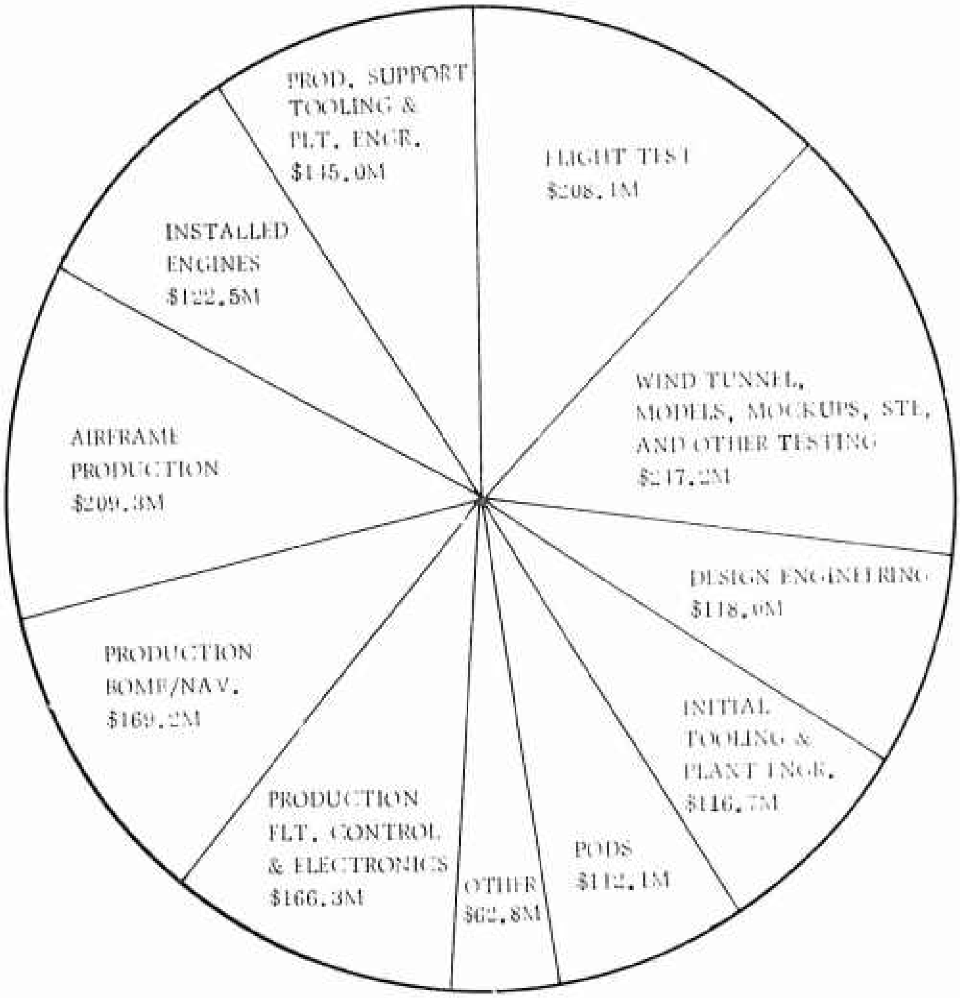


Figure 26. Aircraft Cost Per Pound Vs. Year of Introduction

2.9.4 STRUCTURE SUBASSEMBLY COSTS. This portion of the cost trend study examines available data describing costs of the major substructure assemblies; namely wings, fuselages, horizontal stabilizers and vertical stabilizers. It is desirable to collect cost data purely for structure and eliminate the parts of the various subsystems such as hydraulics, flight control, and instrumentation that are installed concurrently with the structure buildup. Unfortunately, only in those special cases where effort has been expended to subtract out such costs is something close to pure structure cost obtained. The data plotted for the listed structure subassemblies will be "cost center" data and will have varying adjustments based upon the particular description accompanying the data. Data from the F4H is used as the primary adjustment basis.

Figure 28 illustrates the type of plots to be produced, although the example is in hours per pound and therefore does not include material cost. Data will be presented as cumulative average costs for production quantities of 50 and 100 units as well as first unit costs.



NOTES TOTAL DOLLARS = $1677.7M

NONE OF THE FOLLOWING PROGRAM COSTS ARE INCLUDED ABOVE:

MODIFICATIONS	$171.0M
SPARES	12?.?M
AGE	161.?M
PERSONNEL SUBSYSTEMS	69.1M
OTHER	137.7M

AIRFRAME PRODUCTION INCLUDES $91.[illegible] FOR ASSEMBLY & CHECKOUT

Figure 27. B-58 Investment Cost Breakdown, 100 Aircraft Program

2.9.5 SUMMARY. The foregoing illustrates the types of plots and charts that are being prepared. Approximately 40 total figures are contemplated. The resulting collection of cost trend charts is expected to provide a quick overview of cost trends in the indicated areas. Other charts available to date appear in Volume III.

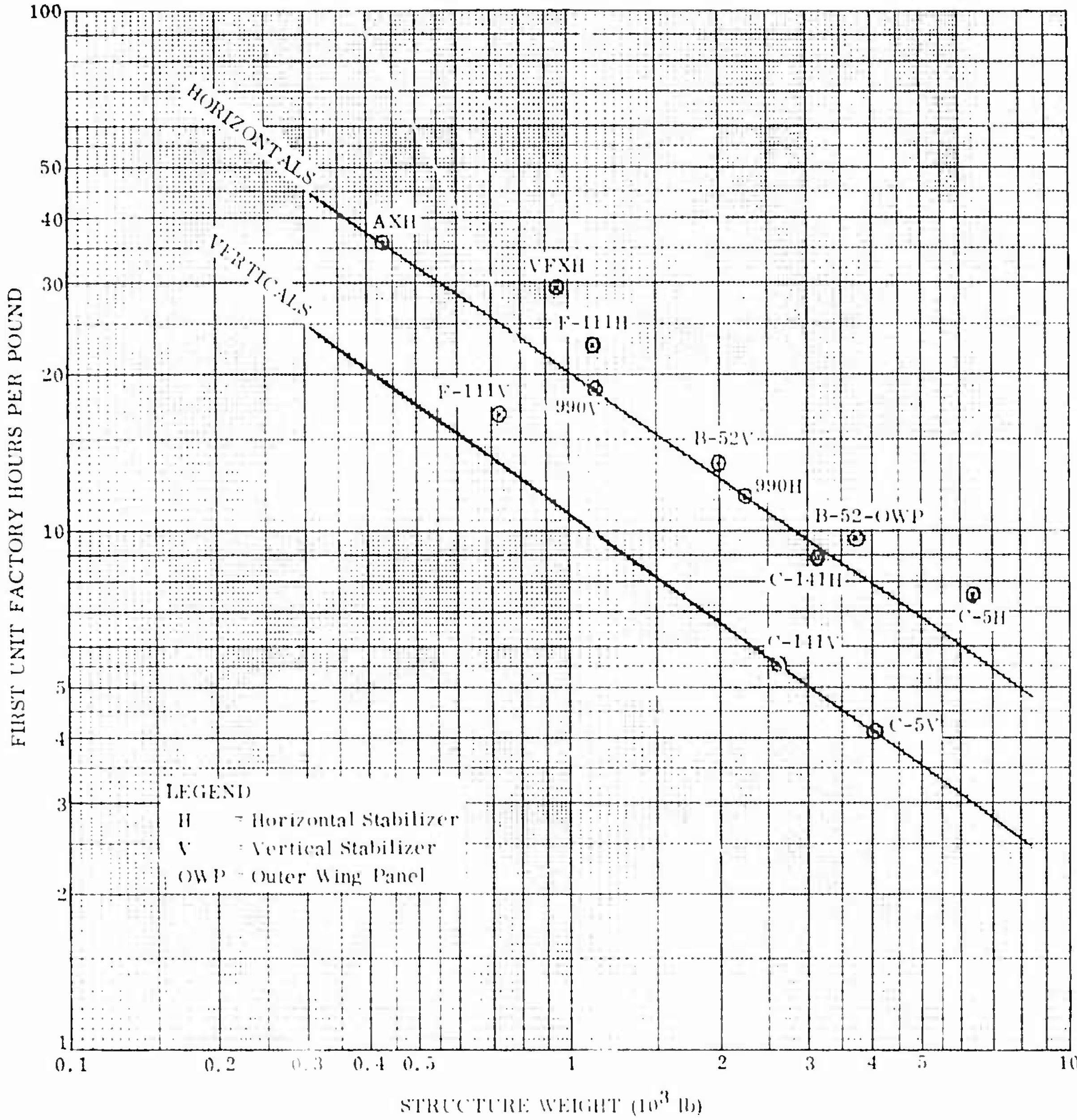


Figure 28. Horizontal Stabilizers, Vertical Stabilizers, and Outer Wing Panels (Factory Labor Hours per Pound)

SECTION 3

CONCLUSIONS AND RECOMMENDATIONS

1. The costing methodology, designed to systematically estimate cost variations due to changes in type of material and type of construction, has been successfully extended from the horizontal stabilizer to the remainder of the aerodynamic surfaces. Greater variation between estimated and actual values is observed in the test cases, but accuracy is expected to improve with further use.

2. Changes have been made in certain of the techniques of estimating. Of particular significance is the change in the CER for subassembly that substituted weight for specific dimensional characteristics as the cost-related variable and that eliminated the separate CER for center-section assembly and center-to-cap assembly. Further investigation of this change and its effect on estimating accuracy is needed.

3. Providing a capability for estimating alternative production quantities to the first unit cost breakout and level of detail is considered to be a desirable feature. It is being investigated for possible incorporation.

4. In addition to the above, the following features merit evaluation for possible incorporation in the estimating method:

   a. The use of individual cost-quantity projections by structural element within the fabrication, subassembly, and material cost categories.

   b. Inclusion of an additional term in certain CERs to give consideration to internal structural commonality.

   c. Consideration of taper in the machining of parts in the development of complexity factors.

Each of these features would add to the flexibility, responsiveness, and accuracy of the estimating method.

5. Considering their present stage of development, the multistation and finite element structural synthesis programs should not be considered as interchangeable options. Rather each has its place. If the structural analysis can be accomplished by the multistation procedures, it should be opted for. The complexity of the structure may dictate the use of the finite element analysis, however, in which case it becomes necessary as a means of augmenting the multistation procedure.

6. Estimating the cost of contemporary and future aircraft designs generally involves consideration of advanced types of construction and material. The method of detailed estimating entailed in the trade study method provides an approach to this problem. The detailed hardware breakout is suited to the evaluation of individual problem areas that can not be accomplished by the normal parametric means.

7. Similar considerations as described in paragraph six above apply to the problem of providing cost data as a design parameter in the problem of designing to a given cost. Detail designs can be analyzed for production cost in an iterative fashion, given the availability of the necessary supporting synthesis programs.

8. The detailed estimating procedure described provides a way of formulating complexity factors that can be used in the quick reaction estimating method at the subsystem level of detail. These are synthesized values but are validated by calibration against historical data as it is accumulated.

APPENDIX A

TYPES OF MATERIAL AND CONSTRUCTION TECHNIQUES — AERODYNAMIC SURFACES

The aerodynamic surfaces of the aircraft indicated have been analyzed to determine the types of construction and material represented thereby. This analysis shows the limited number of variations in structural concepts represented in actual experience and illustrates that cost data would be lacking for some concepts even if a complete cost data reconstruction was possible and affordable. This argument forms a part of the basis for the conclusion that the derived cost estimating methods must necessarily be based on methods other than statistical. The results are shown in Table A-1.

Table A-1. Types of Material and Construction Techniques — Aerodynamic Surfaces

	Wing: Ribs	Wing: Spars	Wing: Covers	Wing: Secondary Structure	Horizontal: Ribs	Horizontal: Spars	Horizontal: Covers	Horizontal: Secondary Structure
F-111								
Construction	Integral Web Stiffener	Integral Web Stiffener	Machined Plate		Honeycomb Core	Integral Web Stiffener	Machined Plate	
Material	Aluminum	Aluminum	Aluminum	Aluminum	Aluminum	Aluminum	Aluminum	Aluminum
A-X								
Construction	Built Up Web Stiffener	Built Up Web Stiffener	Built Up Skin Stringer		Built Up Web Stiffener	Built Up Web Stiffener	Sheet	
Material	Aluminum	Aluminum	Aluminum	Aluminum	Aluminum	Aluminum	Aluminum	Aluminum
C-141								
Construction					Built Up and Integral Truss	Built Up Web Stiffener	Built Up Skin Stringer	
Material					Aluminum	Aluminum	Aluminum	Aluminum
C-5A								
Construction					Built Up Truss	Built Up Web Stiffener	Integral Skin Stringer	
Material					Aluminum	Aluminum	Aluminum	Aluminum
VSX								
Construction	Built Up Truss	Built Up Web Stiffener	Built Up Skin Stringer		Built Up Web Stiffener	Built Up Web Stiffener	Sheet	
Material	Aluminum	Aluminum	Aluminum	Aluminum	Aluminum	Aluminum	Aluminum	Aluminum
VFX								
Construction	Integral Web Stiffener	Integral Web Stiffener	Machined Plate	L. E. & T. E. Fiberglass Slats, Flaps	Sheet Web	Sheet Web	Integral Skin Stringer	T. E. & L. E. Aluminum Fiberglass F. D. Core Sand.
Material	Titanium	Titanium	Titanium	Spoilers, Alum. Skin F. D. Core Sandwich, Phenolic	Titanium	Titanium and Aluminum	Titanium and Aluminum	Tip Boron Epoxy F. D. Core Sandwich
B-52 Outer Wing Panel								
Construction	Built Up Web Stiffener	Built Up Truss	Machined Plate					
Material	Aluminum	Aluminum	Aluminum	Aluminum				

TYPES OF MATERIAL AND CONSTRUCTION TECHNIQUES
AERODYNAMIC SURFACES

	Vertical			Secondary Structure
F-111	Ribs	Spars	Covers	
Construction	Integral Web Stiffener and Integral Truss	Integral Web Stiffener	Machined Plate	
Material	Aluminum	Aluminum	Aluminum	Aluminum
A-X				
Construction	Built Up Web Stiffener	Built Up Web Stiffener	Sheet	
Material	Aluminum	Aluminum	Aluminum	Aluminum
C-141				
Construction	Built Up and Integral Truss	Built Up and Integral Truss Sheet Web	Built Up Skin Stringer	
Material	Aluminum	Aluminum	Aluminum	Aluminum
C 5				
Construction	Built Up Truss	Built Up Web Stiffener	Integral Skin Stringer	
Material	Aluminum	Aluminum	Aluminum	Aluminum
VSX				
Construction	Built Up Web Stiffener	Built Up Web Stiffener	Sheet	
Material	Aluminum	Aluminum	Aluminum	
VFX				
Construction	Sheet Web	Forgings	Machined Plate	L. E., Rudder
Material	Aluminum	Titanium	Titanium & Aluminum	Aluminum Built Up Web Stiffener

FORM 73 1 (REV 6 61)

TYPES OF MATERIAL AND CONSTRUCTION TECHNIQUES
AERODYNAMIC SURFACES

	Wing			Secondary Structure	Horizontal			Secondary Structure
	Ribs	Spars	Covers		Ribs	Spars	Covers	
880								
Construction	Built Up Truss	Built Up Web Stiffener	Built Up Skin Stringer		Built Up Truss	Built Up Web Stiffener	Built Up Skin Stringer	
Material	Aluminum	Aluminum	Aluminum	Aluminum	Aluminum	Aluminum	Aluminum	Aluminum
990								
Construction	Built Up Truss	Built Up Web Stiffener	Built Up Skin Stringer		Built Up Truss	Built Up Web Stiffener	Built Up Skin Stringer	
Material	Aluminum	Aluminum	Aluminum	Aluminum	Aluminum	Aluminum	Aluminum	Aluminum

FORM 73 1 (REV 6 61)

TYPES OF MATERIAL AND CONSTRUCTION TECHNIQUES
AERODYNAMIC SURFACES

	Vertical			Secondary Structure
880	Ribs	Spars	Covers	
Construction	Built Up	Built Up Web	Built Up Skin	
	Truss	Stiffener	Stringer	
Material	Aluminum	Aluminum	Aluminum	Aluminum
990				
Construction	Built Up	Built Up Web	Built Up Skin	
	Truss	Stiffener	Stringer	
Material	Aluminum	Aluminum	Aluminum	Aluminum

APPENDIX B

CERs FOR TRADE STUDY COST ESTIMATING METHOD

The cost estimating relationships described herein comprise the basic trade study cost estimating method as expanded to cover all aerodynamic surface components. Following the list of first unit CERs is a dictionary that relates an initial version of the CER formulation to the CER as it appears in the computer program. Use of this dictionary eliminates the need for a continuous retyping of the original list. These changes involve only the symbology and not the basic of formulations. The final form will be retyped once the method is fixed. CERs are shown for nonrecurring, first unit, and recurring costs.

NONRECURRING DESIGN AND DEVELOPMENT COSTS

Nonrecurring design and development CERs are summarized below, followed by detailed CERs.

NONRECURRING DESIGN AND DEVELOPMENT COSTS

	Empennage Hours	Wing Hours	Fusclage Hours	Nacelle Hours	Subtotal Hours	Dollar Costs
Basic Structure Design Engrg. Hrs.	$Y_1 = a_1 x_1^{b_1}$	$Y_2 = a_2 x_2^{b_2}$	$Y_3 = a_3 x_3^{b_3}$	$Y_4 = a_4 x_4^{b_4}$	$Y_T = Y_1 + Y_2 + Y_3 + Y_4$	-
Configuration Design Engrg. Hrs.					$Y_T F = EH$	E_C
Engineering Material					-	E_M
Total Trade Study Engineering Hrs.					-	$E_C + E_M$

	Horizontal Stabilizer	Vertical Stabilizer	Wing	Fuselage	Nacelle	Sub-Total	Dollar Costs
Basic Tool Mfg. Hours	T_1	T_2	T_3	T_4	T_5	T_T	-
Rate Tooling Mfg. Hours						T_r	-
Total Tool Mfg. Hours						T_R	T_{RC}
Basic Tool Engrg. Hours						T_{EB}	-
Rate Tool Engrg. Hours						T_{ER}	-
Total Tool Engrg. Hours						T_{ET}	T_{oc}
Mfg. Devel. and Plant Engrg. Hours						T_{MD}	T_{MDC}
Tooling Mat'l. and Other Dollars						-	T_{MC}
Manufacturing Support Dollars						-	M_{ES}
Quality Control Hours						QC_H	QC_C

ENGINEERING DIRECT LABOR HOURS

$$EH = Y_T F_i$$

where:

EH = Number of engineering direct labor hours

F_1 = Factor for configuration design engineering

$Y_T = Y_1 + Y_2 + Y_3 + Y_4 + \ldots Y_n$

Y_1 = Engineering hours for empennage

Y_2 = Engineering hours for wing

Y_3 = Engineering hours for fuselage

Y_4 = Engineering hours for nacelle

and

$Y_i = a_i (W_i)^{b_i}$, which is the CER form for engineering labor hours for the elements of basic structure.

W = AMPR weight of the structural element

a = Engineering hours at $W = 1$ lb

b = Scaling of hours to AMPR weight

ENGINEERING DIRECT LABOR COSTS

$$E_C = (EH)(ECLR)$$

where

E_C = Engineering direct labor cost

$ECLR$ = Engineering composite labor rate

ENGINEERING MATERIAL AND OTHER COST

$$E_M = (E_C)(F_2)$$

where

E_M = Engineering material and other cost

F_2 = Percentage factor of engineering labor cost

BASIC TOOL MANUFACTURING HOURS

$$T_i = CMT_i \, (W_{A_i})^C$$

where

T_i = Basic tool manufacturing hours by basic structure component.

CMT_i = Tooling complexity factor by component

W_{A_i} = AMPR weight in pounds by component

C = Scaling of tooling hours by AMPR weight

T_1 = Basic Tool Mfg. Hours for Horizontal Stabilizer

T_2 = Basic Tool Mfg. Hours for Vertical Stabilizer

T_3 = Basic Tool Mfg. Hours for Wing

T_4 = Basic Tool Mfg. Hours for Fuselage

T_5 = Basic Tool Mfg. Hours for Nacelle

$$T_T = T_1 + T_2 + T_3 + T_4 + T_5 \ldots T_n$$

RATE TOOL MANUFACTURING HOURS

$$T_r = T_T \, (T^B - 1)$$

where

T_r = Additional hours required for rate tooling

T = Assumed monthly production rate

B = Tool production rate scaling exponent

TOTAL TOOL MANUFACTURING HOURS

$$T_R = T_T T^B$$

where

T_R = Tool manufacturing hours for a given production rate

BASIC TOOL ENGINEERING HOURS

$$T_{EB} = F_3 (T_T)$$

where

T_{EB} = Basic tool engineering hours

F_3 = Percentage factor of basic tool manufacturing hours

RATE TOOL ENGINEERING HOURS

$$T_{ER} = F_4 (T_r)$$

where

T_{ER} = Rate tool engineering hours

F_4 = Percentage factor of rate tool engineering hours

TOTAL TOOL ENGINEERING HOURS

$$T_{ET} = T_{EB} + T_{ER}$$

MFG. DEVEL. AND PLANT ENGRG. HOURS

$$T_{MD} = F_5 (T_R)$$

where

T_{MD} = Mfg. Devel. and Plant Engrg. Hours

F_5 = Percentage factor of mfg. devel. and plant engrg. hours

TOOL MANUFACTURING DIRECT LABOR COSTS

$$T_{RC} = T_R (T_{HC})$$

where

T_{RC} = Tool manufacturing direct labor costs

T_{HC} = Tool manufacturing labor cost per hour

TOOL ENGINEERING DIRECT LABOR COST

$$T_{OC} = T_{ET} (T_{EC})$$

where

T_{OC} = Tool Engineering direct labor cost

T_{EC} = Tool Engineering labor cost per hour

MFG. DEVEL. AND PLANT ENGRG. DIRECT LABOR COST

$$T_{MDC} = T_{MD} (T_{DC})$$

where

T_{MDC} = Mfg. Devel. and Plant Engrg. direct labor costs

T_{DC} = Composite labor cost for mfg. devel. and plant engrg.

TOOLING MATERIAL AND OTHER

$$T_{MC} = T_R (F_6)$$

where

T_{MC} = Tooling material and other costs

F_6 = Tooling material support factor ($/hr)

MANUFACTURING SUPPORT COSTS

$$M_{ES} = E_C (F_7)$$

where

M_{ES} = Manufacturing support cost for support to engineering during development

F_7 = Development support factor, % of E_C

QUALITY CONTROL DIRECT LABOR HOURS

$$QC_H = (EH)(F_8) + (T_R)(F_9)$$

where

QC_H = Quality Control direct labor hours

F_8 = Percentage of engineering direct labor hours

F_9 = Percentage of tool manufacturing direct labor hours

QUALITY CONTROL DIRECT LABOR COST

$$QC_C = QC_H (R_{QC})$$

where

QC_C = Quality Control dollar cost

R_{QC} = Composite quality control labor rate

FIRST UNIT CERs

A summary of Wing CERs is given below as an illustration of the first unit CER structure used. A similar structure is used for the horizontal stabilizer and the vertical stabilizer.

WING CER FORMULATION

Primary Structure:

- Box Detail Fabrication
  - Ribs
  - Spars
  - Covers
- Subassembly
  - Ribs
  - Spars
  - Covers
- Box Assembly
- Secondary Structure Detail Fabrication and Subassembly
  - Leading Edge
  - Trailing Edge
  - Ailerons
  - Fairings
  - Tips
  - Spoilers
  - Flaps and Flaperons
  - Attachment Structure
  - Access Doors, Frames and Landing Gear Doors
  - Wing Mounted Air Induction
  - High Lift Ducting
  - Slats
  - Hinges, Brackets and Seals
  - Pivots and Folds
  - Center Section
  - Other
- Wing Assembly

Wing

Box Detail Fabrication

Ribs

$$WH_1 = \frac{WW_1 CF_1 + WW_2 CF_2 + WW_3 CF_3}{WW_T} \left(WH_{F1}\right) \left(WW_T\right)^{E_1} \qquad \text{Equa. (1)}$$

where WH_1 = wing detail part fabrication direct labor hours for ribs

WW_1 = wing weight of ribs with complexity of CF_1

CF_1 = complexity factor for given material and construction technique

WW_2 = wing weight of ribs with complexity factor of CF_2

CF_2 = complexity factor for given material and construction technique

WW_3 = wing weight of ribs with complexity factor of CF_3

CF_3 = complexity factor for given material and construction technique

$WW_T = WW_1 + WW_2 + WW_3$

WH_{F1} = fabrication hours per pound for baseline wing ribs

E_1 = weight scaling exponent

Horizontal

Box Detail Fabrication

Ribs

$$HH_1 = \frac{HW_1 CF_4 + HW_2 CF_5 + HW_3 CF_6}{HW_T} \left(HH_{F1}\right)\left(HW_T\right)^{E_2} \qquad \text{Equa. (2)}$$

where HH_1 = horizontal detail part fabrication direct labor hours for ribs

HW_1 = horizontal weight of ribs with complexity of CF_4

CF_4 = complexity factor for given material and construction technique

HW_2 = horizontal weight of ribs with complexity factor of CF_5

CF_5 = complexity factor for given material and construction technique

HW_3 = horizontal weight of ribs with complexity factor of CF_6

CF_6 = complexity factor for given material and construction technique

$HW_T = HW_1 + HW_2 + HW_3$

HH_{F1} = fabrication hours per pound for baseline horizontal ribs

E_2 = weight scaling exponent

VERTICAL

Box Detail Fabrication

Ribs

$$VH_1 = \frac{VW_1 CF_7 + VW_2 CF_8 + VW_3 CF_9}{VW_T} \left(VH_{F1}\right) \left(VW_T\right)^{E_3} \qquad \text{Equa. (3)}$$

where

VH_1 = vertical detail part fabrication direct labor hours for ribs

VW_1 = vertical weight of ribs with complexity of CF_7

CF_7 = complexity factor for given material and construction technique

VW_2 = vertical weight of ribs with complexity of CF_8

CF_8 = complexity factor for given material and construction techniques

VW_3 = vertical weight of ribs with complexity of CF_9

CF_9 = complexity factor for given material and construction technique

VW_T = $VW_1 + VW_2 + VW_3$

VH_{F1} = fabrication hours per pound for baseline vertical ribs

E_3 = weight scaling e[illegible]nt

WING

Box Detail Fabrication

Spars

$$WH_2 = \frac{WW_4 CF_{10} + WW_5 CF_{11} + WW_6 CF_{12}}{WW_{T1}} \left(WH_{F2}\right) \left(WW_{T1}\right)^{E_4}$$

Equa. (4)

where

WH_2 = wing detail part fabrication direct labor hours for spars

WW_4 = wing weight of spars with complexity of CF_{10}

CF_{10} = complexity factor for given material and construction technique

WW_5 = wing weight of spars with complexity of CF_{11}

CF_{11} = complexity factor for given material and construction technique

WW_6 = wing weight of spars with complexity of CF_{12}

CF_{12} = complexity factor for given material and construction technique

WW_{T1} = $WW_4 + WW_5 + WW_6$

WH_{F2} = fabrication hours per pound for baseline wing spars

E_4 = weight scaling exponent

HORIZONTAL

Box Detail Fabrication

Spars

$$HH_2 = \frac{HW_4CF_{13} + HW_5CF_{14} + HW_6CF_{15}}{HW_{T1}} \left(HH_{F2}\right) \left(HW_{T1}\right)^{E_5}$$

Equa. (5)

where

HH_2 = horizontal detail part fabrication direct labor hours for spars

HW_4 = horizontal weight of spars with complexity of CF_1

CF_{13} = complexity factor for given material and construction technique

HW_5 = horizontal weight of spars with complexity of CF_{14}

CF_{14} = complexity factor for given material and construction technique

HW_6 = horizontal weight of spars with complexity of CF_{15}

CF_{15} = complexity factor for given material and construction technique

HW_{T1} = $HW_4 + HW_5 + HW_6$

HH_{F2} = fabrication hours per pound for baseline horizontal spars

E_5 = weight scaling exponent

Vertical

Box Detail Fabrication

Spars

$$VH_2 = \frac{VW_4 CF_{16} + VW_5 CF_{17} + VW_6 CF_{18}}{VW_{T1}} \left(VH_{F2}\right)\left(VW_{T1}\right)^{E_6} \qquad \text{Equa. (6)}$$

where VH_2 = vertical detail part fabrication direct labor hours for ribs

VW_4 = vertical weight of spars with complexity of CF_{16}

CF_{16} = complexity factor for given material and construction technique

VW_5 = vertical weight of spars with complexity of CF_{17}

CF_{17} = complexity factor for given material and construction technique

VW_6 = Vertical weight of spars with complexity of CF_{18}

CF_{18} = complexity factor for given material and construction technique

VW_{T1} = $VW_4 + VW_5 + VW_6$

VH_{F2} = fabrication hours per pound for baseline vertical spars

E_6 = weight scaling exponent

Wing

Box Detail Fabrication

Covers

$$WH_3 = \frac{WW_7 CF_{19} + WW_8 CF_{20} + WW_9 CF_{21}}{WW_{T2}} \left(WH_{F3} \right) \left(WW_{T2} \right)^{E_7}$$

Equa. (7)

where WH_3 = wing detail part fabrication direct labor hours for covers

WW_7 = wing weight of covers with complexity of CF_{19}

CF_{19} = complexity factor for given material and construction technique

WW_8 = wing weight of covers with complexity of CF_{20}

CF_{20} = complexity factor for given material and construction technique

WW_9 = wing weight of covers with complexity of CF_{21}

CF_{21} = complexity factor for given material and construction technique

$WW_{T2} = WW_7 + WW_8 + WW_9$

WH_{F3} = fabrication hours per pound for baseline wing covers

E_7 = weight scaling exponent

Horizontal

Box Detail Fabrication

Covers

$$HH_3 = \frac{HW_7 CF_{22} + HW_8 CF_{23} + HW_9 CF_{24}}{HW_{T2}} \left(HH_{F3}\right)\left(HW_{T2}\right)^{E_8} \qquad \text{Equa. (8)}$$

where HH_3 = horizontal detail part fabrication direct labor hours for covers

HW_7 = horizontal weight of covers with complexity of CF_{22}

CF_{22} = complexity factor for given material and construction technique

HW_8 = horizontal weight of covers with complexity of CF_{23}

CF_{23} = complexity factor for given material and construction technique

HW_9 = horizontal weight of covers with complexity of CF_{24}

CF_{24} = complexity factor for given material and construction technique

$HW_{T2} = HW_7 + HW_8 + HW_9$

HH_{F3} = fabrication hours per pound for baseline horizontal covers

E_8 = weight scaling exponent

Vertical

Box Detail Fabrication

Covers

$$VH_3 = \frac{VW_7 CF_{25} + VW_8 CF_{26} + VW_9 CF_{27}}{VW_{T2}} \left(VH_{F3}\right)\left(VW_{T2}\right)^{E_9} \qquad \text{Equa. (9)}$$

where VH_3 = vertical detail part fabrication direct labor hours for covers

VW_7 = vertical weight of covers with complexity of CF_{25}

CF_{25} = complexity factor for given material and construction technique

VW_8 = vertical weight of covers with complexity of CF_{26}

CF_{26} = complexity factor for given material and construction technique

WW_9 = vertical weight of covers with complexity of CF_{27}

CF_{27} = complexity factor for given material and construction technique

$VW_{T2} = VW_7 + VW_8 + VW_9$

VH_{F3} = fabrication hours per pound for baseline vertical covers

E_9 = weight scaling exponent

WING

Ribs

Subassembly

$$WH_4 = \frac{WW_1 CM_1 + WW_2 CM_2 + WW_3 CM_3}{WW_T} (WH_{F4}) (WW_T)^{E_{10}} \qquad \text{Equa. (10)}$$

where WH_4 = wing subassembly direct labor hours for ribs

WW_1 = wing weight of ribs with complexity of CM_1

CM_1 = complexity factor for given material and construction technique

WW_2 = wing weight of ribs with complexity factor of CM_2

CM_2 = complexity factor for given material and construction technique

WW_3 = wing weight of ribs with complexity factor of CM_3

CM_3 = complexity factor for given material and construction technique

WW_T = $WW_1 + WW_2 + WW_3$

WH_{F4} = subassembly hours per pound for baseline wing ribs

E_{10} = weight scaling exponent

HORIZONTAL

Ribs

Subassembly

$$HH_4 = \frac{HW_1 CM_4 + HW_2 CM_5 + HW_3 CM_6}{HW_T} (HH_{F4}) (HW_T)^{E_{11}} \qquad \text{Equa. (11)}$$

where HH_4 = horizontal subassembly direct labor hours for ribs

HW_1 = horizontal weight of ribs with complexity of CM_4

CM_4 = complexity factor for given material and construction technique

HW_2 = horizontal weight of ribs with complexity of CM_5

CM_5 = complexity factor for given material and construction technique

HW_3 = horizontal weight of ribs with complexity factor of CM_6

CM_6 = complexity factor for given material and construction technique

HW_T = $HW_1 + HW_2 + HW_3$

HH_{F4} = subassembly hours per pound for baseline horizontal ribs

E_{11} = weight scaling exponent

VERTICAL

Ribs

Subassembly

$$VH_4 = \frac{VW_1CM_7 + VW_2CM_8 + VW_3CM_9}{VW_T}(VH_{F4})(VW_T)^{E_{12}} \qquad \text{Equa. (12)}$$

where VH_4 = vertical subassembly direct labor hours for ribs

VW_1 = vertical weight of ribs with complexity of CM_7

CM_7 = complexity factor for given material and construction technique

VW_2 = vertical weight of ribs with complexity of CM_8

CM_8 = complexity factor for given material and construction technique

VW_3 = vertical weight of ribs with complexity of CM_9

CM_9 = complexity factor for given material and construction technique

VW_T = $VW_1 + VW_2 + VW_3$

VH_{F4} = subassembly hours per pound for baseline vertical ribs

E_{12} = weight scaling exponent

WING

Spars

Subassembly

$$WH_5 = \frac{WW_4 + CM_{10} + WW_5 CM_{11} + WW_6 CM_{12}}{WW_{T1}} (WH_{F5}) (WW_{T1})^{E_{13}} \qquad \text{Equa. (13)}$$

where WH_5 = wing subassembly direct labor hours for spars

WW_4 = wing weight of spars with complexity of CM_{10}

CM_{10} = complexity factor for given material and construction technique

WW_5 = wing weight of spars with complexity of CM_{11}

CM_{11} = complexity factor for given material and construction technique

WW_6 = wing weight of spars with complexity of CM_{12}

CM_{12} = complexity factor for given material and construction technique

WW_{T1} = $WW_4 + WW_5 + WW_6$

WH_{F5} = subassembly hours per pound for baseline wing spars

E_{13} = weight scaling exponent

HORIZONTAL

Spars

Subassembly

$$HH_5 = \frac{HW_4 CM_{13} + HW_5 CM_{14} + HW_6 CM_{15}}{HW_{T1}} (HH_{F5}) (HW_{T1})^{E_{14}} \qquad \text{Equa. (14)}$$

where HH_5 = horizontal subassembly direct labor hours for spars

HW_4 = horizontal weight of spars with complexity of CM_{13}

CM_{13} = complexity factor for given material and construction technique

HW_5 = horizontal weight of spars with complexity of CM_{14}

CM_{14} = complexity factor for given material and construction technique

HW_6 = horizontal weight of spars with complexity of CM_{15}

CM_{15} = complexity factor for given material and construction technique

HW_{T1} = $HW_4 + HW_5 + HW_6$

HH_{F5} = subassembly hours per pound for baseline horizontal spars

E_{14} = weight scaling exponent

VERTICAL

Spars

Subassembly

$$VH_5 = \frac{VW_4 CM_{16} + VW_5 CM_{17} + VW_6 CM_{18}}{VW_{T1}} (VH_{F5}) (VW_{T1})^{E_{15}} \qquad \text{Equa. (15)}$$

where VH_5 = vertical subassembly direct labor hours for spars

VW_4 = vertical weight of spars with complexity of CM_{16}

CM_{16} = complexity factor for given material and construction technique

VW_5 = vertical weight of spars with complexity of CM_{17}

CM_{17} = complexity factor for given material and construction technique

VW_6 = vertical weight of spars with complexity of CM_{18}

CM_{18} = complexity factor for given material and construction technique

VW_{T1} = $VW_4 + VW_5 + VW_6$

VH_{F5} = subassembly hours per pound for baseline vertical spars

E_{15} = weight scaling exponent

Covers

Subassembly

$$WH_6 = \frac{WW_7 CM_{19} + WW_8 CM_{20} + WW_9 CM_{21}}{WW_{T2}} (WH_{F6}) (WW_{T2})^{E_{16}} \qquad \text{Equa. (16)}$$

where WH_6 = wing subassembly direct labor hours for covers

WW_7 = wing weight of covers with complexity of CM_{19}

CM_{19} = complexity factor for given material and construction technique

WW_8 = wing weight of covers with complexity of CM_{20}

CM_{20} = complexity factor for given material and construction technique

WW_9 = wing weight of covers with complexity of CM_{21}

CM_{21} = complexity factor for given material and construction technique

WW_{T2} = $WW_7 + WW_8 + WW_9$

WH_{F6} = subassembly hours per pound for baseline wing covers

E_{16} = weight scaling exponent

HORIZONTAL

Covers

Subassembly

$$HH_6 = \frac{HW_7 CM_{22} + HW_8 CM_{23} + HW_9 CM_{24}}{HW_{T2}} (HH_{F6}) (HW_{T2})^{E_{17}} \qquad \text{Equa. (17)}$$

where HH_6 = horizontal subassembly direct labor hours for covers

HW_7 = horizontal weight of covers with complexity of CM_{22}

CM_{22} = complexity factor for given material and construction technique

HW_8 = horizontal weight of covers with complexity of CM_{23}

CM_{23} = complexity factor for given material and construction technique

HW_9 = horizontal weight of covers with complexity of CM_{24}

CM_{24} = complexity factor for given material and construction technique

HW_{T2} = $HW_7 + HW_8 + HW_9$

HH_{F6} = subassembly hours per pound for baseline horizontal covers

E_{17} = weight scaling exponent

VERTICAL

Covers

Subassembly

$$VH_6 = \frac{VW_7 CM_{25} + VW_8 CM_{26} + VW_9 CM_{27}}{VW_{T2}} (VH_{F6}) (VW_{T2})^{E_{18}} \qquad \text{Equa. (18)}$$

where VH_6 = vertical subassembly direct labor hours for covers

VW_7 = vertical weight of covers with complexity of CM_{25}

CM_{25} = complexity factor for given material and construction technique

VW_8 = vertical weight of covers with complexity of CM_{26}

CM_{26} = complexity factor for given material and construction technique

VW_9 = vertical weight of covers with complexity of CM_{27}

CM_{27} = complexity factor for given material and construction technique

VW_{T2} = $VW_7 + VW_8 + VW_9$

VH_{F6} = subassembly hours per pound for baseline vertical covers

E_{18} = weight scaling exponent

Wing

Primary Box Assembly

Transportation and Positioning

$$WH_{12} = (WW_B)(WH_{SA1}) + \left[WH_{SA2}\,(C_N + R_N + S_{NE} + S_{NI})\right]^Q \qquad \text{Equa. (19)}$$

where WH_{12} = assembly hours for transporting and positioning

$WW_B = WW_1 + WW_2 + WW_3 + WW_4 + WW_5 + WW_6 + WW_7 + WW_8 + WW_9$

WW_1 = wing weight of ribs with complexity of CF_1

WW_2 = wing weight of ribs with complexity of CF_2

WW_3 = wing weight of ribs with complexity of CF_3

WW_4 = wing weight of spars with complexity of CF_{10}

WW_5 = wing weight of spars with complexity of CF_{11}

WW_6 = wing weight of spars with complexity of CF_{12}

WW_7 = wing weight of covers with complexity of CF_{19}

WW_8 = wing weight of covers with complexity of CF_{20}

WW_9 = wing weight of covers with complexity of CF_{21}

WH_{SA1} = assembly hours per unit weight for transporting and positioning

WH_{SA2} = assembly hours per subassembly for transporting and positioning

C_N = number of cover panels

R_N = number of ribs

S_{NE} = number of external spars

S_{NI} = number of internal spars

Q = quantity scaling factor

Panel Fit & Trim

$$WH_{13} = 2\,(S_{PE} + R_P)(H_T)(T_{J4})$$ Equa. (20)

where WH_{13} = hours for panel fit and trim

S_{PE} = average wing spar perimeter in feet

R_P = average wing rib perimeter in feet

H_T = hours per lineal foot for fit and trim

T_{J4} = joint thickness ratio $\frac{2T_S}{.04}$

T_S = average skin thickness

Assembly Clamp & Layout

$$WH_{14} = \left[(R_P)^R (R_N)^Q + (S_{PE})^R (S_{NE} + S_{NI})^Q\right] H_{LL}\,(2)$$ Equa. (21)

where WH_{14} = hours for assembly clamp and layout

R = size scaling exponent

H_{LL} = assembly hours per unit length for clamp and layout

Hole Drilling

$$WH_{15} = \left[(R_P)^R (R_N)^Q + (S_{PE})^R (S_{NE} + S_{NI})^Q\right] (H_D)(T_{J4})(2)$$ Equa. (22)

where WH_{15} = hours for hole drilling

H_D = drilling hours per foot

Finish Operations

$$WH_{16} = \left[(R_P)^R (R_N)^Q + (S_{PE})^R (S_{NE} + S_{NI})^Q\right] (H_E)(T_{J4})(FT_{22})(2)$$ Equa. (23)

where WH_{16} = hours for finishing operations

H_E = finish hours per unit length

FT_{22} = factor for fastener selection

Fastener Installation

$$WH_{17} = \left[(R_P)^R (R_N)^Q + (S_{PE})^R (S_{NE} + S_{NI})^Q \right] (H_{FI})(T_{J4})(FT_{23})(2) \qquad \text{Equa. (24)}$$

where WH_{17} = hours for fastener installation

H_{FI} = installation hours per foot for fastener installation

FT_{23} = factor for fastener selection

Horizontal

Primary Box Assembly

Transportation and Positioning

Equa. (25)

$$HH_{12} = (HW_B)(HH_{SA1}) + \left[HH_{SA2}\,(C_{N1} + R_{N1} + S_{NE1} + S_{NI1})^{Q_1}\right]2$$

where HH_{12} = assembly hours for transporting and positioning

$HW_B = HW_1 + HW_2 + HW_3 + HW_4 + HW_5 + HW_6 + HW_7 + HW_8 + HW_9$

HW_1 = horizontal weight of ribs with complexity of CF_4

HW_2 = horizontal weight of ribs with complexity of CF_5

HW_3 = horizontal weight of ribs with complexity of CF_6

HW_4 = horizontal weight of spars with complexity of CF_{13}

HW_5 = horizontal weight of spars with complexity of CF_{14}

HW_6 = horizontal weight of spars with complexity of CF_{15}

HW_7 = horizontal weight of covers with complexity of CF_{22}

HW_8 = horizontal weight of covers with complexity of CF_{23}

HW_9 = horizontal weight of covers with complexity of CF_{24}

HH_{SA1} = assembly hours per unit weight for transporting and positioning

HH_{SA2} = assembly hours per subassembly for transporting and positioning

C_{N1} = number of cover panels

R_{N1} = number of ribs

S_{NE1} = number of external spars

S_{NI1} = number of internal spars

Q_1 = quantity scaling factor

Panel Fit & Trim

$$HH_{13} = 2(S_{PE1} + R_{P1})(H_{T1})(T_{J5}) \qquad \text{Equa. (26)}$$

where HH_{13} = hours for panel fit and trim

S_{PE1} = average horizontal spar perimeter in feet

R_{P1} = average horizontal rib perimeter in feet

H_{T1} = hours per lineal foot for fit and trim

T_{J5} = joint thickness ratio $\frac{2T_S}{.04}$

T_S = average skin thickness

Assembly Clamp and Layout

Equa. (27)

$$HH_{14} = \left[(R_{P1})^{R_1}(R_{N1})^{Q_1} + (S_{PE1})^{R_1}(S_{NE1} + S_{N11})^{Q_1}\right] H_{LL1}\ (2)$$

where HH_{14} = hours for assembly clamps and layout

R_1 = size scaling exponent

H_{LL1} = assembly hours per unit length for clamp and layout

Hole Drilling

Equa. (28)

$$HH_{15} = \left[(R_{P1})^{R_1}(R_{N1})^{Q_1} + (S_{PE1})^{R_1}(S_{NE1} + S_{N11})^{Q_1}\right](H_{D1})(T_{J5})(2)$$

where HH_{15} = hours for hole drilling

H_{D1} = drilling hours per foot

Finish Operations

Equa. (29)

$$HH_{16} = \left[(R_{P1})^{R_1}(R_{N1})^{Q_1} + (S_{PE1})^{R_1}(S_{NE1} + S_{N11})^{Q_1}\right](H_{E1})(T_{J5})(F_{24})(2)$$

where HH_{16} = hours for finishing operations

H_{E1} = finish hours per unit length

F_{24} = factor for fastener selection

<u>Fastener Installation</u>

$$HH_{17} = \left[(R_{P1})^{R_1} (R_{N1})^{Q_1} + (S_{PE1})^{R_1} (S_{NE1} + S_{N1})^{Q_1} \right] (H_{FI1})(T_{J5})(FT_{25})(2)$$

where HH_{17} = hours for fastener installation Equa. (30)

H_{FI1} = installation hours per foot for fastener installation

FT_{25} = factor for fastener selection

Vertical

Primary Box Assembly

Transportation and Positioning

Equa. (31)

$$VH_{12} = (VW_B)(VH_{SA1}) + \left[VH_{SA2}\,(C_{N2} + R_{NZ} + S_{NEZ} + S_{NI2})^{Q_2}\right] 2$$

where VH_{12} = assembly hours for transporting and positioning

$VW_B = VW_1 + VW_2 + VW_3 + VW_4 + VW_5 + VW_6 + VW_7 + VW_8 + VW_9$

VW_1 = vertical weight of ribs with complexity of CF_7

VW_2 = vertical weight of ribs with complexity of CF_8

VW_3 = vertical weight of ribs with complexity of CF_9

VW_4 = vertical weight of spars with complexity of CF_{16}

VW_5 = vertical weight of spars with complexity of CF_{17}

VW_6 = vertical weight of spars with complexity of CF_{18}

VW_7 = vertical weight of covers with complexity of CF_{25}

VW_8 = vertical weight of covers with complexity of CF_{26}

VW_9 = vertical weight of covers with complexity of CF_{27}

VH_{SA1} = assembly hours per unit weight for transporting and positioning

VH_{SA2} = assembly hours per subassembly for transporting and positioning

C_{N2} = number of cover panels

R_{N2} = number of ribs

S_{NE2} = number of external spars

S_{NI2} = number of internal spars

Q_2 = quantity scaling factor

Panel Fit and Trim

$$VH_{13} = 2(S_{PE2} + R_{P2})(H_{T2})(T_{J6}) \qquad \text{Equa. (32)}$$

where VH_{13} = hours for panel fit and trim

S_{PE2} = average vertical spar perimeter in feet

R_{P1} = average vertical rib perimeter in feet

H_{T2} = hours per lineal foot for fit and trim

T_{J6} = joint thickness ratio: $\frac{2T_S}{.04}$

T_S = average skin thickness

Assembly Clamp and Layout

$$VH_{14} = \left[(R_{P2})^{R_2}(R_{N2})^{Q_2} + (S_{PE2})^{R_2}(S_{NI2})^{Q_2}\right](H_{LL2})(2) \qquad \text{Equa. (33)}$$

where VH_{14} = hours for assembly clamp and layout

R_2 = size scaling exponent

H_{LL2} = assembly hours per unit length for clamp and layout

Hole Drilling

$$VH_{15} = \left[(R_{P2})^{R_2}(R_{N2})^{Q_2} + (S_{PE2})^{R_2}(S_{NE2} + S_{NI2})^{Q_2}\right](H_{D2})(T_{J6})(2) \qquad \text{Equa. (34)}$$

Where VH_{15} = hours for hole drilling

H_{D2} = drilling hours per foot

Finish Operations

$$VH_{16} = \left[(R_{P2})^{R_2}(R_{N2})^{Q_2} + (S_{PE2})^{R_2}(S_{NE2} + S_{NI2})^{Q_2}\right](H_{E2})(T_{J6})(FT_{26})(2) \qquad \text{Equa. (35)}$$

where VH_{16} = hours for finishing operations

H_{E2} = finish hours per unit length

FT_{26} = factor for fastener selection

Fastener Installation

Equa. (36)

$$VH_{17} = \left[(R_{P2})^{R_2} (R_{N2})^{Q_2} + (S_{PE2})^{R_2} (S_{NE2} + S_{NI2})^{Q_2} \right] (H_{FI2}) (T_{JC})(FT_{27})(2)$$

where VH_{17} = hours for fastener installation

H_{FI2} = installation hours per foot for fastener installation

FT_{27} = factor for fastener selection

WING

Secondary Structure

Basic equation forms:

$$WH_i = CB_i\,(WC_i)\,(WD_i)^{E_i}$$

where WH_i = detail fabrication hours

CB_i = complexity factor for given material and construction technique

WC_i = hours per pound of structural weight

WD_i = weight of structural element

E_i = weight scaling exponent

and $$WE_i = CC_i\,(WF_i)\,(WD_i)^{F_i}$$

where WE_i = subassembly hours

CC_i = complexity factor for given material and construction technique

WF_i = hours per pound of structural weight

WD_i = weight of structural element

E_i = weight scaling exponent

Leading Edge

$$WH_{18} = CB_1\,(WC_1)\,(WD_1)^{E_{19}} \qquad \text{Equa. (40)}$$

$$WE_{18} = CC_1\,(WF_1)\,(WD_1)^{F_{19}} \qquad \text{Equa. (41)}$$

Trailing Edge

$$WH_{19} = CB_2\,(WC_2)\,(WD_2)^{E_{20}} \qquad \text{Equa. (42)}$$

$$WE_{19} = CC_2\,(WF_2)\,(WD_2)^{F_{20}} \qquad \text{Equa. (43)}$$

Ailerons

$$WH_{20} = CB_3 (WC_3) (WD_3)^{E_{21}} \qquad \text{Equa. (44)}$$

$$WE_{20} = CC_3 (WF_3)(WD_3)^{F_{21}} \qquad \text{Equa. (45)}$$

Fairings

$$WH_{21} = CB_4 (WC_4) (WD_4)^{E_{22}} \qquad \text{Equa. (46)}$$

$$WE_{21} = CC_4 (WF_4) (WD_4)^{F_{22}} \qquad \text{Equa. (47)}$$

Tips

$$WH_{22} = CB_5 (WC_5) (WD_5)^{E_{23}} \qquad \text{Equa. (48)}$$

$$WE_{22} = CC_5 (WF_5) (WD_5)^{F_{23}} \qquad \text{Equa. (49)}$$

Spoilers

$$WH_{23} = CB_6 (WC_6) (WD_6)^{E_{24}} \qquad \text{Equa. (50)}$$

$$WE_{23} = CC_6 (WF_6) (WD_6)^{F_{24}} \qquad \text{Equa. (51)}$$

Flaps & Flaperons

$$WH_{24} = CB_7 (WC_7) (WD_7)^{E_{25}} \qquad \text{Equa. (52)}$$

$$WE_{24} = CC_7 (WF_7) (WD_7)^{F_{25}} \qquad \text{Equa. (53)}$$

Attachment Structure

$$WH_{25} = CB_8 (WC_8) (WD_8)^{E_{26}} \qquad \text{Equa. (54)}$$

$$WE_{25} = CC_8 (WF_8) (WD_8)^{F_{26}} \qquad \text{Equa. (55)}$$

Access Doors, Frames & Landing Gear Doors

$$WH_{26} = CB_{9} (WC_{9}) (WD_{9})^{E_{27}}$$ Equa. (56)

$$WE_{26} = CC_{9} (WF_{9}) (WD_{9})^{F_{27}}$$ Equa. (57)

Wing Mounted Air Induction

$$WH_{27} = CB_{10} (WC_{10}) (WD_{10})^{E_{28}}$$ Equa. (58)

$$WE_{27} = CC_{10} (WF_{10}) (WD_{10})^{F_{28}}$$ Equa. (59)

High Lift Ducting

$$WH_{28} = CB_{11} (WC_{11}) (WD_{11})^{E_{29}}$$ Equa. (60)

$$WE_{28} = CC_{11} (WF_{11}) (WD_{11})^{F_{29}}$$ Equa. (61)

Slats

$$WH_{29} = CB_{12} (WC_{12}) (WD_{12})^{E_{30}}$$ Equa. (62)

$$WE_{29} = CC_{12} (WF_{12}) (WD_{12})^{F_{30}}$$ Equa. (63)

Hinges, Brackets & Seals

$$WH_{30} = CB_{13} (WC_{13}) (WD_{13})^{E_{31}}$$ Equa. (64)

$$WE_{30} = CC_{13} (WF_{13}) (WD_{13})^{F_{31}}$$ Equa. (65)

Pivots and Folds

$$WH_{31} = CB_{14} (WC_{14} (WD_{14})^{E_{32}}$$ Equa. (66)

$$WE_{31} = CC_{14} (WF_{14}) (WD_{14})^{F_{32}}$$ Equa. (67)

Center Section

$$WH_{32} = CB_{15} (WC_{15}) (WD_{15})^{E_{33}}$$ Equa. (68)

$$WE_{32} = CC_{15} (WF_{15}) (WD_{15})^{F_{33}}$$ Equa. (69)

Other

$$WH_{33} = CB_{16} (WC_{16}) (WD_{16})^{E_{34}}$$ Equa. (70)

$$WE_{33} = CC_{16} (WF_{16}) (WD_{16})^{F_{34}}$$ Equa. (71)

HORIZONTAL

Secondary Structure

Basic equation forms:

$$HH_i = CB_i (HC_i)(HD_i)^{E_i}$$

where HH_i = detail fabrication hours

CB_i = complexity factor for given material and construction technique

HC_i = hours per pound of structural weight

HD_i = weight of structural element

E_i = weight scaling exponent

and $$HE_i = CC_i (HF_i)(HD_i)^{F_i}$$

where HE_i = subassembly hours

CC_i = complexity factor for given material and construction technique

HF_i = hours per pound of structural weight

HD_i = weight of structural element

F_i = weight scaling exponent

Leading Edges

$$HH_{18} = CB_{17} (HC_1)(HD_1)^{E_{35}} \qquad \text{Equa. (72)}$$

$$HE_{18} = CC_{17} (HF_1)(HD_1)^{F_{35}} \qquad \text{Equa. (73)}$$

Trailing Edge

$$HH_{19} = CB_{18} (HC_2)(HD_2)^{E_{36}} \qquad \text{Equa. (74)}$$

$$HE_{19} = CC_{18} (HF_2)(HD_2)^{F_{36}} \qquad \text{Equa. (75)}$$

Fairings

$$HH_{20} = CB_{19} (HC_3) (HD_3)^{E_{37}}$$ Equa. (76)

$$HE_{20} = CC_{19} (HF_3) (HD_3)^{F_{37}}$$ Equa. (77)

Elevators

$$HH_{21} = CB_{20} (HC_4) (HD_4)^{E_{38}}$$ Equa. (78)

$$HE_{21} = CC_{20} (HF_4) (HD_4)^{F_{38}}$$ Equa. (79)

Balance Weight

$$HH_{22} = CB_{21} (HC_5) (HD_5)^{E_{39}}$$ Equa. (80)

$$HE_{22} = CC_{21} (HF_5) (HD_5)^{F_{39}}$$ Equa. (81)

Tips

$$HH_{23} = CB_{22} (HC_6) (HD_6)^{E_{40}}$$ Equa. (82)

$$HE_{23} = CC_{22} (HF_6) (HD_6)^{F_{40}}$$ Equa. (83)

Hinges, Brackets and Seals

$$HH_{24} = CB_{23} (HC_7) (HD_7)^{E_{41}}$$ Equa. (84)

$$HE_{24} = CC_{23} (HF_7) (HD_7)^{F_{41}}$$ Equa. (85)

Access Doors & Frames

$$HH_{25} = CB_{24} (HC_8) (HD_8)^{E_{42}}$$ Equa. (86)

$$HE_{25} = CC_{24} (HF_8) (HD_8)^{F_{42}}$$ Equa. (87)

Attachment Structure

$$HH_{26} = CB_{25}\,(HC_9)\,(HD_9)^{E_{43}} \qquad \text{Equa. (88)}$$

$$HE_{26} = CC_{25}\,(HF_9)\,(HD_9)^{F_{43}} \qquad \text{Equa. (89)}$$

Pivots and Folds

$$HH_{27} = CB_{26}\,(HC_{10})\,(HD_{10})^{E_{44}} \qquad \text{Equa. (90)}$$

$$HE_{27} = CC_{26}\,(HF_{10})\,(HD_{10})^{F_{44}} \qquad \text{Equa. (91)}$$

Center Section

$$HH_{28} = CB_{27}\,(HC_{11})\,(HD_{11})^{E_{45}} \qquad \text{Equa. (92)}$$

$$HE_{28} = CC_{27}\,(HF_{11})\,(HD_{11})^{F_{45}} \qquad \text{Equa. (93)}$$

Other

$$HH_{29} = CB_{28}\,(HC_{12})\,(HD_{12})^{E_{46}} \qquad \text{Equa. (94)}$$

$$HE_{29} = CC_{28}\,(HF_{12})\,(HD_{12})^{F_{46}} \qquad \text{Equa. (95)}$$

VERTICAL

Secondary Structure

Basic equation forms:

$$VH_i = CB_i (VC_i) (VD_i)^{E_i}$$

where VH_i = detail fabrication hours

CB_i = complexity factor for given material and construction technique

VC_i = hours per pound of structural weight

VD_i = weight of structural element

E_i = weight scaling exponent

and $VE_i = CC_i (VF_i) (VD_i)^{F_i}$ = subassembly hours

CC_i = complexity factor for given material and construction technique

VF_i = hours per pound of structural weight

VD_i = weight of structural element

F_i = weight scaling exponent

Leading Edge

$$VH_{18} = CB_{29} (VC_1) (VD_1)^{E_{47}} \quad \text{Equa. (96)}$$

$$VE_{18} = CC_{29} (VF_1) (VD_1)^{F_{47}} \quad \text{Equa. (97)}$$

Trailing Edge

$$VH_{19} = CB_{30} (VC_2) (VD_2)^{E_{48}} \quad \text{Equa. (98)}$$

$$VE_{19} = CC_{30} (VF_2) (VD_2)^{F_{48}} \quad \text{Equa. (99)}$$

Fairings

$$VH_{20} = CB_{31} (VC_3) (VD_3)^{E_{49}} \qquad \text{Equa. (100)}$$

$$VE_{20} = CC_{31} (VF_3) (VD_3)^{F_{49}} \qquad \text{Equa. (101)}$$

Rudder

$$VH_{21} = CB_{32} (VC_4) (VD_4)^{E_{50}} \qquad \text{Equa. (102)}$$

$$VE_{21} = CC_{32} (VF_4) (VD_4)^{F_{50}} \qquad \text{Equa. (103)}$$

Balance Weight

$$VH_{22} = CB_{33} (VC_5) (VD_5)^{E_{51}} \qquad \text{Equa. (104)}$$

$$VE_{22} = CC_{33} (VF_5) (VD_5)^{F_{51}} \qquad \text{Equa. (105)}$$

Tips

$$VH_{23} = CB_{34} (VC_6) (VD_6)^{E_{52}} \qquad \text{Equa. (106)}$$

$$VE_{23} = CC_{34} (VF_6) (VD_6)^{F_{52}} \qquad \text{Equa. (107)}$$

Hinges, Brackets and Seals

$$VH_{24} = CB_{35} (VC_7) (VD_7)^{E_{53}} \qquad \text{Equa. (108)}$$

$$VE_{24} = CC_{35} (VF_7) (VD_7)^{F_{53}} \qquad \text{Equa. (109)}$$

Access Doors and Frames

$$VH_{25} = CB_{36} (VC_8) (VD_8)^{E_{54}} \qquad \text{Equa. (110)}$$

$$VE_{25} = CC_{36} (VF_8) (VD_8)^{F_{54}} \qquad \text{Equa. (111)}$$

Attachment Structure

$$VH_{26} = CB_{37} (VC_9)^{E_{55}} (VD_9)^{F_{55}}$$ Equa. (112)

$$VE_{26} = CC_{37} (VF_9)^{E_{55}} (VD_9)^{F_{55}}$$ Equa. (113)

Pivots and Folds

$$VH_{27} = CB_{38} (VC_{10})^{E_{56}} (VD_{10})^{F_{56}}$$ Equa. (114)

$$VE_{27} = CC_{38} (VF_{10})^{E_{56}} (VD_{10})^{F_{56}}$$ Equa. (115)

Others

$$VH_{28} = CB_{39} (VC_{11})^{E_{57}} (VD_{11})^{F_{57}}$$ Equa. (116)

$$VE_{28} = CC_{39} (VF_{11})^{E_{57}} (VD_{11})^{F_{57}}$$ Equa. (117)

Wing Assembly

$$WH_{37} = \left[(WRRP)(WC_S) + 2WFSL + 2WERL + 2WRSL\right]^{WR_1} \qquad \text{Equa. (118)}$$

$$(T_{J7})(FT_{28})(HE_1)\ CM_{B18}$$

where WH_{37} = wing final assembly hours

$WRRP$ = root rib length (ft.)

WC_S = center section operator: 1 without, 2 with

$WFSL$ = front spar length (ft.)

$WERL$ = end rib length (ft.)

$WRSL$ = rear spar length (ft.)

WR_1 = size scaling parameters

T_{J7} = joint thickness ratio, $\dfrac{2T_s}{.04}$

T_S = average skin thickness

FT_{28} = factor for fastener selection

HE_1 = cost per unit length for assembly

CM_{B18} = complexity factor

Horizontal

Horizontal Assembly

$$HH_{30} = \left[(HRRP)(HC_S) + 2HFSL + 2HERL + 2HRSL \right]^{HR_1} (T_{J8})(FT_{29})(HE_2)\, CM_{B19}$$

Equa. (119)

where HH_{30} = horizontal final assembly hours

$HRRP$ = root rib length (ft.)

HC_S = center section operator: 1 without, 2 with

$HFSL$ = front spar length (ft.)

$HERL$ = end rib length (ft.)

$HRSL$ = rear spar length (ft.)

HR_1 = size scaling parameter

T_{J8} = joint thickness ratio: $\dfrac{2T_S}{.04}$

[illegible]$_S$ = av[illegible]age skin thickness

FT_{29} = factor for fastener selection

HE_2 = cost per unit length for assembly

CM_{B19} = complexity factor

Vertical

Vertical Assembly

Equa. (120)

$$VH_{29} = (VRRP + VFSL + VERL + VRSL)^{VR_1} (T_{J9})(FT_{30})(HE_3)\ CM_{B20}$$

where VH_{29} = vertical final assembly hours

$VRRP$ = root rib length (ft.)

$VFSL$ = front spar length (ft.)

$VERL$ = end rib length (ft.)

$VRSL$ = rear spar length (ft.)

VR_1 = size scaling parameter

T_{J9} = joint thickness ratio: $\frac{2T_s}{.01}$

T_S = average skin thickness

FT_{30} = factor for fastener selection

HE_3 = cost per unit length for assembly

CM_{B20} = complexity factor

Wing

Paint & Finish

$$WH_{38} = (WA_S)(WH_S)(2) \qquad \text{Equa. (121)}$$

where WH_{38} = hours for paint and finish

WA_S = wing surface area – ft.^{2} (one side only)

WH_S = hours per square foot factor for paint finish

Rework

$$WH_{39} = \sum_{1}^{37} WH's\ (WF) \qquad \text{Equa. (122)}$$

where WH_{39} = hours for rework

$\sum_{1}^{37} WH's$ – summation of all fabrication and assembly hours

WF = rework factor

Horizontal

Paint & Finish

$$HH_{31} = (HA_S)(HH_S)(2) \qquad \text{Equa. (123)}$$

where HH_{31} = hours for paint and finish

HA_S = horizontal surface area - ft.^{2} (one side only)

HH_S = hours per square foot factor for paint and finish

Rework

$$HH_{32} = \sum_{1}^{30} HH's\,(HU) \qquad \text{Equa. (124)}$$

where HH = hours for rework

$\sum_{1}^{30} HH's$ = summation of all fabrication and assembly hours

HU = rework factor

Vertical

Paint & Finish

$$VH_{30} = (VA_S)(VH_S)(2)$$ Equa. (125)

where VH_{30} = hours for paint and finish

VA_S = horizontal surface area-ft.^{2} (one side only)

VH_S = hours per square foot factor for paint and finish

Rework

$$VH_{31} = \sum_{1}^{29} VH's\ (VU)$$ Equa. (126)

where VH = hours for rework

$\sum_{1}^{29} VH's$ summation of all fabrication and assembly hours

VU = rework factor

Wing Material

Primary Box Structural Material Cost

$WM_i = WW_i(RMC_i)(SF_i)$

where WM_i = material cost

WW_i = weight of finished structure

RMC_i = raw material cost per pound

SF_i = scrappage factor

Ribs

$WM_1 = WW_1(RMC_1)(SF_1)$ Equa. (127)

$WM_2 = WW_2(RMC_2)(SF_2)$ Equa. (128)

$WM_3 = WW_3(RMC_3)(SF_3)$ Equa. (129)

Spars

$WM_4 = WW_4(RMC_4)(SF_4)$ Equa. (130)

$WM_5 = WW_5(RMC_5)(SF_5)$ Equa. (131)

$WM_6 = WW_6(RMC_5)(SF_6)$ Equa. (132)

Covers

$WM_7 = WW_7(RMC_7)(SF_7)$ Equa. (133)

$WM_8 = WW_8(RMC_8)(SF_8)$ Equa. (134)

$WM_9 = WW_9(RMC_9)(SF_9)$ Equa. (135)

Wing Secondary Structure Material Cost

$WM_i = WD_i(RMC_i)(SF_i)$

where WM_i = material cost

WD_i = weight of finished structure

RMC_i = raw material cost per pound

SF_i = scrappage factor

Leading Edge

$$WM_{10} = WD_1(RMC_{10})(SF_{10}) \qquad \text{Equa. (136)}$$

Trailing Edge

$$WM_{11} = WD_2(RMC_{11})(SF_{11}) \qquad \text{Equa. (137)}$$

Ailerons

$$WM_{12} = WD_3(RMC_{12})(SF_{12}) \qquad \text{Equa. (138)}$$

Fairings

$$WM_{13} = WD_4(RMC_{13})(SF_{13}) \qquad \text{Equa. (139)}$$

Tips

$$WM_{14} = WD_5(RMC_{14})(SF_{14}) \qquad \text{Equa. (140)}$$

Spoilers

$$WM_{15} = WD_6(RMC_{15})(SF_{15}) \qquad \text{Equa. (141)}$$

Flaps & Flaperons

$$WM_{16} = WD_7(RMC_{16})(SF_{16}) \qquad \text{Equa. (142)}$$

Attachment Structure

$$WM_{17} = WD_8(RMC_{17})(SF_{17}) \qquad \text{Equa. (143)}$$

Access Doors, Frames & Landing Gear Doors

$$WM_{18} = WD_9(RMC_{18})(SF_{18}) \qquad \text{Equa. (144)}$$

Wing Mounted Air Induction

$$WM_{19} = WD_{10}(RMC_{19})(SF_{19}) \qquad \text{Equa. (145)}$$

High Lift Ducting

$$WM_{20} = WD_{11}(RMC_{20})(SF_{20}) \qquad \text{Equa. (146)}$$

Slats

$$WM_{21} = WD_{12}(RMC_{21})(SF_{21}) \qquad \text{Equa. (147)}$$

Hinges, Brackets and Seals

$$WM_{22} = WD_{13}(RMC_{22})(SF_{22}) \qquad \text{Equa. (148)}$$

Pivots and Folds

$$WM_{23} = WD_{14}(RMC_{23})(SF_{23}) \qquad \text{Equa. (149)}$$

Center Section

$$WM_{24} = WD_{15}(RMC_{24})(SF_{24}) \qquad \text{Equa. (150)}$$

Other

$$WM_{25} = WD_{16}(RMC_{25})(SF_{25}) \qquad \text{Equa. (151)}$$

Horizontal Material

Primary Box Structural Material Cost

$HM_i = HW_i(RMC_i)(SF_i)$

where HM_i = material cost

HW_i = weight of finished structure

RMC_i = raw material cost per pound

SF_i = scrappage factor

Ribs

$HM_1 = HW_1(RMC_{26})(SF_{26})$ Equa. (152)

$HM_2 = HW_2(RMC_{27})(SF_{27})$ Equa. (153)

$HM_3 = HW_3(RMC_{28})(SF_{28})$ Equa. (154)

Spars

$HM_4 = HW_4(RMC_{29})(SF_{29})$ Equa. (155)

$HM_5 = HW_5(RMC_{30})(SF_{30})$ Equa. (156)

$HM_6 = HW_6(RMC_{31})(SF_{31})$ Equa. (157)

Covers

$HM_7 = HW_7(RMC_{32})(SF_{32})$ Equa. (158)

$HM_8 = HW_8(RMC_{33})(SF_{33})$ Equa. (159)

$HM_9 = HW_9(RMC_{34})(SF_{34})$ Equa. (160)

Horizontal Secondary Structure Material Cost

$HM_i = HD_i(RMC_i)(SF_i)$

where HM_i = material cost

HD_i = weight of finished structure

RMC_i = raw material cost per pound

SF_i = scrappage factor

Leading Edge

$$HM_{10} = HD_1(RMC_{35})(SF_{35}) \quad \text{Equa. (161)}$$

Trailing Edge

$$HM_{11} = HD_2(RMC_{36})(SF_{36}) \quad \text{Equa. (162)}$$

Fairings

$$HM_{12} = HD_3(RMC_{37})(SF_{37}) \quad \text{Equa. (163)}$$

Elevators

$$HM_{13} = HD_4(RMC_{38})(SF_{38}) \quad \text{Equa. (164)}$$

Balance Weight

$$HM_{14} = HD_5(RMC_{39})(SF_{39}) \quad \text{Equa. (165)}$$

Tips

$$HM_{15} = HD_6(RMC_{40})(SF_{40}) \quad \text{Equa. (166)}$$

Hinges, Brackets & Seals

$$HM_{16} = HD_7 (RMC_{41}) (SF_{41}) \quad \text{Equa. (167)}$$

Access Doors & Frames

$$HM_{17} = HD_8(RMC_{42})(SF_{42}) \quad \text{Equa. (168)}$$

Attachment Structure

$$HM_{18} = HD_9(RMC_{43}) (SF_{43}) \quad \text{Equa. (169)}$$

Pivots & Folds

$$HM_{19} = HD_{10}(RMC_{44})(SF_{44}) \quad \text{Equa. (170)}$$

Center Section

$$HM_{20} = HD_{11}(RMC_{45})(SF_{45}) \quad \text{Equa. (171)}$$

Other

$$HM_{21} = HD_{12}(RMC_{46})(SF_{46}) \quad \text{Equa. (172)}$$

Vertical Material

Primary Box Structural Material Cost

$$VM_i = VW_i(RMC_i)(SF_i)$$

where VM_i = material cost

VW_i = weight of finished structure

RMC_i = raw material cost per pound

SF_i = scrappage factor

Ribs

$$VM_1 = VW_1(RMC_{47})(SF_{47}) \quad \text{Equa. (173)}$$

$$VM_2 = VW_2(RMC_{48})(SF_{48}) \quad \text{Equa. (174)}$$

$$VM_3 = VW_3(RMC_{49})(SF_{49}) \quad \text{Equa. (175)}$$

Spars

$$VM_4 = VW_4(RMC_{50})(SF_{50}) \quad \text{Equa. (176)}$$

$$VM_5 = VW_5(RMC_{51})(SF_{51}) \quad \text{Equa. (177)}$$

$$VM_6 = VW_6(RMC_{52})(SF_{52}) \quad \text{Equa. (178)}$$

Covers

$$VM_7 = VW_7(RMC_{53})(SF_{53}) \quad \text{Equa. (179)}$$

$$VM_8 = VW_8(RMC_{54})(SF_{54}) \quad \text{Equa. (180)}$$

$$VM_9 = VW_9(RMC_{55})(SF_{55}) \quad \text{Equa. (181)}$$

Vertical Secondary Structure Material Cost

$$VM_i = VD_i(RMC_i)(SF_i)$$

where VM_i = material cost

VD_i = weight of finished structure

RMC_i = raw material cost per pound

SF_i = scrappage factor

Leading Edge

$$VM_{10} = VD_1(RMC_{56})(SF_{56}) \qquad \text{Equa. (182)}$$

Trailing Edge

$$VM_{11} = VD_2(RMC_{57})(SF_{57}) \qquad \text{Equa. (183)}$$

Fairings

$$VM_{12} = VD_3(RMC_{58})(SF_{58}) \qquad \text{Equa. (184)}$$

Rudder

$$VM_{13} = VD_4(RMC_{59})(SF_{59}) \qquad \text{Equa. (185)}$$

Balance Weight

$$VM_{14} = VD_5(RMC_{60})(SF_{60}) \qquad \text{Equa. (186)}$$

Tips

$$VM_{15} = VD_6(RMC_{61})(SF_{61}) \qquad \text{Equa. (187)}$$

Hinges, Brackets and Seals

$$VM_{16} = VD_7(RMC_{62})(SF_{62}) \qquad \text{Equa. (188)}$$

Access Doors and Frames

$$VM_{17} = VD_8(RMC_{63})(SF_{63}) \qquad \text{Equa. (189)}$$

Attachment Structure

$$VM_{18} = VD_9(RMC_{64})(SF_{64}) \qquad \text{Equa. (190)}$$

Pivots and Folds

$$VM_{19} = VD_{10}(RMC_{65})(SF_{65}) \qquad \text{Equa. (191)}$$

Others

$$VM_{20} = VD_{11}(RMC_{66})(SF_{66}) \qquad \text{Equa. (192)}$$

Wing

Primary Box Assembly Material Cost

$$WA_1 = \sum_{12}^{17} WH(AMF_1)(FM_1) \qquad \text{Equa. (193)}$$

where

WA_1 = primary box assembly material cost

$\sum_{12}^{17} WH$ = total assembly labor hours for primary box

AMF_1 = assembly material per labor hour

FM_1 = fastener type complexity factor

Wing Assembly Material Cost (Excluding primary box)

$$WA_2 = WH_{37}(AMF_4)(FM_4) \qquad \text{Equa. (194)}$$

where

WA_2 = wing assembly material cost

WH_{37} = wing final assembly hours

AMF_4 = assembly material per labor hour

FM_4 = fastener type complexity factor

Horizontal

Primary Box Assembly Material

$$HA_1 = \sum_{12}^{17} HH(AMF_2)(FM_2) \qquad \text{Equa. (195)}$$

where

HA_1 = primary box assembly material cost

$\sum_{12}^{17} HH$ = total assembly labor hours for primary box

AMF_2 = assembly material per labor hour

FM_2 = fastener type complexity factor

Horizontal Assembly Material Cost (Excluding primary box)

$$HA_2 = HH_{30}(AMF_5)(FM_5) \qquad \text{Equa. (196)}$$

where

HA_2 = horizontal assembly material cost

HH_{30} = horizontal final assembly hours

AMF_5 = assembly material per labor hour

FM_5 = fastener type complexity factor

Vertical

Primary Box Assembly Material

$$VA_1 = \sum_{12}^{17} VH(AMF_3)(FM_3) \qquad \text{Equa. (197)}$$

where

VA_1 = primary box assembly material cost

$\sum_{12}^{17} VH$ = total assembly labor hours for primary box

AMF_3 = assembly material per labor hour

FM_3 = fastener type complexity factor

Vertical Assembly Material Cost (Excluding primary box)

$$VA_2 = VH_{29}(AMF_6)(FM_6) \qquad \text{Equa. (198)}$$

where

VA_2 = vertical assembly material cost

VH_{29} = vertical finai assembly hours

AMF_6 = assembly material per labor hour

FM_6 = fastener type complexity factor

Conversions to Computer Program Symbology

Variable (NAMELIST)

Use on WING, HSTAB, VSTAB

BOX DETAIL FABRICATION

W1	Weight of ribs
W2	Weight of ribs
W3	Weight of ribs
WT	Total weight of W1, W2, W3
W4	Weight of spars
W5	Weight of spars
W6	Weight of spars
WT1	Total weight of W4, W5, W6
W7	Weight of covers
W8	Weight of covers
W9	Weight of covers
WT2	Total weight of W7, W8, W9
CF1	Complexity factor — ribs
CF2	Complexity factor — ribs
CF3	Complexity factor — ribs
CF4	Complexity factor — spars
CF5	Complexity factor — spars
CF6	Complexity factor — spars
CF7	Complexity factor — covers
CF8	Complexity factor — covers
CF9	Complexity factor — covers

Subassembly

CM1	Complexity factor — ribs
CM2	Complexity factor — ribs
CM3	Complexity factor — ribs
CM4	Complexity factor — spars
CM5	Complexity factor — spars
CM6	Complexity factor — spars
CM7	Complexity factor — covers
CM8	Complexity factor — covers
CM9	Complexity factor — covers

Primary Box Assembly

CN	Number of cover panels
RN	Number of ribs
SNE	Number of external spars

SNI	Number of internal spars
SPE	Average spar perimeter in feet
RP	Average rib perimeter in feet
TJ4	Joint thickness ratio
TS4	Average skin thickness
FF1	Factor for fastener selection
FF2	Factor for fastener selection

Secondary Structure

CB1	Complexity factor — leading edge
WD1	Weight — leading edge
CC1	Complexity factor — leading edge
CB2	Complexity factor — trailing edge
WD2	Weight — trailing edge
CC2	Complexity factor — trailing edge
CB3	Complexity factor — aileron, elevator, rudder
WD3	Weight — aileron, elevator, rudder
CC3	Complexity factor — aileron, elevator, rudder
CB4	Complexity factor — fairings
WD4	Weight — fairings
CC4	Complexity factor — fairings
CB5	Complexity factor — tips
WD5	Weight — tips
CC5	Complexity factor — tips
CB6	Complexity factor — spoilers
WD6	Weight — spoilers
CC6	Complexity factor — spoilers
CB7	Complexity factor — flaps
WD7	Weight — flaps
CC7	Complexity factor — flaps
CB8	Complexity factor — attachment struct.
WD8	Weight — attachment structure
CC8	Complexity factor — attachment struct.
CB9	Complexity factor — access doors, etc.
WD9	Weight — access doors, etc.
CC9	Complexity factor — access doors, etc.
CB10	Complexity factor — air induction
WD10	Weight — air induction
CC10	Complexity factor — air induction
CB11	Complexity factor — high lift ducting
WD11	Weight — high lift ducting
CC11	Complexity factor — high lift ducting
CB12	Complexity factor — slats
WD12	Weight — slats
CC12	Complexity factor — slats

CB13	Complexity factor — hinges, etc.
WD13	Weight — hinges, etc.
CC13	Complexity factor — hinges, etc.
CB14	Complexity factor — pivots and folds
WD14	Weight — pivots and folds
CC14	Complexity factor — pivots and folds
CB15	Complexity factor — center section
WD15	Weight — center section
CC15	Complexity factor — center section
CB16	Complexity factor — other
WD16	Weight — other
CC16	Complexity factor — other
CB17	Complexity factor — balance weight
WD17	Weight — balance weight
CC17	Complexity factor — balance weight

Final Assembly

WRRP	Root rib length
CSO	Center section operator
FSL	Front spar length
ERL	End rib length
RSL	Rear spar length
TJ7	Joint thickness ratio
TS7	Average skin thickness
FF3	Factor for fastener selection
CMB	Complexity factor
AS2	Surface area — $ft.^2$

Primary Box — Material Cost

RMC1	Raw material cost — ribs
SF1	Scrappage factor — ribs
RMC2	Raw material cost — ribs
SF2	Scrappage factor — ribs
RMC3	Raw material cost — ribs
SF3	Scrappage factor — ribs
RMC4	Raw material cost — spars
SF4	Scrappage factor — spars
RMC5	Raw material cost — spars
SF5	Scrappage factor — spars
RMC6	Raw material cost — spars
SF6	Scrappage factor — spars
RMC7	Raw material cost — covers
SF7	Scrappage factor — covers
RMC8	Raw material cost — covers
SF8	Scrappage factor — covers

RMC9	Raw material cost — covers
SF9	Scrappage factor — covers

Secondary Structure Material Cost

RMC10	Raw material cost — leading edge
SF10	Scrappage factor — leading edge
RMC11	Raw material cost — trailing edge
SF11	Scrappage factor — trailing edge
RMC12	Raw material cost — aileron, elevator, rudder
SF12	Scrappage factor — aileron, elevator, rudder
RMC13	Raw material cost- fairings
SF13	Scrappage factor — fairings
RMC14	Raw material cost — tips
SF14	Scrappage factor — tips
RMC15	Raw material cost — spoilers
SF15	Scrappage factor — spoilers
RMC16	Raw material cost — flaps
SF16	Scrappage factor — flaps
RMC17	Raw material cost — attachment structure
SF17	Scrappage factor — attachment structure
RMC18	Raw material cost — access doors, etc.
SF18	Scrappage factor — access doors, etc.
RMC19	Raw material cost — air induction
SF19	Scrappage factor — air induction
RMC20	Raw material cost — high lift ducting
SF20	Scrappage factor — high lift ducting
RM21	Raw material cost — slats
SF21	Scrappage factor — slats
RMC22	Raw material cost — hinges, etc.
SF22	Scrappage factor — hinges, etc.
RMC23	Raw material cost — pivots and folds
SF23	Scrappage factor — pivots and folds
RMC24	Raw material cost — center section
SF24	Scrappage factor — center section
RMC25	Raw material cost — other
SF25	Scrappage factor — other
RMC26	Raw material cost — balance weight
SF26	Scrappage factor — balance weight

Primary Box Assembly Material Cost

FM1	Complexity factor — fastener type

Assembly Material Cost

FM2	Complexity factor — fastener type

Variable Name (Not Namelist)	Use — WING, HSTAB, VSTAB
Box Detail Fabrication	
HF1	Fabrication hours — ribs
E1	Exponent — ribs
HF2	Fabrication hours — spars
E2	Exponent — spars
HF3	Fabrication hours — covers
E3	Exponent — covers
Subassembly	
HF4	Subassembly hours — ribs
E4	Exponent — ribs
HF5	Subassembly hours — spars
E5	Exponent — spars
HF6	Subassembly hours — covers
E6	Exponent — covers
Primary Box Assembly	
HSA1	Assembly hours per unit weight
HSA2	Assembly hours per subassembly
Q	Quantity scaling factor
HT	Hours per lineal foot
HLL	Assembly hours per unit length
R	Size scaling exponent
HD	Drilling hours per foot
HE	Finish hours, per unit length
HFI	Installation hours per foot
Secondary Structure	
WC1	Hours per pound — leading edge
E7	Exponent — leading edge
WF1	Hours per pound — leading edge
F1	Exponent — leading edge
WC2	Hours per pound — trailing edge
E8	Exponent — trailing edge
WF2	Hours per pound — trailing edge
F2	Exponent — trailing edge
WC3	Hours per pound — aileron, elevator, rudder
E9	Exponent — aileron, elevator, rudder
WF3	Hours per pound — aileron, elevator, rudder
F3	Exponent — aileron, elevator, rudder
WC4	Hours per pound — fairings
E10	Exponent — fairings

WF4	Hours per pound	— fairings
F4	Exponent	— fairings
WC5	Hours per pound	— tips
E11	Exponent	— tips
WF5	Hours per pound	— tips
F5	Exponent	— tips
WC6	Hours per pound	— spoiler
E12	Exponent	— spoiler
WF6	Hours per pound	— spoiler
F6	Exponent	— spoiler
WC7	Hours per pound	— flaps
E13	Exponent	— flaps
WF7	Hours per pound	— flaps
F7	Exponent	— flaps
WC8	Hours per pound	— attachment structure
E19	Exponent	— attachment structure
WF8	Hours per pound	— attachment structure
F8	Exponent	— attachment structure
WC9	Hours per pound	— access doors, etc.
E20	Exponent	— access doors, etc.
WF9	Hours per pound	— access doors, etc.
F9	Exponent	— access doors, etc.
WC10	Hours per pound	— air induction
E21	Exponent	— air induction
WF10	Hours per pound	— air induction
F10	Exponent	— air induction
WC11	Hours per pound	— high lift ducting
E22	Exponent	— high lift ducting
WF11	Hours per pound	— high lift ducting
F11	Exponent	— high lift ducting
WC12	Hours per pound	— slats
E23	Exponent	— slats
WF12	Hours per pound	— slats
F12	Exponent	— slats
WC13	Hours per pound	— hinges, etc.
E24	Exponent	— hinges, etc.
WF13	Hours per pound	— hinges, etc.
F13	Exponent	— hinges, etc.
WC14	Hours per pound	— pivots and folds
E25	Exponent	— pivots and folds
WF14	Hours per pound	— pivots and folds
F14	Exponent	— pivots and folds
WC15	Hours per pound	— center section
E26	Exponent	— center section

WF15	Hours per pound	— center section
F15	Exponent	— center section
WC16	Hours per pound	— other
E27	Exponent	— other
WF16	Hours per pound	— other
F16	Exponent	— other
WC17	Hours per pound	— balance weight
E28	Exponent	— balance weight
WF17	Hours per pound	— balance weight
F17	Exponent	— balance weight

Final Assembly

R1	Size scaling parameters
HE1	Cost per unit length for assembly
HS	Hours per square foot factor
U	Rework factor

Primary Box Assembly Material Cost

AMF1	Assembly material per labor hour

Assembly Material Cost

AMF4	Assembly material per labor hours

RECURRING AIRFRAME PRODUCTION COSTS

Recurring airframe production CERs are summarized by the following chart followed by the detailed CERs.

	Horiz. Stab.	Vertical Stab.	Wing	Fuselage	Nacelle	Hours	Dollars
Recurring Production Costs							
RDT&E Articles (Qty)							
Sustaining Engineering						$E_{SUST\,1}$	$E_{SC\,1}$
Sustaining Tooling						$T_{SUST\,1}$	$T_{SC\,1}$
Manufacturing:	Horiz. Stab.	Vertical Stab.	Wing	Fuselage	Nacelle		
Detail Fab Hours	H_{DF1}	H_{DF2}	H_{DF3}	H_{DF4}	H_{DF5}	H_{DFS}	H_{DFC}
Assembly Hours	H_{AS1}	H_{AS2}	H_{AS3}	H_{AS4}	H_{AS5}	H_{ASS}	H_{ASC}
Quality Control Hours	-	-	-	-	-	H_{QC1}	QC_{C1}
Material and Other	MM_{C1}	MM_{C2}	MM_{C3}	MM_{C4}	MM_{C5}	-	MM_{CS}
Procurement Articles (Qty)							
Sustaining Engineering						$E_{SUST\,2}$	$E_{SC\,2}$
Sustaining Tooling						$T_{SUST\,2}$	$T_{SC\,2}$
Manufacturing:	Horiz. Stab.	Vertical Stab.	Wing	Fuselage	Nacelle		
Detail Fab Hours	H_{DF11}	H_{DF12}	H_{DF13}	H_{DF14}	H_{DF15}	H_{DFSP}	H_{DFCP}
Assembly Hours	H_{AS11}	H_{AS12}	H_{AS13}	H_{AS14}	H_{AS15}	H_{ASSP}	H_{ASCP}
Quality Control Hours	-	-	-	-	-	H_{QC2}	QC_{C2}
Material and Other	MM_{C11}	MM_{C12}	MM_{C13}	MM_{C14}	MM_{C15}	-	MM_{CSP}

RDT&E RECURRING PRODUCTION

SUSTAINING ENGINEERING HOURS

$$E_{SUST\ 1} = EH\left[N_1^{ES} - 1\right]$$

where

EH = Nonrecurring engineering direct labor hours

N_1 = Number of RDT&E airframes

ES = Scaling of sustaining engrg. with quantity

SUSTAINING ENGINEERING LABOR COSTS

$$E_{SC\ 1} = E_{SUST\ 1}\ (ECLR)$$

SUSTAINING TOOLING HOURS

$$T_{SUST\ 1} = T_S\left[N_1^{TU} - 1\right]$$

where

$$T_S = T_R + T_{ET} + T_{MD}$$

TU = Scaling of sustaining tooling with quantity

SUSTAINING TOOLING LABOR COSTS

$$T_{SC\ 1} = (T_{SUST\ 1})\ (R_T)$$

where

R_T = Composite tooling labor rate

MANUFACTURING HOURS

$$H_{DFi} = (FU_{DFi})\left(\sum_{i=1}^{N_1} N_i^K\right)$$

where

H_{DFi} = Total detailed fabrication hours for a quantity N_1 of a given basic structure component for RDT&E test hardware.

$$FU_{DFi} = \sum_{1}^{n} (\ \ )DF_i :$$

$i = 1$, $n = 32$	for horizontal stabilizer
$i = 2$, $n = 31$	for vertical stabilizer
$i = 3$, $n = 39$	for wing
$i = 4$, n = to be determined	for fuselage
$i = 5$, n = to be determined	for nacelle

(The above summations are accomplished twice: once for detailed fabrication hours and once for assembly hours. H_{ASi} = assembly hours. FU_{DF} and FU_{AS} represents hours for first unit.)

$\sum_{i=1}^{N_1} N_i^{K}$ = Production quantity with a learning function

$K = \dfrac{\log PC_i}{\log 2}$, where PC_i = learning curve expressed as a decimel fraction, and

PC_1 = Learning curve decimal fraction for detailed fabrication hous.

PC_2 = Learning curve decimal fraction for assembly hours.

MANUFACTURING LABOR COST

$H_{DFC} = H_{DFS} \times$ (Mfg. labor rate) = Detailed fab labor cost for RDT&E articles

where

$$H_{DFS} = H_{DF1} + H_{DF2} + H_{DF3} + H_{DF4} + H_{DF5}$$

and

$H_{ASC} = H_{ASS} \times$ (Mfg. labor rate) - Assembly labor cost for RDT&E articles

where

$$H_{ASS} = H_{AS1} + H_{AS2} + H_{AS3} + H_{AS4} + H_{AS5}$$

QUALITY CONTROL HOURS

$$H_{QC1} = (H_{DFS} + H_{ASS})\, F_{10}$$

where

H_{QC1} = Quality Control hours for RDT&E production units.

F_{10} = Ratio between quality control and manufacturing hours.

QUALITY CONTROL LABOR COSTS

$$QC_{C1} = (H_{QC1})\,(R_{QC})$$

where

QC_{C1} = Quality control labor cost

MANUFACTURING MATERIALS AND OTHER COST

$$MM_{Ci} = (HS_M) \sum_{i=1}^{N_1} N_i^{K}$$

where

MM_{Ci} = Dollar cost of manufacturing materials for the various structural componen.s for RDT&E hardware.

MM_{C1} = Horizontal stabilizer cost.

MM_{C2} = Vertical stabilizer cost.

MM_{C3} = Wing cost

MM_{C4} = Fuselage cost

MM_{C5} = Nacelle cost

HS_M = First unit material cost for horizontal stabilizer

VS_M = First unit material cost for vertical stabilizer

W_M = First unit material cost for wing.

F_M = First unit material cost for fuselage

N_M = First unit material cost for nacelle.

K = Material learning curve factor.

$$= \frac{\log pc_3}{\log 2}$$

and

MM_{CS} = Total manufacturing material cost

$$= MM_{C1} + MM_{C2} + MM_{C3} + MM_{C4} + MM_{C5}$$

PROCUREMENT RECURRING PRODUCTION

SUSTAINING ENGINEERING HOURS

$$E_{SUST\ 2} = EH \left(N_2^{ES} - N_1^{ES} \right)$$

where

N_2 = Sum of RDT&E and procurement production quantities

SUSTAINING ENGINEERING LABOR COSTS

$$E_{SC\ 2} = (E_{SUST\ 2})\ (ECLR)$$

SUSTAINING TOOLING HOURS

$$T_{SUST\ 2} = T_S \left[N_2^{TU} - N_1^{TU} \right]$$

SUSTAINING TOOLING LABOR COST

$$T_{SC\ 2} = (T_{SUST\ 2})\ (R_T)$$

MANUFACTURING HOURS

$$H_{DF1i} = (FU_{DFi}) \left(\sum_{i = N_1}^{N_2} N_i^K \right) = \text{Detail fab hours for } N_2 - N_1 \text{ quantity}$$

$$H_{AS1i} = (FU_{ASi}) \left(\sum_{i = N_1}^{N_2} N_i^K \right) = \text{Assembly hours for } N_2 - N_1 \text{ quantity.}$$

MANUFACTURING LABOR COST

$$H_{DFCP} = H_{DFSP} \times (\text{Mfg. labor rate}) = \text{Detailed fab labor cost for procurement articles.}$$

where

$$H_{DFSP} = H_{DF11} + H_{DF12} + H_{DF13} + H_{DF14} + H_{DF15}$$

and

$$H_{ASCP} = H_{ASSP} \times (\text{Mfg. labor rate}) = \text{Assembly labor cost for procurement articles.}$$

where

$$H_{ASSP} = H_{AS11} + H_{AS12} + H_{AS13} + H_{AS14} + H_{AS15}$$

QUALITY CONTROL HOURS

$$H_{QC2} = (H_{DFSP} + H_{ASSP})\ F_{11}$$

where

H_{QC2} = Quality Control hours for procurement production units.

F_{11} = Ratio between quality control and manufacturing hours for procurement production

QUALITY CONTROL LABOR COST

$$QC_{C2} = (H_{QC2})\ (R_{QC})$$

MANUFACTURING MATERIALS

$$MM_{C1i} = (HS_M)\left(\sum_{i = N_1}^{N_2} N_i^{K}\right)$$

and

MM_{CSP} = Total manufacturing material cost for procurement production articles

$$= MM_{C11} + MM_{C12} + MM_{C13} + MM_{C14} + MM_{C15}$$

APPENDIX C

INPUT DATA VALUES AND DATA SUMMARY FOR DEMONSTRATION CASES

Table C-1 gives the input values used for the estimates comprising the test cases. These inputs relate to the CERs in Appendix B. The column headed "Input Source" indicates whether the input is obtained from the augmented APAS program, from the complexity factor tables, or from "Other Inputs," as organized and described in Volume IV. These sources are represented by the following symbols:

Input Source	Input Source Symbol
Synthesis Program Output	A
Complexity Factor Tables	C
Other	O

The input source symbology is elaborated on in Volume 4 as a guide to actually performing an estimate. The essential information conveyed by this Appendix is the input values used in the test cases.

Table C-1 Input Data Form and Data Summary for Demonstration Cases

Nonrecurring Design and Development Costs CER Where First Used: Input Name	Input Symbol	Input Source	F-111 Wing	F-111 Vert.	C-5 Hor.	C-5 Vert.
Engineering Director Labor Hours						
AMPR Weight of Structural Element	Wi	A	8557.7	761.2	6566.2	5794.8
Engineering Hours at W 1 lb	ai	O	126.	60.	60.	60.
Scaling of Hours to AMPR Weight	bi	O	0.82	0.35	0.95	0.95
Factor for Configuration Design Engineering	F1	O	1.15	1.15	1.15	1.15
Engineering Director Labor Costs						
Engineering Composite Labor Rate	ECLR	O	20.	20.	20.	20.
Engineering Material and Other Cost						
Percentage Factor of Engineering Labor Cost	F2	O	0.10	0.10	0.10	0.10
Basic Tool Manufacturing Hours						
Tooling Complexity Factor by Component	CMTi	O	133.	133.	70.	70.
Scaling of Tooling Hours by AMPR Weight	C	O	1.	1.	1.	1.
Rate Tool Manufacturing Hours						
Assumed Monthly Production Rate	T	O	16.	16.	3.	3.
Tool Production Rate Scaling Exponent	B	O	0.2	0.2	0.2	0.2
Basic Tool Engineering Hours						
Percentage Factor of Basic Tool Manufacturing Hours	F3	O	0.40	0.40	0.40	0.40
Rate Tool Engineering Hours						
Percentage Factor of Rate Tool Manufacturing Hours	F4	O	0.20	0.20	0.20	0.20

Nonerecurring Design and Development Costs

CER Where First Used: Input Name	Input Symbol	Input Source	F-111 Wing	F-111 Vert.	C-5 Hor.	C-5 Vert.
Manufacturing Development & Plant Engrg. Hours						
Percentage Factor of Mfg. Devel. & Plant Engrg. Hours.	F5	O	0.02	0.02	0.02	0.02
Tool Manufacturing Direct Labor Costs						
Tool Manufacturing Labor Cost Per Hour	THC	O	15.60	15.60	15.60	15.60
Tool Engineering Direct Labor Cost						
Tool Engineering Labor Cost Per Hour	TEC	O	17.92	17.92	17.92	17.92
Mfg. Devel. & Plant Engrg. Director Labor Costs						
Composite Labor Cost for Mfg. Devel. & Plant Engrg.	TDC	O	14.30	14.30	14.30	14.30
Tooling Material and Other						
Tooling Material Support Factor	F6	O	1.00	1.00	1.00	1.00
Manufacturing Support Costs						
Development Support Factor, % of EC	F7	O	0.10	0.10	0.10	0.10
Quality Control Direct Labor Hours						
Percentage of Engineering Direct Labor Hours	F8	O	0.01	0.01	0.01	0.01
Percentage of Tool Mfg. Director Labor Hours	F9	O	0.06	0.06	0.06	0.06
Quality Control Direct Labor Cost						
Composite Quality Control Labor Rate	RQC	O	14.50	14.50	14.50	14.50

Recurring Airframe Production Costs

CER Where First Used: Input Name	Input Symbol	Input Source	F-111 Wing	F-111 Vert.	C-5 Hor.	C-5 Vert.
Sustaining Engineering Hours						
Number of RDT&E Airframes	N1	O	18.00	18.00	7.00	7.00
Sum of RDT&E and Procurement Production Quantities	N2	O	506.	506.	80.	80.
Scaling of Sustaining Engrg. With Quantity	ES	O	0.2	0.2	0.2	0.2
Sustaining Tooling Hours						
Scaling of Sustaining Tooling With Quantity	TU	O	0.14	0.14	0.14	0.14
Sustaining Tooling Labor Costs						
Composite Tooling Labor Rate	RT	O	16.40	16.40	16.40	16.40
Manufacturing Hours						
Learning Curve Decimal Fraction for Detailed Fabrication Hours	PC1	O	0.74	0.74	0.74	0.74
Learning Curve Decimal Fraction for Assembly Hours	PC2	O	0.81	0.81	0.81	0.81
Manufacturing Labor Cost						
Manufacturing Labor Rate		O	14.00	14.00	14.00	14.00
Quality Control Hours						
Ratio Between Quality Control and Manufacturing Hours	F10	O	0.10	0.10	0.10	0.10
Sustaining Engineering Hours						
Sum of RDT&E & Procurement Production Quantities						
Quality Control Hours						
Ratio Between Quality Control and Manufacturing Hours for Procurement	F11	O	0.10	0.10	0.10	0.10
Material Costs						
Learning Curve Decimal Fraction for Material Costs	PC3	O	0.93	0.93	0.93	0.93

CER Where First Used: Input Name	Input Symbol	Input Source	F-111A Wing	A(X) Wing
First Unit Hardware Cost: Wing Box Detail Fabrication				
Construction Material Complexity Factor				
Ribs	CF1W	C	.99	1.00
Ribs	CF2W	C	0	0
Ribs	CF3W	C	0	0
Spars	CF4W	C	1.72	1.00
Spars	CF5W	C	0	0
Spars	CF6W	C	0	0
Covers	CF7W	C	2.40	1.00
Covers	CF8W	C	0	0
Covers	CF9W	C	0	0
Baseline Hours per Pound				
Ribs	HF1W	O	51.	51.
Spars	HF2W	O	52.	52.
Covers	HF3W	O	11.	11.
Estimated Weight of Components (Total Wing)				
Ribs	WTW	A	91.8	
	W1W	A	91.8	
	W2W	A	0	
	W3W	A	0	
Spars	WT1W	A	731.1	
	W4W	A	731.1	

	Input Symbol	Input Source	F-111A Wing	A(X) Wing
	W5W	A	0	
	W6W	A	0	
Covers	WT2W	A	1927.6	
	W7W	A	1927.6	
	W8W	A	0	
	W9W	A	0	
Weight Scaling Exponent				
Ribs	E1W	O	.67	.67
Spars	E2W	O	.67	.67
Covers	E3W	O	.67	.67
Wing Box Subassembly				
Construction Material Complexity Factor				
Ribs	CM1W	C	0	1.00
Ribs	CM2W	C	0	0
Ribs	CM3W	C	0	0
Spars	CM4W	C	0	1,00
Spars	CM5W	C	0	0
Spars	CM6W	C	0	0
Covers	CM7W	C	0	1.00
Covers	CM8W	C	0	0
Covers	CM9W	C	0	0
Baseline Hours per Pound				
Ribs	HF4W	O	14.5	14.5
Spars	HF5W	O	19.	19.

	Input Symbol	Input Source	F-111A Wing	A(X) Wing
Covers	HF6W	O	7.2	7.2
Estimated Weight of Components (Total Wing)				
Ribs	WTW	A	91.8	
	W1W	A	91.8	
	W2W	A	0	
	W3W	A	0	
Spars	WT1W	A	731.1	
	W4W	A	731.1	
	W5W	A	0	
	W6W	A	0	
Covers	WT2W	A	1927.6	
	W7W	A	1927.6	
	W8W	A	0	
	W9W	A	0	
Weight Scaling Exponent				
Ribs	E4W	O	.67	.67
Spars	E5W	O	.67	.67
Covers	E6W	O	.67	.67
Wing Box Final Assembly				
Weight of Wing Box Assembly	WWB	A		
Hours for Transporting & Positioning (Wt)	WHSA1	A	.10	.10
Hours for Transporting & Positioning (Qty)	WHSA2	A	2.	2.
Number of cover panels	CN	A	2.	10.
Number of ribs	RN	A	7.	14.

	Input Symbol	Input Source	F-111A Wing	A(X) Wing
Number of external spars	SNE	A	2.	2.
Number of internal spars	SNI	A	3.	1.
Quantity scaling factor	Q	O	.95	.95
Average wing spar perimeter (ft.)	SPE	A	48.2	42.0
Average wing rib perimeter (ft.)	RP	A	8.65	9.0
Hours per lineal foot for fit and trim	HT	O	.216	.216
Joint thickness ratio	TJ4	O		
Average skin thickness	TS4	A	.35	.092
Size scaling exponent	R	O	.95	.95
Assembly hours per unit length for clamp and layout	HLL	O	1.238	1.238
Drilling hours per foot	HD	O	.557	.557
Finish hours per unit length	HE	O	.810	.810
Factor for fastener selection	WFF1	O	1.9	1.83
Install hrs. per ft. for fastener installation	HFI	O	.972	.972
Factor for fastener selection	WFF2	O	1.9	1.83
Secondary Structure				
Leading Edge				
Complex factor for material & constr.	CB1	C	1.0	
Hrs. per pound of structural weight	WC1	O	55.	55.
Weight of structural element	WD1	A	113.4	
Weight scaling exponent	E19	O	.67	.67
Complex factor for material & constr.	CC1	C	1.0	1.0
Hrs per pound of structural weight	WF1	O	48.	48.
Weight scaling exponent	F19	O	.67	.67
Trailing Edge				

	Input Symbol	Input Source	F-111A Wing	A(X) Wing
Complex factor for mat'l. & construction	CB2	C	1.0	
Hours per pound of structural weight	WC2	O	29.	29.
Weight of structural element	WD2	A	189.2	
Weight scaling exponent	E2O	O	.67	.67
Complex factor for mat'l. & construction	CC2	C	1.0	1.0
Hrs. per pound of structural weight	WF2	O	23.	23.
Weight scaling exponent	F2O	O	.67	.67
Ailerons				
Complex factor for mat'l. & construction	CB3	C	0	
Hrs. per pound of structural weight	WC3	O	0	
Weight of structural element	WD3	A	0	
Weight scaling exponent	E21	O	0	
Complex factor for mat'l. & construction	CC3	C	0	
Hrs. per pound of structure weight	WF3	O	0	
Weight scaling exponent	F21	O	0	
Fairings				
Complex factor for mat'l. & construction	CB4	C	0	
Hrs. per pound of structural weight	WC4	O	0	
Weight of structural element	WD4	A	0	
Weight scaling exponent	E22	O	0	
Complex factor for mat'l. & construction	CC4	C	0	
Hrs per pound of structural weight	WF4	O	0	
Weight scaling exponent	F22	O	0	
Tips				
Complex factor for mat'l. & construction	CB5	C	1.0	1.0
Hrs. per pound of structural weight	WC5	O	60.	60.
Weight of structural element	WD5	A	48.	

	Input Symbol	Input Source	F-111A Wing	A(X) Wing
Weight scaling exponent	E23	O	.67	.67
Complex factor for mat'l. & construction	CC5	C	1.0	1.0
Hrs. per pound of structural weight	WF5	O	45.	45.
Weight scaling exponent	F23	O	.67	.67
Spoilers				
Complex factor for mat'l. & construction	CB6	C	0	
Hrs. per pound of structural weight	WC6	O	0	
Weight of structural element	WD6	A	0	
Weight scaling exponent	E24	O	0	
Complex factor for mat'l. & construction	CC6	C	0	
Hrs. per pound of structural weight	WF6	O	0	
Weight scaling exponent	F24	O	0	
Flaps and Flaperons				
Complex factor for mat'l. & construction	CB7	C	1.0	1.0
Hrs. per pound of structural weight	WC7	O	46.	46.
Weight of structural element	WD7	A	912.8	
Weight scaling exponent	E25	O	.67	.67
Complex factor for mat'l. & construction	CC7	C	1.0	1.0
Hrs. per pound of structure weight	WF7	O	42.	42.
Weight scaling exponent	F25	O	.67	.67
Attachment Structure				
Complex factor for mat'l. & construction	CB8	C	0	
Hrs. per pound of structural weight	WC8	O	0	
Weight of structural element	WD8	A	0	
Weight scaling exponent	E26	O	0	
Complex factor for mat'l. & construction	CC8	C	0	
Hrs. per pound of structural weight	WF8	O	0	

	Inlet Symbol	Inlet Source	F-111A Wing	A(X) Wing
Weight scaling exponent	F26	O	0	
Access Doors, Frames & Landing Gear Doors				
Complex factor for mat'l. & construction	CB9	C	0	
Hrs. per pound of structural weight	WC9	O	0	
Weight of structural element	WD9	A	0	
Weight scaling exponent	E27	O	0	
Complex factor for mat'l. & construction	CC9	C	0	
Hrs. per pound of structural weight	WF9	O	0	
Weight scaling exponent	F27	O	0	
Wing Mounted Air Induction				
Complex factor for mat'l. & construction	CB10	C	0	
Hrs. per pound of structural weight	WC10	O	0	
Weight of structural element	WD10	A	0	
Weight of scaling exponent	E28	O	0	
Complex factor for mat'l. & construction	CC10	C	0	
Hrs. per pound of structural weight	WF10	O	0	
Weight scaling exponent	F28	O	0	
High Lift Ducting				
Complex factor for mat'l. & construction	CB11	C	0	
Hrs. per pound of structural weight	WC11	O	0	
Weight of structural element	WD11	A	0	
Weight scaling exponent	E29	O	0	
Complex factor for mat'l. & construction	CC11	C	0	
Hrs. per pound of structural weight	WF11	O	0	
Weight scaling exponent	F29	O	0	
Slats				
Complex factor for mat'l. & construction	CB12	C	0	

	Inlet Symbol	Inlet Source	F-111A Wing	A(X) Wing
Hrs. per pound of structural weight	WC12	O	0	
Weight of structural element	WD12	A	0	
Weight scaling exponent	E30	O	0	
Complex factor for mat'l. & construction	CC12	C	0	
Hrs. per pound of structural weight	WF12	O	0	
Weight scaling exponent	F30	O	0	
Hinges, Brackets & Seals				
Complex factor for mat'l. & construction	CB13	C	0	
Hrs. per pound of structural weight	WC13	O	0	
Weight of structural element	WD13	A	0	
Weight scaling exponent	E31	O	0	
Complex factor for mat'l. & construction	CC13	C	0	
Hrs. per pound of structural weight	WF13	O	0	
Weight scaling exponent	F31	O	0	
Pivots and Folds				
Complex factor for mat'l. & construction	CB14	C	0	
Hrs. per pound of structural weight	WC14	O	0	
Weight of structural element	WD14	A	0	
Weight scaling exponent	E32	O	0	
Complex factor for mat'l. & construction	CC14	C	0	
Hrs. per pound of structural weight	WF14	O	0	
Weight scaling exponent	F32	O	0	
Center Section				
Complex factor for mat'l. & construction	CB15	C	0	
Hrs. per pound of structural weight	WC15	O	0	
Weight of structural element	WD15	A	0	
Weight scaling exponent	E33	O	0	

	Input Symbol	Input Source	F-111A Wing	A(X) Wing
Complex factor for mat'l. & construction	CC15	C	0	
Hrs. per pound of structural weight	WF15	O	0	
Weight scaling exponent	F33	O	0	
Other				
Complex factor for mat'l. & construction	CB16	C	1.0	1.0
Hrs. per pound of structural weight	WC16	O	50.	50.
Weight of structural element	WD16	A	771.0	
Weight scaling exponent	E34	O	.67	.67
Complex factor for mat'l. & construction	CC16	C	1.0	1.0
Hrs. per pound of structural weight	WF16	O	30.	30.
Weight scaline exponent	F34	O	.67	.67
Wing Assembly				
Root rib length (ft.)	WRRP	A	5.33	5.00
Center section operator	WCS	A	2.	2.
Front spar length (ft.)	WFSL	A	21.6	20.8
End rib length (ft.)	WERL	A	1.7	2.0
Rear spar length (ft.)	WRSL	A	22.2	19.7
Size scaling parameter	WR1	O	.95	.95
Joint thickness ratio	TJ7	O		
Average skin thickness	TS7	A	.35	.092
Factor for fastener selection	WFF3	O	1.9	1.83
Cost per unit length for assembly	HE1	O	2.48	2.48
Complexity factor	CMB1	C	1.0	1.0

	Input Symbol	Input Source	F-111A Wing	A(X) Wing
Paint and Finish				
Wing surface area, (ft^2) (One side)	WAS	A	525.	380.
Hours/sq. ft. factor for paint & finish	WHS	O	.07	.07
Rework				
Rework factor	WU	O	.1	.1
Wing primary Box Structural Material Cost				
Ribs Weight scaling factor	G	O	.77	
Weight of finished structure	W1W	A		
Raw material cost per pound	RMC1	O	18.	
Scrappage factor	SF1	O	5.3	
Weight of finished structure	W2W	A		
Raw material cost per pound	RMC2	O	0	
Scrappage factor	SF2	O	0	
Weight of finished structure	W3W	A		
Raw material cost per pound	RMC3	O	0	
Scrappage factor	SF3	O	0	
Spars Weight scaling factor	G		.77	
Weight of finished structure	W4W	A		
Raw material cost per pound	RMC4	O	18.	
Scrappage factor	SF4	O	5.3	
Weight of finished structure	W5W	A		
Raw material cost per pound	RMC5	O	0	
Scrappage factor	SF5	O	0	

	Input Symbol	Input Source	F-111A Wing	A(X) Wing
Weight of finished structure	W6W	A		
Raw material cost per pound	RMC6	O	0	
Scrappage factor	SF6	O	0	
Covers Weight scaling factor	G		.77	
Weight of finished structure	W7W	A		
Raw material cost per pound	RMC7	O	18.	
Scrappage factor	SF7	O	4.5	
Weight of finished structure	W8W	A		
Raw material cost per pound	RMC8	O	0	
Scrappage factor	SF8	O	0	
Weight of finished structure	W9W	A		
Raw material cost per pound	RMC9	O	0	
Scrappage factor	SF9	O	0	
Wing Secondary Structure Material Cost				
Leading Edge Weight scaling factor	G	O	.77	
Weight of finished structure	WD1	A		
Raw material cost per pound	RMC10	O	18.	
Scrappage factor	SF10	O	2.	
Trailing Edge Weight scaling factor	G		.77	
Weight of finished structure	WD2	A		
Raw material cost per pound	RMC11	O	18.	
Scrappage factor	SF11	O	2.	
Ailerons Weight scaling factor	G		.77	
Weight of finished structure	WD3	A		
Raw material cost per pound	RMC12	O	0	
Scrappage factor	SF12	O	0	

	Input Symbol	Input Source	F-111A Wing	A(X) Wing
Scrappage factor	SF12	O	0	
Fairings Weight scaling factor	G		.77	
Weight of finished structure	WD4	A		
Raw material cost per pound	RMC13	O	0	
Scrappage factor	SF13	O	0	
Tips Weight scaling factor	G	O	.77	
Weight of finished structure	WD5	A		
Raw material cost per pound	RMC14	O	18.	
Scrappage factor	SF14	O	2.0	
Spoilers Weight scaling factor	G	O	.77	
Weight of finished structure	WD6	A		
Raw material cost per pound	RMC15	O	0	
Scrappage factor	SF15	O	0	
Flaps and Flaperons Weight scaling factor		O	.77	
Weight of finished structure	WD7	A		
Raw material cost per pound	RMC16	O	18.	
Scrappage factor	SH16	O	2.0	
Attachment Structure Weight scaling factor	G	O	.77	
Weight of finished structure	WD8	A		
Raw material cost per pound	RMC17	O	0	
Scrappage factor	SF17	O	0	
Access Doors, Frames & Landing Gear Doors Weight scaling factor	G	O	.77	
Weight of finished structure	WD9	A		
Raw material cost per pound	RMC18	O	0	
Scrappage factor	SF18	O	0	
Wing Mounted Air Induction Weight Scaling factor	G	O	.77	

	Input Symbol	Input Source	F-111A Wing	A(X) Wing
Weight of finished structure	WD10	A		
Raw material cost per pound	RMC19	O	0	
Scrappage factor	SF19	O	0	
High Lift Ducting Weight scaling factor	G	O	.77	
Weight of finished structure	WD11	A		
Raw material cost per pound	RMC20	O	0	
Scrappage factor	SF20	O	0	
Hinges, Brackets & Seals Weight scaling factor	G	O	.77	
Weight of finished structure	WD13	A		
Raw material cost per pound	RMC22	O	0	
Scrappage factor	SF22	O	0	
Pivots & Folds Weight scaling factor	G	O	.77	
Weight of finished structure	WD14	A		
Raw material cost per pound	RMC23	O	0	
Scrappage factor	SF23	O	0	
Center Section Weight scaling factor	G	O	.77	
Weight of finished structure	WD15	A		
Raw material cost per pound	RMC24	O	0	
Scrappage factor	SF24	O	0	
Other Weight scaling factor	C	O	.77	
Weight of finished structure	WD16	A		
Raw material cost per pound	RMC25	O	18.	
Scrappage factor	SF25	O	2.0	
Wing Primary Box Assembly Material Cost		O		
Assembly material per labor hour	AMF1	O	.68	
Fastener type complexity factor	FM1	O	1.5	

	Input Symbol	Input Source	F-111A Wing	A(X) Wing
Wing Assembly Material Cost				
Assembly material per labor hour	AMF4	O	.68	
Fastener type complexity factor	FM4	C	2.0	

CER Where First Used: Input Name	Input Symbol	Input Source	C-5A Hor.	C-141 Hor.
First Unit Hardware Cost: Hor. Box Detail Fabrication				
Construction Material Complexity Factor				
Ribs	CF1H	C	.7	.96
Ribs	CF2H	C	0	
Ribs	CF3H	C	0	
Spars	CF4H	C	1.0	1.00
Spars	CF5H	C	0	
Spars	CF6H	C	0	
Covers	CF7H	C	2.2	1.00
Covers	CF8H	C	0	
Covers	CF9H	C	0	
Baseline Hours per Pound				
Ribs	HF1H	O	51.	51.
Spars	HF2H	O	52.	25.
Covers	HF3H	O	11.	11.
Estimated Weight of Components (Total Hor.)				
Ribs	WTH	A		
	W1H	A	522.	
	W2H	A	0	
	W3H	A	0	
Spars	WT1H	A		
	W4H	A	896.	

	Input Symbol	Input Source	C-5A Hor.	C-141 Hor.
	W5H	A	0	
	W6H	A	0	
Covers	WT2H	A		
	W7H	A	2320	
	W8H	A	0	
	W9H	A	0	
Weight Scaling Exponent				
Ribs	E1H	O	.67	.67
Spars	E2H	O	.67	.67
Covers	E3H	O	.67	.67
Hor. Box Subassembly:				
Construction Material Complexity Factor				
Ribs	CM1H	C	.89	.89
Ribs	CM2H	C	0	
Ribs	CM3H	C	0	
Spars	CM4H	C	1.0	1.00
Spars	CM5H	C	0	
Spars	CM6H	C	0	
Covers	CM7H	C	0	1.00
Covers	CM8H	C	0	
Covers	CM9H	C	0	
Baseline Hours per Pound				
Ribs	HF4H	O	14.5	14.5
Spars	HF5H	O	19.	19.

	Input Symbol	Input Source	C-5A Hor.	C-141 Hor.
Covers	HF6H	O	7.2	7.2
Estimated Weight of Components (Total Hor.)				
Ribs	WTH	A		
	W1H	A	522.	
	W2H	A	0	
	W3H	A	0	
Spars	WT1H	A		
	W4H	A	896.	
	W5H	A	0	
	W6H	A	0	
Covers	WT2H	A		
	W7H	A	2320.	
	W8H	A	0	
	W9H	A	0	
Weight Scaling Exponent				
Ribs	E4H	O	.67	.67
Spars	E5H	O	.67	.67
Covers	E6H	O	.67	.67
Hor. Box Final Assembly				
Weight of Hor. Box Assembly	HWB	A		
Hours for Transporting & Positioning (Wt.)	HHSA1	O	.1	.1
Hours for Transporting & Positioning (Qty.)	HHSA2	O	2.	2.
Number of cover panels	CN1	A	10.	8.

	Input Symbol	Input Source	C-5A Hor.	C-141 Hor.
Number of ribs	RN1	A	17.	16.
Number of external spars	SNE1	A	2.	2.
Number of internal spars	SNI1	A	0	0
Quantity scaling factor	Q1	O	.95	.95
Average hor. spar perimeter (ft.)	SPE1	A	62.5	52.0
Average hor. rib perimeter (ft.)	RP1	A	16.5	12.0
Hours per lineal foot for fit and trim	HT1	O	.216	.216
Joint thickness ratio	TJ5	O		
Average skin thickness	TS5	A	.10	.095
Size scaling exponent	R1	O	.95	.95
Assembly hrs. per unit length for clamps and layout	HLL1	O	1.238	1.238
Drilling hours per foot	HD1	O	.557	.557
Finish hours per unit length	HE1	O	.810	.810
Factor for fastener selection	HFF1	O	1.	1.2
Install, hours per ft. for fastener installation	HFI1	O	.972	.972
Factor for fastener selection	HFF2	O		
Secondary Structure				
Leading Edge				
Complex factor for mat'l & construction	CB17	C	1.0	1.0
Hrs. per pound of structural weight	HC1	O	55.	55.
Weight of structural element	HD1	A	136.	
Weight scaling exponent	G1	O	.67	.67
Complex factor for mat'l & construction	CC17	C	1.0	1.0
Hrs per pound of structural weight	HF1	O	48.	48.

	Input Symbol	Input Source	C-5A Hor.	C-141 Hor.
Weight scaling exponent	H1	O	.67	.67
Trailing Edge				
Complex factor for mat'l & construction	CB18	C	1.0	1.0
Hrs per pound of structural weight	HC2	O	29.	29.
Weight of Structural element	HD2	A	172.	
Weight scaling exponent	G2	O	.67	.67
Complex factor for mat'l & construction	CC18	C	1.0	1.0
Hrs. per pound of structural weight	HF2	O	23.	23.
Weight scaling exponent	H2	O	.67	.67
Fairing				
Complex factor for mat'l & construction	CB19	C	1.0	1.0
Hrs. per pound of structural weight	HC3	O	36.	36.
Weight of structural element	HD3	A	500.	
Weight scaling exponent	G3	O	.67	.67
Complex factor for mat'l & construction	CC19	C	1.0	1.0
Hrs. per pound of structural weight	HF3	O	34.	34.
Weight scaling exponent	H3	O	.67	.67
Elevators				
Complex factor for mat'l & construction	CB20	C	1.0	1.0
Hrs. per pound of structural weight	HC4	O	67.	67.
Weight of structural element	HD4	A	798.	
Weight scaling exponent	G4	O	.67	.67
Complex factor for mat'l & construction	CC20	C	1.0	1.0
Hrs. per pound of structural weight	HF4	O	67.	67.
Weight scaling exponent	H4	O	.67	.67
Balance Weight				

	Input Symbol	Input Source	C-5A Hor.	C-141 Hor.
Complex factor for mat'l & construction	CB21	C	1.0	1.0
Hrs. per pound of structural weight	HC5	O	5.5	5.5
Weight of structural element	HD5	W	176.	
Weight scaling exponent	G5	O	.67	.67
Complex factor for mat'l & construction	CC21	C	1.0	1.0
Hrs. per pound of structural weight	HF5	O	5.5	5.5
Weight scaling exponent	H5	O	.67	.67
Tips				
Complex factor for mat'l & construction	CB22	C	1.0	1.0
Hours per pound of structural weight	HC6	O	60.	60.
Weight of structural element	HD6	A	180.	
Weight scaling exponent	G6	O	.67	.67
Complex factor for mat'l & construction	CC22	C	1.0	1.0
Hrs per pound of structural weight	HF6	O	45.	45..
Weight scaling exponent	H6	O	.67	.67
Hinges, Brackets & Seals				
Complex factor for mat'l & construction	CB23	C	1.0	1.0
Hours per pound of structural weight	HC7	O	25.	25.
Weight of structural element	HD7	A	122.	122.
Weight scaling exponent	G7	O	.67	.67
Complex factor for mat'l & construction	CC23	C	1.0	1.0
Hrs. per pound of structural weight	HF7	O	21.	21.
Weight scaling exponent	H7	O	.67	.67
Access Doors & Frames				
Complex factor for mat'l & construction	CB24	C	1.0	1.0
Hrs. per pound of structural weight	HC8	O	13.	13.

	Input Symbol	Input Source	C-5A Hor.	C-141 Hor.
Weight of structural element	HD8	A	66.	
Weight scaling exponent	G8	O	.67	.67
Complex factor for mat'l & construction	CC24	C	1.0	1.0
Hrs per pound of structural weight	HF8	O	28.	28.
Weight scaling exponent	H8	O	.67	.67
Attachment structure				
Complex factor for mat'l & construction	CB25	C	1.0	1.0
Hrs. per pound of structural weight	HC9	O	18.	18.
Weight of structural element	HD9	A	14.	
Weight scaling exponent	G9	O	.67	.67
Complex factor for mat'l & construction	CC25	C	1.0	1.0
Hrs. per pound of structural weight	HF9	O	17.5	17.5
Weight scaling exponent	H9	O	.67	.67
Pivots & Folds				
Complex factor for mat'l & construction	CB26	C	1.0	1.0
Hrs. per pound of structural weight	HC10	O	1.0	1.0
Weight of structural element	HD10	A	378.	
Weight scaling exponent	B10	O	.67	.67
Complex factor for mat'l & construction	CC26	C	1.0	1.0
Hrs. per pound of structural weight	HF10	O	10.	10.
Weight scaling exponent	H10	O	.67	.67
Center Section				
Complex factor for mat'l & construction	CB27	C		
Hrs. per pound of structural weight	HC11	O		
Weight of structural element	HD11	A		
Weight scaling exponent	G11	O		

	Input Symbol	Input Source	C-5A Hor.	C-141 Hor.
Complex. factor for mat'l. & construction	CC27	C		
Hrs. per pound of structural weight	HF11	O		
Weight scaling exponent	H11	O		
Other				
Complex factor for mat'l. & construction	CB28	C		
Hrs. per pound of structural weight	HC12	O		
Weight of structural element	HD12	A		
Weight scaling exponent	G12	O		
Complex. factor for mat'l. & construction	CC28	C		
Hrs. per pound of structural weight	HF12	O		
Weight scaling exponent	H12	O		
Horizontal Assembly				
Root rib length (ft.)	HRRP	A		7.25
Center section operator	HCS	A	1.	2.
Front spar length (ft.)	HFSL	A	33.2	28.7
End rib length (ft.)	HERL	A	4.4	2.7
Rear spar length (ft.)	HRSL	A	30.5	26.1
Size scaling parameter	HR1	O	.95	.95
Joint thickness ratio	TJ8	O		
Average skin thickness	TS8	A	.10	.095
Factor for fastener selection	HFF3	O	1.9	1.2
Cost per unit length for assembly	HE2	O	2.48	2.48
Complexity factor	CMB2	C	1.0	1.0

	Input Symbol	Input Source	C-5A Hor.	C-141 Hor.
Paint and Finish				
Horizontal surfaces area (ft^2) one side	HAS	A	1001.	483.
Hours/sq. ft. factor for paint & finish	HHS	O	.07	.07
Rework				
Rework factor	HU	O	.1	
Horizontal Primary Box Structural Material Cost				
Ribs Weight scaling factor	G	O	.77	
Weight of finished structure	W1H	A		
Raw material cost per pound	RMC1H	O	18.	
Scrappage factor	SF1H	O	2.	
Weight of finished Structure	W2H	A		
Raw material cost per pound	RMC2H	O		
Scrappage factor	SF2H	O		
Weight of finished structure	W3H	A		
Raw material cost per pound	RMC3H	O		
Scrappage factor	SF3H	O		
Spars Weight scaling factor	G	O	.77	
Weight of finished structure	W4H	A		
Raw material cost per pound	RMC4H	O	18.	
Scrappage factors	SF4H	O	3.	
Weight of finished structure	W5H	A		
Raw material cost per pound	RMC5H	O		
Scrappage factor	SF5H	O		
Weight of finished structure	W6H	A		

	Input Symbol	Input Source	C-5A Hor.	C-141 Hor.
Raw material cost per pound	RMC6H	O		
Scrappage factor	SF6H	O		
Covers Weight scaling factor	G	O	.77	
Weight of finished structure	W7H	A		
Raw material cost per pound	RMC7H	O	18.	
Scrappage factor	SF7H	O	5.3	
Weight of finished structure	W8H	A		
Raw material cost per pound	RMC8H	O		
Scrappage factor	SF8H	O		
Weight of finished structure	W9H	A		
Raw material cost per pound	RMC9H	O		
Scrappage factor	SF9H	O		
Horizontal Secondary Structure Material Cost				
Leading Edge Weight scaling factor	G	O	.77	
Weight of finished structure	HD1	A		
Raw material cost per pound	RMC10H	O	18.	
Scrappage factor	SF10H	O	3.	
Trailing Edge Weight scaling factor	G	O	.77	
Weight of finished structure	HD2	A		
Raw material cost per pound	RMC11H	O	18.	
Scrappage factor	SF11H	O	3.	
Fairings Weight scaling factor	G	O	.77	
Weight of finished structure	HD3	A		
Raw material cost per pound	RMC13H	C	18.	
Scrappage factor	SF13H	O	3.	
Elevators Weight scaling factor	G	O	.77	

	Input Symbol	Input Source	C-5A Hor.	C-141 Hor.
Weight of finished structure	HD4	A		
Raw material cost per pound	RMC12H	O	18.	
Scrappage factor	SF12H	O	3.	
Balance Weight Weight scaling factor	G	O	.77	
Weight of finished structure	HD5	A		
Raw material cost per pound	RMC26H	O	18.	
Scrappage factor	SF26H	O	3.	
Tips Weight Scaling factor	G	O	.77	
Weight of finished structure	HD6	A		
Raw material cost per pound	RMC14H	O	18.	
Scrappage factor	SF14H	O	3.	
Hinges, Brackets & Seals Weight seal. factor	G	O	.77	
Weight of finished structure	HD7	A		
Raw material cost per pound	RMC22H	O	18.	
Scrappage factor	SF22H	O	3.	
Access Doors & Frames Weight seal. factor	G	O	.77	
Weight of finished structure	HD8	A		
Raw material cost per pound	RMC18H	O	18.	
Scrappage factor	SH18H	O	3.	
Attachment Struct. Weight scaling factor	G	O	.77	
Weight of finished structure	HD9	A		
Raw material cost per pound	RMC17H	O	18.	
Scrappage factor	SF17H	O	3.	
Pivots & Folds Weight scaling factor	G	O	.77	
Weight of finished structure	HD10	A		
Raw material cost per pound	RMC23H	O	18.	
Scrappage factor	SF23H	O	3.	

	Input Symbol	Input Source	C-5A Hor.	C-141 Hor.
Center Section Weight scaling factor	G	O	.77	
Weight of finished structure	HD11	A		
Raw material cost per pound	RMC24H	O	18.	
Scrappage factor	SF24H	O	3.	
Other Weight scaling factor	G	O	.77	
Weight of finished structure	HD12	A		
Raw material cost per pound	RMC25H	O	18.	
Scrappage factor	SF25H	O	3.	
Horizontal Primary Box Assembly Material				
Assembly material per labor hour	AMF2	O	.34	
Fastener type complexity factor	FM2	O	2.6	
Horizontal Assembly Material Cost				
Assembly material per labor hour	AMF5	O	.68	
Fastener type complexity factor	FM5	O		

CER Where First Used: Input Name	Input Symbol	Input Source	F-111 Vertical	C-5 Vertical
First Unit Hardware Cost:				
Vert. Box Detail Fabrication				
Construction Material Complexity Factor				
Ribs	CF1V	C	.99	.70
Ribs	CF2V	C		
Ribs	CF3V	C		
Spars	CF4V	C	1.72	1.00
Spars	CF5V	C		
Spars	CF6V	C		
Covers	CF7V	C	2.40	2.72
Covers	CF8V	C		
Covers	CF9V	C		
Baseline Hours per Pound				
Ribs	HF1V	O	51.	51.
Spars	HF2V	O	52.	52.
Covers	HF3V	O	11.	11.
Estimated Weight of Components (Total Vert.)				
Ribs	WTV	A	43.8	
	W1V	A	43.8	
	W2V	A		
	W3V	A		
Spars	WT1V	A	101.0	
	W4V	A	101.0	

	Input Symbol	Input Source	F-111 Vertical	C-5 Vertical
	W5V	A		
	W6V	A		
Covers	WT2V	A	313.1	
	W7V	A	313.1	
	W8V	A		
	W9V	A		
Weight Scaling Exponent				
Ribs	E1V	O	.67	.67
Spars	E2V	O	.67	.67
Covers	E3V	O	.67	.67
Vertical Box Subassembly				
Construction Material Complexity Factor				
Ribs	CM1V	C	0	.89
Ribs	CM2V	C	0	
Ribs	CM3V	C	0	
Spars	CM4V	C	0	1.00
Spars	CM5V	C	0	
Spars	CM6V	C	0	
Covers	CM7V	C	0	1.00
Covers	CM8V	C	0	
Covers	CM9V	C	0	
Baseline hours per pound				
Ribs	HF4V	O	14.5	14.5
Spars	HF5V	O	19.	19.

	Input Symbol	Input Source	F-111 Vertical	C-5 Vertical
Covers	HF6V	O	7.2	7.2
Estimated Weight of Components (Total Vert.)				
Ribs	WTV	A	43.8	
	W1V	A	43.8	
	W2V	A		
	W3V	A		
Spars	WT1V	A	101.0	
	W4V	A	101.0	
	W5V	A		
	W6V	A		
Covers	WT2V	A	313.1	
	W7V	A	313.1	
	W8V	A		
	W9V	A		
Weight Scaling Exponent				
Ribs	E4V	O	.67	.67
Spars	E5V	O	.67	.67
Covers	E6V	O	.67	.67
Vert. Box Final Assembly				
Weight of Vert. Box Assembly	VWB	A		
Hours for Transportation and Positioning (Wt.)	VHSA1	O	.10	.10
Hours for Transportation and Positioning (Qty)	VHSA2	O	2.	2.
Number of cover panels	CN2	A	2.	16.

	Input Symbol	Input Source	F-111 Vertical	C-5 Vertical
Number of ribs	RN2	A	5.	15.
Number of external spars	SNE2	A	2.	2.
Number of internal spars	SNI2	A	3.	0
Quantity scaling factor	Q2	O	.95	.95
Average ver. spar perimeter (ft.)	SPE2	A	21.6	97.2
Average vert. rib perimeter (ft.)	RP2	A	9.6	28.5
Hours per linial foot for fit and trim	HT2	O	.216	.216
Joint thickness ratio	TJ6	O		
Average skin thickness	TS6	A	.16	.133
Size scaling exponent	R2	O	.95	.95
Assembly hours per unit length for clamp & layout	HLL2	O	1.238	1.238
Drilling hours per foot	HD2	O	.557	.557
Finish hours per unit length	HE2	O	.810	.810
Factor for fastener selection	VFF1	O	1.6	1.83
Install. hours per ft. for fastener installation	HFI2	O	.97	.97
Factor for fastener selection	VFF2	O	1.6	1.83
Secondary Structure				
Leading Edge				
Complex. factor for mat'l & constr.	CB29	C	1.0	1.0
Hrs. per pound of structural weight	VC1	O	55.	55.
Weight of structural element	VD1	A	78.7	
Weight scaling exponent	K1	O	.67	.67
Complex factor for mat'l & constr.	CC29	C	1.0	1.0
Hrs. per pound of structural weight	VF1	O	48.	48.

	Input Symbol	Input Source	F-111 Vertical	C-5 Vertical
Weight scaling exponent	L1	O	.67	.67
Trailing Edge				
Complex. factor for mat'l & constr.	CB30	C	0	
Hours per pound of structural weight	VC2	O	0	
Weight of structural element	VD2	A	0	
Weight scaling exponent	K2	O	0	
Complex factor for mat'l & constr.	CC30	C	0	
Hrs. per pound of structural weight	VF2	O	0	
Weight scaling exponent	L2	O	0	
Fairings				
Complex. factor for mat'l & constr.	CB31	C	0	
Hrs. per pound of structural weight	VC3	O	0	
Weight of structural element	VD3	A	0	
Weight scaling exponent	K3	O	0	
Complex. factor for mat'l & constr.	CC31	C	0	
Hrs. per pound of structural weight	VF3	O	0	
Weight scaling exponent	L3	O	0	
Rudder				
Complex. factor for mat'l & constr.	CB32	C	1.0	1.0
Hours per pound of structural weight	VC4	O	60.	60.
Weight of structural element	VD4	A	139.7	
Weight scaling exponent	K4	O	.67	.67
Complex. factor for mat'l & constr.	CC32	C	1.0	1.0
Hours per pound of structural weight	VF4	O	45.	45.
Weight scaling exponent	L4	O	.67	.67

	Input Symbol	Input Source	F-111 Vertical	C-5 Vertical
Tips				
Complex. factor for mat'l & constr.	CB34	C	1.0	1.0
Hrs. per pound of structural weight	VC6	O	60.	60.
Weight of structural element	VD6	A	21.3	
Weight scaling exponent	K6	O	.67	.67
Complex. factor for mat'l & constr.	CC34	C	1.0	1.0
Hrs. per pound of structural weight	VF6	O	45.	45.
Weight scaling exponent	L6	O	.67	.67
Hinges,Brackets and Seals				
Complex. factor for mat'l & constr.	CB35	C	0	
Hrs. per pound of structural weight	VC7	O	0	
Weight of structural element	VD7	A	0	
Weight scaling exponent	K7	O	0	
Complex. factor for mat'l & constr.	CC35	C	0	
Hrs. per pound of structural weight	VF7	O	0	
Weight scaling exponent	L7	O	0	
Access Doors & Frames				
Complex. factor for mat'l & constr.	CB36	C	0	
Hours per pound of structural weight	VC8	O	0	
Weight of structural element	VD8	A	0	
Weight scaling exponent	K8	O	0	
Complex. factor for mat'l & constr.	CC36	C	0	
Hrs. per pound of structural weight	VF8	O	0	
Weight scaling exponent	L8	O	0	
Attachment Structure				
Complex. factor for mat'l & constr.	CB37	C	0	

	Input Symbol	Input Source	F-111 Vertical	C-5 Vertical
Hrs. per pound of structural weight	VC9	O	0	
Weight of structural element	VD9	A	0	
Weight scaling exponent	K9	O	0	
Complex. factor for mat'l & constr.	CC37	C	0	
Hrs. per pound of structure weight	VF9	O	0	
Weight scaling exponent	L9	O	0	
Pivots and Folds				
Complex. factor for mat'l & constr.	CB38	C	0	
Hrs. per pound of structural weight	VC10	O	0	
Weight of structural element	VD10	A	0	
Weight scaling exponent	K10	O	0	
Complex. factor for mat'l & constr.	CC38	C	0	
Hrs. per pound of structure weight	VF10	O	0	
Weight scaling exponent	L10	O	0	
Other				
Complex. factor for mat'l & constr.	CB39	C	0	
Hrs. per pound of structural weight	VC11	O	0	
Weight of structural element	VD11	A	0	
Weight scaling exponent	K11	O	0	
Complex. factor for mat'l & constr.	CC39	C	0	
Hrs. per pound of structural weight	VF11	O	0	
Weight scaling exponent	L11	O	0	
Vertical Assembly				
Root rib length (ft.)	VRRP	A	5.6	13.6
Front spar length (ft.)	VFSL	A	11.3	41.0

	Input Symbol	Input Source	F-111 Vertical	C-5 Vertical
End rib length (ft.)	VERL	A	3.0	11.1
Rear spar length (ft.)	VRSL	A	9.3	31.9
Size scaling parameter	VR1	O	.95	.95
Joint thickness ratio	TJ9	O		
Average skin thickness	TS9	A	.16	.133
Factor for fastener selection	VFF3	O	1.9	1.83
Cost per unit length for assembly	HE3	O	2.48	2.48
Complexity factor	CMB3	C	1.0	1.0
Paint and Finish				
Vertical surface area (ft^2) one side	VAS	A	313.	961.
Hours per square ft factor for paint & finish	VHS	O	.07	.07
Rework				
Rework factor	VU	O	.1	.1
Vertical Primary Box Structural Material Cost				
Ribs Weight scaling factor	G	O	.77	
Weight of finished structure	W1V	A		
Raw material cost per pound	RMC1V	O	18.	
Scrappage factor	SF1V	O	2.5	
Weight of finished structure	W2V	A		
Raw material cost per pound	RMC2V	O		
Scrappage factor	SF2V	O		
Weight of finished structure	W3V	A		

		Input Symbol	Input Source	F-111 Vertical	C-5 Vertical
	Raw material cost per pound	RMC3V	O		
	Scrappage factor	SF3V	O		
Spars	Weight scaling factor	G	O	.77	
	Weight of finished structure	W4V	A		
	Raw material cost per pound	RMC4V	O	18.	
	Scrappage factor	SF4V	O	5.3	
	Weight of finished structure	W5V	A		
	Raw material cost per pound	RMC5V	O		
	Scrappage factor	SF5V	O		
	Weight of finished structure	W6V	A		
	Raw material cost per pound	RMC6V	O		
	Scrappage factor	SF6V	O		
Covers	Weight scaling factor	G	O	.77	
	Weight of finished structure	W7V	A		
	Raw material cost per pound	RMC7V	O	18.	
	Scrappage factor	SF7V	O	4.5	
	Weight of finished structure	W8V	A		
	Raw material cost per pound	RMC8V	O		
	Scrappage factor	SF8V	O		
	Weight of finished structure	W9V	A		
	Raw material cost per pound	RMC9V	O		
	Scrappage factor	SF9V	O		
Vertical Secondary Structure Material Cost					
Leading Edge	Weight scaling factor	G	O	.77	
	Weight of finished structure	VD1	A		

	Input Symbol	Input Source	F-111 Vertical	C-5 Vertical
Raw material cost per pound	RMC10V	O	18.	
Scrappage factor	SF10V	O	3.	
Trailing Edge Weight scaling factor	G	O	.77	
Weight of finished structure	VD2	A		
Raw material cost per pound	RMC11V	O	18.	
Scrappage factor	SF11V	O	3.	
Fairings Weight scaling factor	G	O	.77	
Weight of finished structure	VD3	A		
Raw material cost per pound	RMC13V	O	18.	
Scrappage factor	SF13V	O	3.	
Rudder Weight scaling factor	G	O	.77	
Weight of finished structure	VD4	A		
Raw material cost per pound	RMC12V	O	18.	
Scrappage factor	SF12V	O	3.	
Tips Weight scaling factor	G	O	.77	
Weight of finished structure	VD6	A		
Raw material cost per pound	RMC14V	O	18.	
Scrappage factor	SF14V	O	3.	
Hinges, Brackets & Seals Weight scaling factor	G	O	.77	
Weight of finished structure	VD7	A		
Raw material cost per pound	RMC22V	O	18.	
Scrappage factor	SF22V	O	3.	
Access Doors & Frames Weight scaling factor	G	O	.77	
Weight of finished structure	VD8	A		
Raw material cost per pound	RMC18V	O	18.	
Scrappage factor	SF18V	O	3.	

	Input Symbol	Input Source	F-111 Vertical	C-5 Vertical
Attachment Structure Weight scaling factor	G	O	.77	
Weight of finished structure	VD9	A		
Raw material cost per pound	RMC17V	O	18.	
Scrappage factor	SF17V	O	3.	
Pivots and Folds Weight scaling factor	G	O	.77	
Weight of finished structure	VD10	A		
Raw material cost per pound	RMC23V	O	18.	
Scrappage factor	SF23V	O	3.	
Other Weight scaling factor	G	O	.77	
Weight of finished structure	VD11	A		
Raw material cost per pound	RMC25V	O	18.	
Scrappage factor	SF25V	O	3.	
Vertical Primary Box Assembly Material				
Assembly material per labor hour	AMF3	O	.68	
Fastener type complexity factor	FM3	O	1.5	
Vertical Assembly Material Cost				
Assembly material per labor hour	AMF6	O	.68	
Fastener type complexity factor	FM6	O	2.0	

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