OPTIMIZING AEROSPACE STRUCTURES FOR MANUFACTURING COST

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Abstract

The evolution of design/manufacturing interaction reveals the need for design methodologies to reduce aerospace systems cost. Cost-driver identification related to performance, design, materials, and manufacturing emphasizes the importance of the preliminary design phase. Data are required on designer-influenced cost elements, for example, with composites these are, hybrids, ply count, curing method, and quality requirements. A "Manufacturing Cost/Design Guide" (MC/DG) for composite and metallic airframes, and also electronics, is discussed. Using examples of components and fuselage panels, the utilization of designer-oriented formats for relative and quantitative costs of manufacturing processes in trade-studies involving structural performance is shown. The MC/DG will also indicate potential cost savings of emerging technologies which accelerate technology transfer.

I. Introduction

The need to arrest and reduce costs at all levels of the aircraft system life-cycle is becoming increasingly important. Qualitative and quantitative data and other information on cost-drivers useful during the design, manufacturing, operation, and maintenance of aircraft systems are essential. This is particularly so because the reduction of newly developed aircraft types has required a need for increased performance; implying reduced weight, better quality, lower ownership costs, and lower energy consumption. Performance must be provided which is affordable. The distribution of costs among major subsystems is shown in Figure 1.

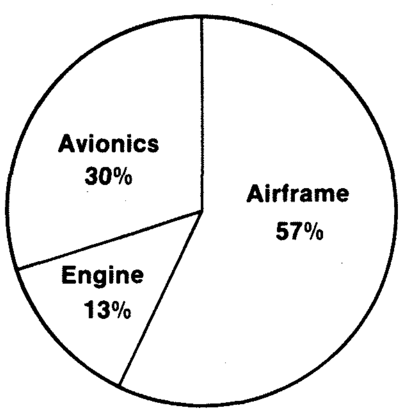


FIGURE 1. Cost Apportionment for an Advanced Supersonic Aircraft

Increased aircraft performance depends upon the excellence of engineering design. Affordable aircraft performance depends upon manufacturing technology recognizing cost-drivers, in both design and manufacture--avoiding cost-drivers in new designs, and by improving manufacturing methods for existing products. Cost-drivers can be avoided in aircraft design by design-to-cost (DTC). Early identification of cost-drivers and corrective action in existing and new products depends upon proficiency in manufacturing-to-cost (MTC). There is a need for proven innovative manufacturing technology <u>ahead</u> of advanced aerospace systems design.

The following are cost-drivers related to various categories of aircraft system development. These are:

- Performance
- Design
- Material selection
- Manufacturing.

As an example, the cost-drivers for auxiliary components are listed below:

- Performance related
  - Reduced weight
  - Higher operating speeds
  - Increased reliability and maintainability
- Design related
  - High part-count
  - Nonstandardization
  - Tight tolerances
- Material related
  - Cost
  - Availability
  - Utilization
  - Energy
  - Inventory
- Manufacturing related
  - Inspection
  - Equipment
  - Cyclic production
  - Small lot sizes
  - Job shop environment
  - Highly skilled labor
  - Metal removal
  - High scrap rate
  - Deburring/hand-finishing
  - Heat treatment
  - Hand fit-up
  - Energy (autoclave curing).

Cost-drivers sometimes result from progress in technology. For example, aircraft structural concepts utilizing advanced composites or superplastic-formed/diffusion-bonded (SPF/DB) titanium require new developments in manufacturing technology. This is necessary if the requirements for increased performance are to be met, while, at the same time, industry remain competitive. To alleviate these problems, the most promising avenue of development is manufacturing sophistication, e.g., computer-aided manufacturing (CAM), robotics and adaptive process control.

The individual designer has seldom been trained or has the experience to conduct structural performance/manufacturing cost trade-studies in his daily efforts. However, today the designer is rated not only on his ingenuity to meet the weight and cost objectives but also to achieve this within design schedule limitations (Figures 2 and 3). Design-to-lowest cost is now a design discipline. However, Tables 1 and 2 show the significant differences between aircraft types. Design teams must be provided with:

- Tools
  - Identification and documentation of cost-drivers and cost reduction methods in airframe design and manufacture
- Incentives
  - Cost targets against which performance of design personnel can be manufactured.

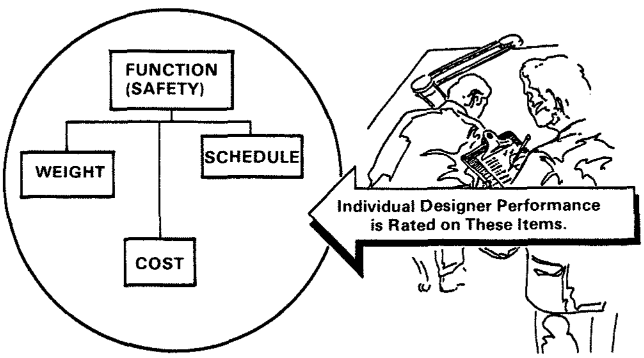


FIGURE 2. Present Aircraft Design Team Priorities

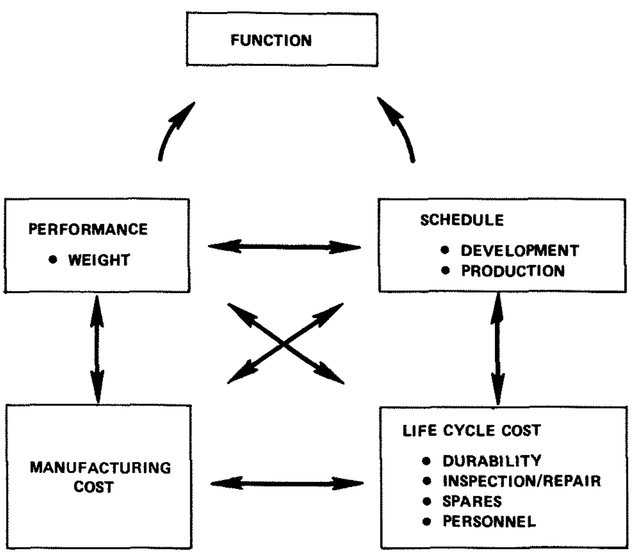


FIGURE 3. Interaction Between Design and Other Disciplines

In the past, the designer had only one resource to determine cost: the cost estimator. The cost estimator is still an important factor in the final iteration of the design prior to production commitment. However, it is often difficult to meet scheduling requirements, as well as, considering an adequate number of design alternatives while ascertaining, with confidence, that the selected design is actually the lowest cost alternative.

Strong interaction between design and manufacturing is essential to achieve this required advancement in manufacturing sophistication and refinements. A "Manufacturing Cost/Design Guide" (MC/DG), under development, provides an unprecedented opportunity for the designer to study a large number, e.g., 10 of alternative design configurations of airframe subassemblies to achieve the lowest manufacturing cost. The scope of the guide is shown in Figure 4.

MC/DG VOLUME CONTENTS: "MANUFACTURING TECHNOLOGIES FOR AIRFRAMES"

I	II	III	IV	V	VI	VII
PROCURED ITEM COSTS	MATERIAL REMOVAL COSTS	DETAIL FABRICATION COSTS	MATERIAL TREATMENT COSTS	PERMANENT JOINING* COSTS	ASSEMBLY* COSTS	TEST, INSPECTION AND EVALUATION COSTS
FORGINGS CASTINGS EXTRUSIONS MATERIALS FASTENERS	MACHINING CHEMICAL MILLING ELECTRICAL DISCHARGE MACHINING EMERGING PROCESSES	METALLIC NON-METALLICS EMERGING PROCESSES	HEAT TREATMENT SURFACE TREATMENT EMERGING PROCESSES	WELDING ADHESIVE BONDING BRAZING EMERGING PROCESSES *SUB-ASSEMBLY	METALLIC ASSEMBLY NON-METALLIC ASSEMBLY EMERGING PROCESSES *MAJOR AND FINAL ASSEMBLY	METALLIC PARTS & ASSEMBLIES NON-METALLIC PARTS & ASSEMBLIES

CATEGORIES = MATERIAL REMOVAL, ETC.
SECTIONS = MACHINING, ETC.
SUBSECTIONS = TURNING AND MILLING, ETC.

FIGURE 4. Design Guide Contents

The MC/DG identifies the cost-drivers over which the designer has control and which he can trade back for performance once the basic performance requirements of the system have been exceeded. The MC/DG also provides information to promote interaction between manufacturing and design, for example, alternative facilities due to shop loading requirements. While the designer is principally interested in the lowest cost process in the manufacture of airframe, avionics, or other subsystem discrete parts, when communicating with manufacturing, the principal discussions may revolve around the alternative methods to produce a certain part. Therefore, the MC/DG man-hour information is presented in basically three forms. These are the lowest cost processes for the designer; manufacturing methods for multiple discrete parts; and multiple manufacturing methods for single discrete parts. The contents of a typical section of the guide are shown on the following page.

While the MC/DG can be used at all levels of the design process, the importance of the preliminary design phase, the "window of opportunity," needs to be emphasized. Figure 5 illustrates how the cost savings leverage decreases as the program progresses. The preliminary design phase is industry's opportunity to achieve a low cost design. It is here where radically innovative approaches to structural design concepts and manufacturing technology choices can significantly impact cost. Configuration selection frequently offers the major

TABLE 1. LOW COST-DESIGN FEATURES OF SOME SUBSONIC AIRCRAFT

Engine

- Use existing engine

Structure

- Primarily aluminum sheet-metal
  - Limited use of forgings and machined parts
- Straight spars (built-up)
- Beaded panel construction versus skin/formers
- Constant section wing-ribs
- Constant section fuselage
  - Straight longerons
  - Common formers

  } Reduction of part count and number of tools
- Constant section control surfaces
  - Reduced tool count
- Skin thickness variation achieved with straight-line cuts (no tapered machining)
- Extensive use of LH/RH interchangeable components (landing gear, control surfaces, etc.)
- Sandwich construction (wing LE & TE and control surfaces)

Assembly

- Use of conventional rivets
  - Minimum use of counter-sinking
- Designed for automatic riveting
  - Minimum use of special fasteners, e.g., Hi-Lok, Hi-Tigue, and two-piece fasteners
- Maximum break-back subassemblies (permits smaller subassemblies and better accessibility)
- Lap joints on skins

Installations

- Early installation of wiring, tubing, avionics, etc., in major sections
- Simple low-pressure hydraulic systems (fewer leak problems)
- Good accessibility for installing wiring and tubing (minimum high density areas; maximum use of prefabricated wire harness and tubing subassemblies)

In General

- Some weight penalty for cost savings
- A good-trade-off study between performance and cost

TABLE 2. DESIGN FEATURES OF SUPERSONIC AIRCRAFT

Engine

- In development phase (engine development parallels with airplane - problems with both systems)

Structure

- Heavy emphasis on use of forgings
- Extensive use of high strength steels and titanium
- Double curvature contours
  - Extensive stretch-forming of sheet-metal
  - Scarfing of machined parts
  - Extensive profiling to contour

  } Excessive tooling costs--these items are cost-drivers vers
- Tapered wings, controlled surfaces, etc.
  - LH/RH components
- Extensive weight saving operations
  - Sculpturing sheet-metal and machined parts
  - Tight radii for sheet-metal and machined parts
  - Hand blending of machined parts

Assembly

- Use of special purpose fasteners
  - Tension bolts, bimetallic, hi-shear
  - Blind fasteners, taper lok
  - Flush head, rivet shaving, etc.

  } Reduces use of automatic riveting
- Assembly break-backs less adaptable to automatic riveting (extensive use of heavy sections, machined parts, etc., fewer break-backs mean higher density assembly lines)
- Butt joints
- Sealing
  - Pressurization (rivets and joints)
  - Faying surfaces
- Special welding techniques

In General

- High performance is prime objective. Cost savings must be proven to be considerable to sacrifice performance opportunity to reduce costs. It is at this preliminary design phase, as Figure 5 indicates, where only a few percent of the program costs have been expended, yet decisions have been made which influence 90 to 95 percent of the total cost including operations and maintenance costs. As the program progresses through detail design and production, it is extremely difficult to reduce the cost by more than a few percent, even with innovative approaches to design and manufacturing. As soon as the detail design phase is approached, the majority of components considered for redesign to utilize alternative advanced manufacturing processes or materials must meet Form, Fit, and Function requirements of the part being replaced. Figures 6 and 7 show the cost impact of decisions as a function of the number of decisions. The major milestones are indicated throughout the development of, in this case, an aircraft system committed to production.

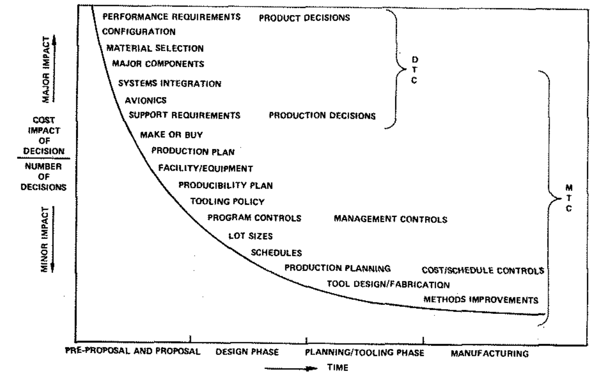


FIGURE 6. Impact of Cost vs Decision

EXAMPLE OF SECTION CONTENTS: SHEET-METAL AEROSPACE DISCRETE PART DEMONSTRATION SECTION

- OVERVIEW SELECTION AID
- FORMAT SELECTION AIDS
- BASE PARTS ANALYZED
  - ALUMINUM
  - TITANIUM
  - STEEL
- DESIGNER-INFLUENCED COST ELEMENTS (DICE)
- MANUFACTURING TECHNOLOGIES
- EXAMPLES OF UTILIZATION
  - ALUMINUM FAIRING
  - STEEL SKIN
  - TITANIUM STRINGER
- FORMATS
  - ALUMINUM: LOWEST COST PROCESSES
  - TITANIUM: LOWEST COST PROCESSES
  - STEEL: LOWEST COST PROCESSES
  - DESIGNER-INFLUENCED COST ELEMENTS (DICE)
  - COMPARISON OF MANUFACTURING TECHNOLOGIES
  - COMPARISON OF STRUCTURAL SECTIONS

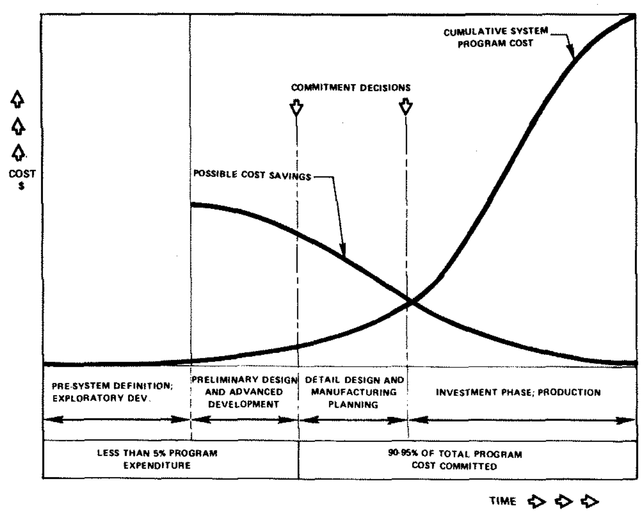


FIGURE 5. Decreasing Leverage to Reduce Cost as System Evolves

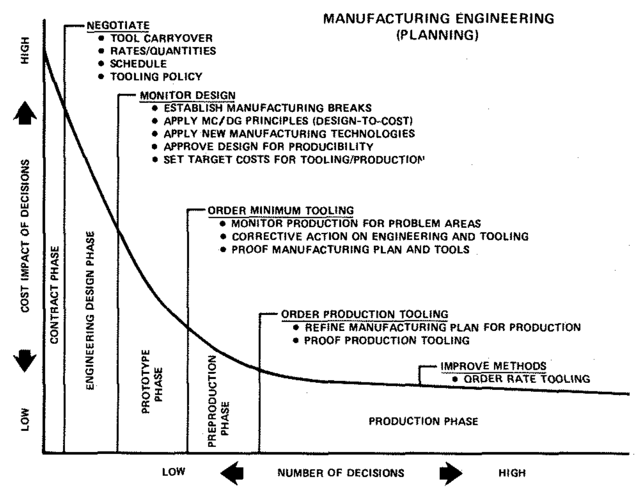


FIGURE 7. Impact of Early Decisions on Cost

Objectives of Design Guide

The objectives of the MC/DG are to:

- Provide to designers urgently-needed, quick, simple, and quantitative cost comparisons of manufacturing processes
- Emphasize design orientation of MC/DG formats and manufacturing man-hour data for use at all phases of design process, i.e., preliminary and detail design, therefore, increasing emphasis on cost as a vital design parameter
- Enable more extensive manufacturing cost trade-offs to be conducted on airframe components and aerospace electronics fabrication and assembly
- Emphasize potential cost advantages of emerging materials and manufacturing methods accelerating the transfer to production hardware of these technologies

- Guide the designer to the lowest cost manufacturing process early in the design phase to avoid cost-drivers
- Identify cost-driving manufacturing operational sequences which provide targets for future computer-aided manufacturing (CAM) efforts.

Design/manufacturing interaction is, of course, crucial in the development of the MC/DG and when the guide is complete, it will serve as a unique and valuable tool to achieve and maintain this interaction. The contents are shown in Figure 4.

Guide Project Organization

This program is administered under the technical direction of Capt. Richard R. Preston, Computer Integrated Manufacturing Branch, Materials Laboratory (AFWAL/MLTC), Air Force Wright Aeronautical Laboratories, AFSC, Wright-Patterson Air Force Base, Ohio 45433.

Battelle's Columbus Laboratories (BCL) is the prime contractor on the MC/DG Data Development Program. The Program Manager at BCL is Mr. Bryan R. Noton. The program is supported by the following airframe and electronics industry subcontractors:

Airframe/Avionic Company	Program Managers
General Dynamics Corporation, Fort Worth Division	P. M. Bunting B. E. Kaminski
Grumman Aerospace Corporation	V. T. Padden A. J. Tornabe
Honeywell, Incorporated	R. Remski
Lockheed-California Company	J. F. Workman
Northrop Corporation, Aircraft Group	J. R. Hendel A. P. Langlois
Rockwell International Corporation, North American Aircraft Operations	R. A. Anderson
Rockwell International Corporation, Avionics & Missiles Group, Collins Avionics Division	J. G. Vecellio

Boeing Commercial Airplane Company also participated in the first two MC/DG programs. Mr. R. H. Hammer, Mr. David Weiss and Mr. Peter H. Bain were the Program Managers.

Multi-Company Approach

Important advantages are evident in the development of manufacturing man-hour data by a team of major aerospace companies. The principal advantages are as follows:

- Provides a cross-section of small and large aircraft for the entire industry; both military and commercial.
- Present team members have large interface with all levels of designers. Industry will, therefore, utilize the MC/DG rapidly in the design process.
- Team draws on each company's expertise making results more viable (expertise and installed manufacturing facilities vary across industry).
- Team has an extensive source of available data and provides a broad base from which to collect and develop data.
- Team provides the required base for deriving <u>average</u> industry data (which cannot be achieved without the team approach).
- Team can verify and thus provide confidence to data and formats for designer use, rather than a parochial point of view of a single company.
- Team provides a broad base for emerging technologies and utilization of DoD manufacturing technology (MT) research program results.

MC/DG and Cost-Estimating Manuals

The team developing the guide assessed Cost-Estimating Manuals (CEM) and compared the objectives and organization of these with those of the MC/DG. The following are the principal differences:

- A CEM is not designer-oriented. It is an estimating tool used primarily by cost-estimators.
- A CEM does not meet the MC/DG development criteria.
- A CEM format is, therefore, not simple for designers to use. It is time consuming and involves complex calculations which will severely conflict with design schedules.
- A CEM does not illustrate or emphasize cost-drivers.
- A CEM does not present relative trade-off data in a form readily accessible by designers at different levels of the design process.
- The number of cost trades, which can be conducted by the airframe industry on different designs involving different manufacturing methods, is limited because of the features of CEMs and the limited number of experienced cost-estimators available.

The Air Force ICAM Thrusts

Because of the complex nature of the objectives of designing and manufacturing aircraft systems to the lowest possible cost, manufacturers are turning increasingly to the use of the digital computer for both the design and manufacture of aircraft. The computer-aided concept is the basis of the Air Force's Integrated Computer-Aided Manufacturing Program, known as ICAM. ICAM will help industry to revolutionize its approach to improving overall productivity, at all levels of the manufacturing hierarchy, from the shop floor operations to executive decision making.

The MC/DG is a critical part of the ICAM program. The MC/DG, at this time, covers design, fabrication, and assembly. Current efforts include test, inspection and evaluation (TI&E), as well as the cost reduction potential of emerging technologies. The following are the thrust areas and planning designations to which the MC/DG is primarily related (Figure 8):

- Fabrication (2000)
- Design (4000)
- Assembly (7000)
- Test, Inspection and Quality Assurance (0000).

MC/DG IMPACT ON ICAM THRUST AREAS

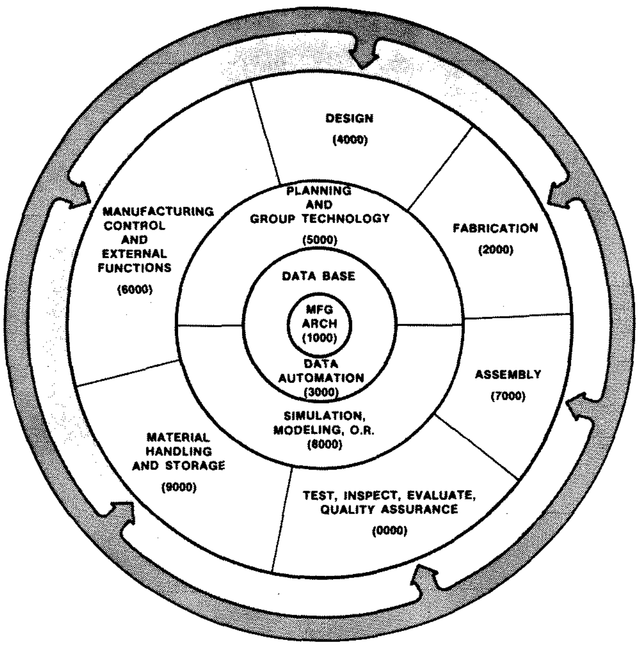


FIGURE 8. Impact of Guide on Major Thrusts of Integrated Computer-Aided Program

Methodologies for Presenting Data to Designers

When presenting cost-drivers and manufacturing man-hour data to designers, the following terminologies are useful:

- Cost-Driver Effects (CDE)
- Cost-Estimating Data (CED).

The objectives of the CDE and CED methodologies are:

- To develop a simple approach for the use of formatted data by designers to achieve lower fabrication costs during design phases: both CDE and CED } DIRECTION
- To provide qualitative cost guidance to perform simple trade-offs to achieve lowest fabrication cost: CDE } COMPARISON
- To provide the designer with the capability to perform trade-offs to achieve quantitative rough-order-of magnitude (ROM) estimated fabrication costs: CED. } COST

The CDE and CED methodologies provide the designer with cost guidance for achieving lower manufacturing costs at the preliminary and detailed design phases:

- Cost-Driver Effects (CDE) achieves qualitative results
- Cost-Estimating Data (CED) provides quantitative results.

The CDE approach enables preliminary and production designers to:

- Identify the intensive cost-drivers that increase the manufacturing cost of the design
- Determine the relative effects of cost-drivers over which he has control
- Utilize cost data enabling simple trade-offs to be performed to achieve comparative costs for those configurations evaluated.

The CDE approach motivates designers. Low cost designs can be realized providing full advantage was taken of the CDE data and <u>lower end of the cost range</u> used wherever possible, while satisfying the performance and reliability requirements.

The CED approach provides preliminary and detail designers with:

- Ability to perform cost-estimates through the use of simplified formats showing manufacturing man-hour data.

The utilization of the formats is indicated in Figure 9.

Designer-Oriented Format/Chart Criteria

The designer-oriented formats developed were reviewed by interdisciplinary groups in industry. Furthermore, designer surveys were conducted and the feedback received on the MC/DG was as follows:

- Must be simple whenever possible
- Must not be time-consuming to use in the design process
- Complicated calculations should be avoided
- Manufacturing data are urgently needed, but with designer orientation
- No single airframe company can provide all manufacturing cost data required due to varying expertise

- Designers are more concerned that it is the lowest cost rather than what it costs, i.e., qualitative comparisons are important.

The MC/DG team agreed that the formats must be created in accordance with the following criteria:

- Emphasize cost-drivers
- Be simple to use
- Use designer language
- Instill confidence
- Be economical
- Be accessible
- Be maintainable.

An example of a format selection aid for the MC/DG sections is shown in Figure 10. An alternate approach is shown in Figure 11.

Airframe Part Definitions

The following indicates the subdivision of airframe parts to determine manufacturing man-hours (composites selected):

1. Base Part: A detailed part in its simplest form, i.e., without complexities such as strip-plies, cut-outs, and doublers.
2. Designer-Influenced Cost Elements (DICE): Includes strip-plies, cut-outs, doublers, and special tolerances that add cost to the increased fabrication operations and tooling required over the standard manufacturing method (SMM) for the base part.
3. Detailed or Discrete Parts: A distinct airframe structural part which may incorporate complexities, e.g., a base part plus DICE, ready for assembly to perform its required function in the airframe.

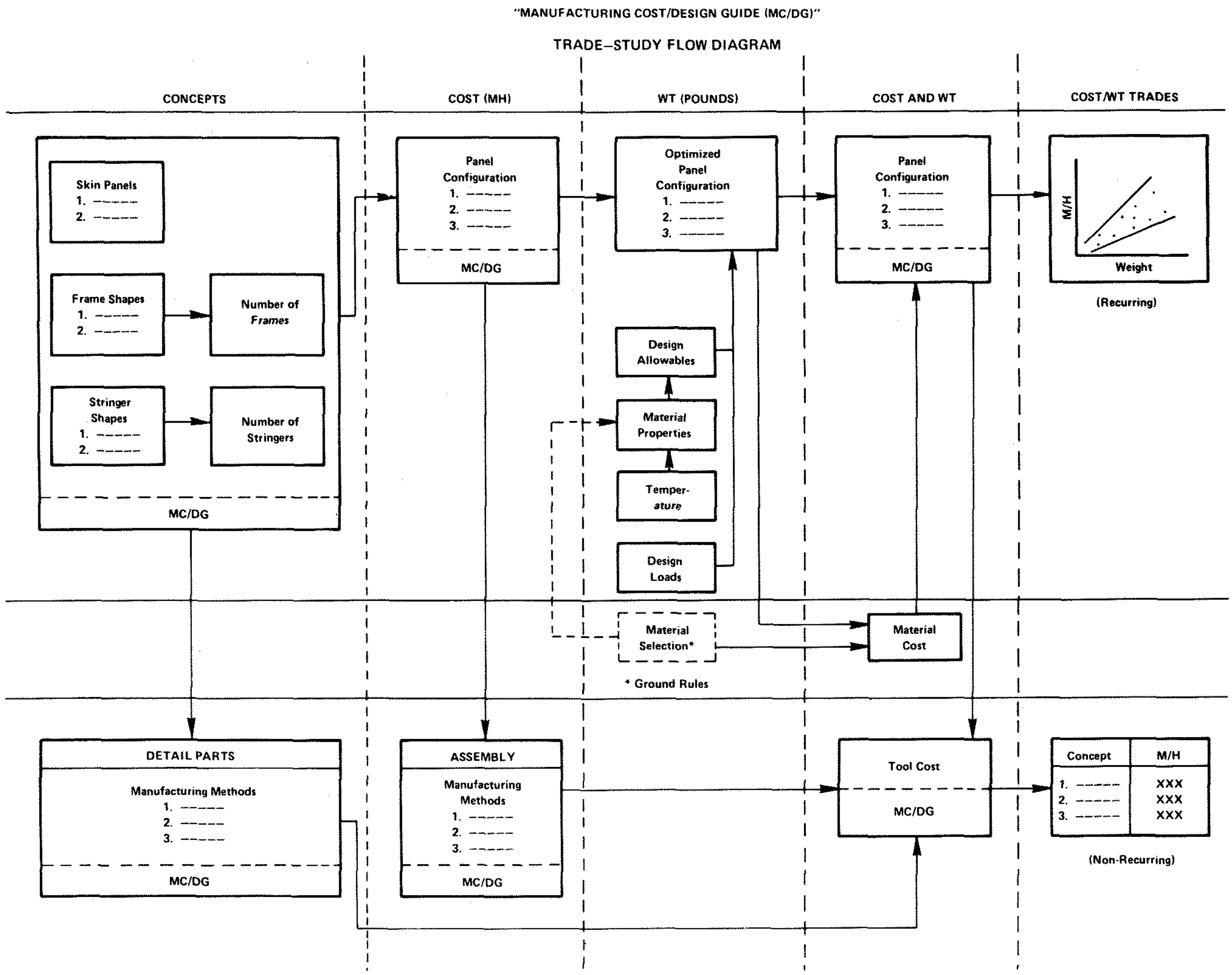


FIGURE 9. Use of Design Guide

Examples of DICE for sheet-metal are shown below:

MC/DG SECTION SELECTION AID

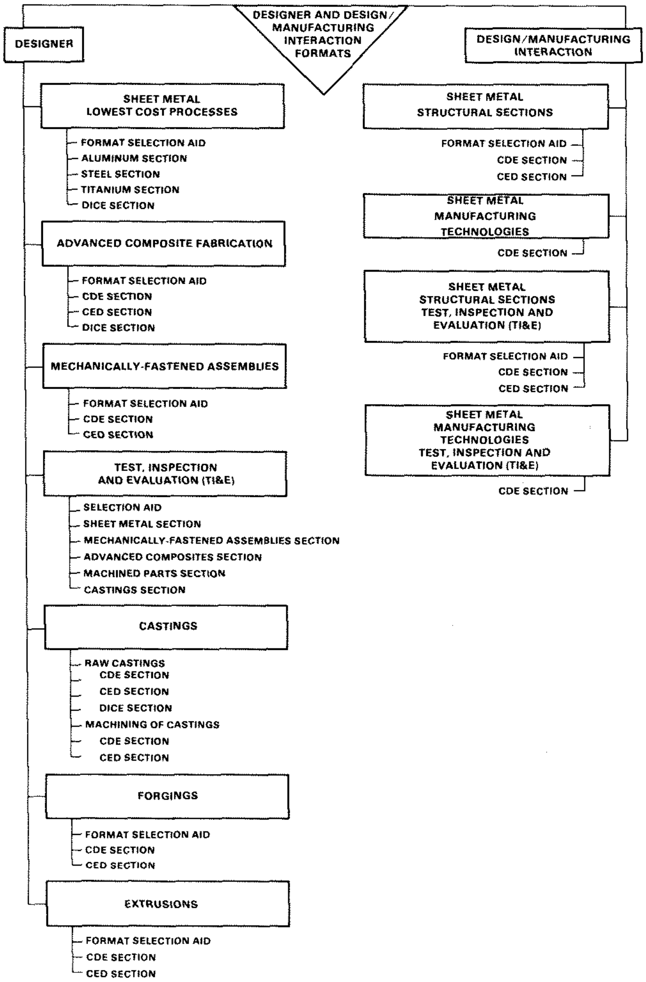


FIGURE 10. Guide Sections Developed

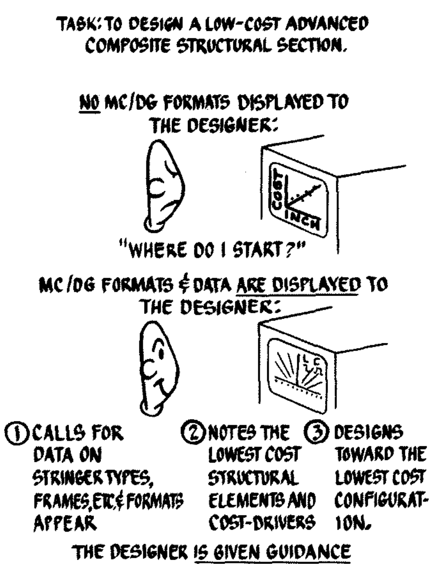


FIGURE 11. Guide Formats Stimulate Trade-Studies

Examples of DICE for sheet-metal are shown below:

DESIGNER–INFLUENCED COST ELEMENTS (DICE)

TWO DISTINCT TYPES

- ADDED STANDARD MANUFACTURING OPERATIONS
  - JOGGLES
  - FLANGED HOLES
  - SPECIAL LINEAL TRIM
  - SPECIAL END TRIM
  - BEND RADII
  - BEADS

  → NORMAL SHOP OPERATIONS

- MANUFACTURING COMPLEXITIES
  - HEAT TREATMENT
  - SPECIAL TOLERANCES
  - SPECIAL FINISH

  → SPECIAL SHOP OPERATIONS

The utilization of these part definitions is shown in Figure 12.

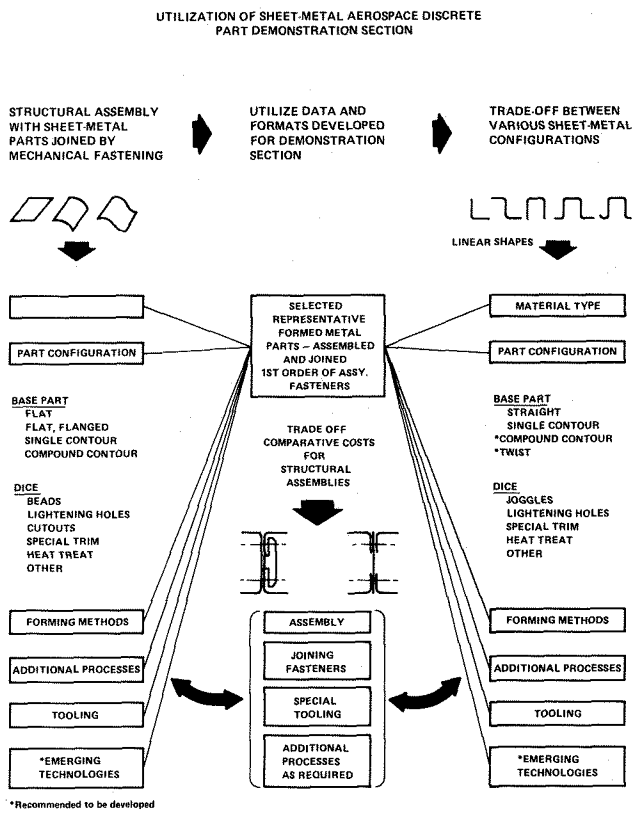


FIGURE 12. Utilization of Base Parts, Designer-Influenced Cost Elements, etc., to Study Assembly

Actual stiffening elements and panels analyzed to determine manufacturing cost are shown in Figures 13 and 14.

COMPOSITE LINEAL SHAPES USED TO DEVELOP FORMATS (INFORMATION ONLY)

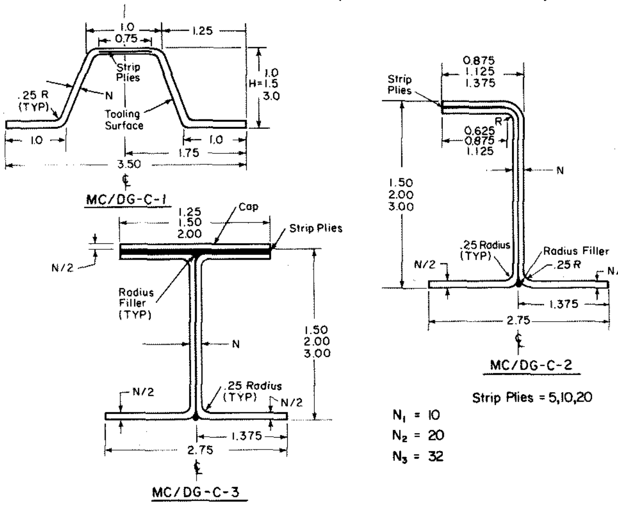


FIGURE 13. Examples of Structural Shapes Studied for Composite Section

COMPOSITE PANEL STRUCTURES

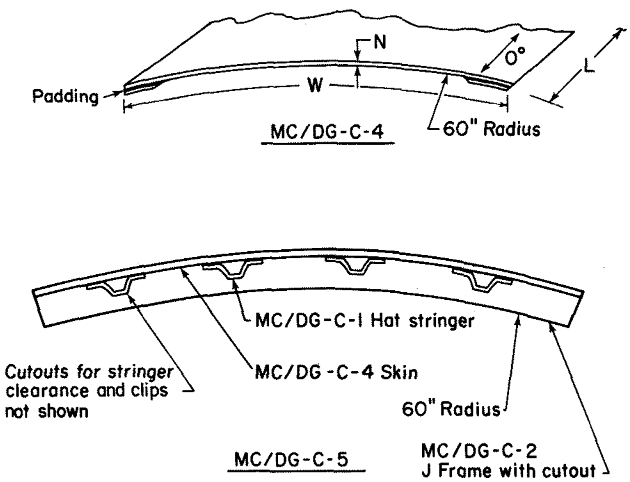


FIGURE 14. Example of Composite Panels Analyzed

To develop the model, or section-by-section layout of the MC/DG, it was necessary to identify the cost-drivers for each conventional and emerging manufacturing technology included in the list of contents, Figure 4. These cost-drivers enabled the data requirements to be specified for subsequent development of the designer-oriented formats, e.g., Figures 15 to 19.

GUIDE TO DESIGNER INFLUENCED COST ELEMENTS (DICE)

MATERIAL	DESIGNER INFLUENCED COST ELEMENTS / BASE PART MANUFACTURING METHOD	STANDARD JOGGLE	FLANGED HOLES	BEADS	HEAT TREATMENT	SPECIAL FINISH	SPECIAL TOLERANCE	LINEAL TRIM	END TRIM	CUTOUTS W/O FLANGES
ALUMINUM	BRAKE FORM	L	L	X	H	L	H	L	L	L
	BRAKE/BUFFALO ROLL	L	L	X	H	L	H	A	A	A
	BRAKE STRETCH	L	L	X	H	L	N	A	A	A
	DIE FORM	N	N	N	N	L	N	L	L	L
	DROP HAMMER	N	N	N	L	L	H	L	X	A
	FARNHAM ROLL	X	L	X	H	L	H	L	X	A
	ROUTED FLAT SHEET	X	L	X	H	L	H	L	X	L
	RUBBER PRESS	N	N	N	H	L	A	L	L	L
	STRETCH FORM	X	L	X	A	L	N	A	X	A
	YODER ROLL	L	L	X	H	L	H	A	A	A
	YODER STRETCH	L	L	X	H	L	N	A	L	A
TITANIUM	BRAKE FORM R.T.	A	L	X	X	L	H	H	H	L
	R.T. BRAKE/HOT STRETCH*	A	L	X	X	L	L	H	H	H
	CREEP FORM*	X	L	X	X	L	L	H	H	H
	FARNHAM ROLL	X	L	X	X	L	H	H	H	H
	HOT PRESS*	N	L	N	X	L	L	N	N	L
	PREFORM/HOT SIZE*	N	L	N	X	L	L	N	N	L
STEEL	BRAKE AND BUFFALO ROLL	A	L	X	X	L	H	H	A	L
	BRAKE FORM R.T.	A	L	X	X	L	H	L	L	L
	BRAKE/R.T. STRETCH	A	L	X	X	L	A	H	L	A
	FARNHAM ROLL	X	L	X	X	L	H	H	L	A
	RUBBER PRESS	N	N	N	X	L	A	L	L	L
	STRETCH FORM	X	L	X	X	L	A	H	A	L

LEGEND

RATING	
X	NOT APPLICABLE
N	NO ADDITIONAL COST INCL. IN BASE PART COST
L	LOW ADDITIONAL COST
A	AVERAGE ADDITIONAL COST
H	HIGH ADDITIONAL COST

Percentage Cost Ranges For Above

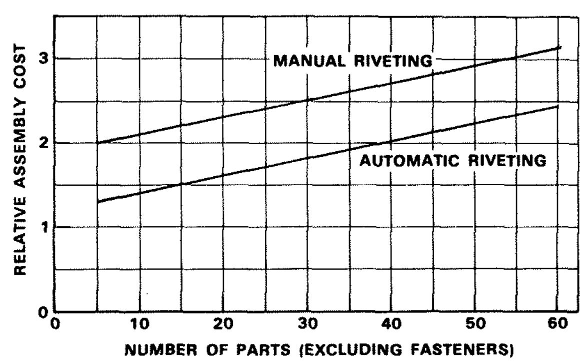
L	Up to 10%
A	10–30%
H	Above 30%

*Denotes one or more elevated temperature processing steps.

DICE-0

FIGURE 15. Cost Guide to Sheet-Metal Design Features (CDE)

EFFECT OF PART COUNT AND FASTENING METHOD



CDE-MFA-II

FIGURE 16. Design Format (CDE) for Sheet-Metal Assembly

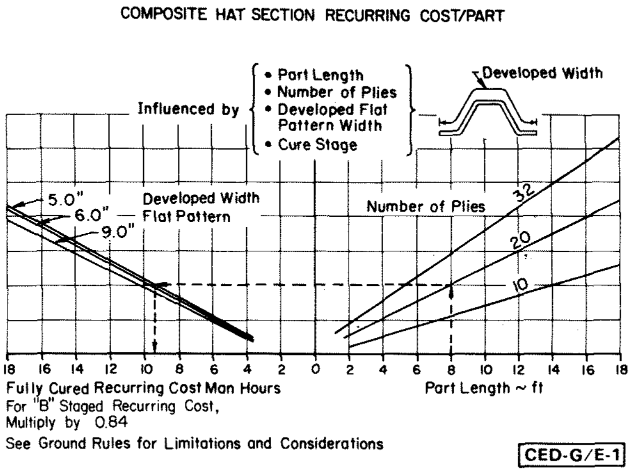


FIGURE 17. Cost Estimating Data Format for Typical Composite Structural Section

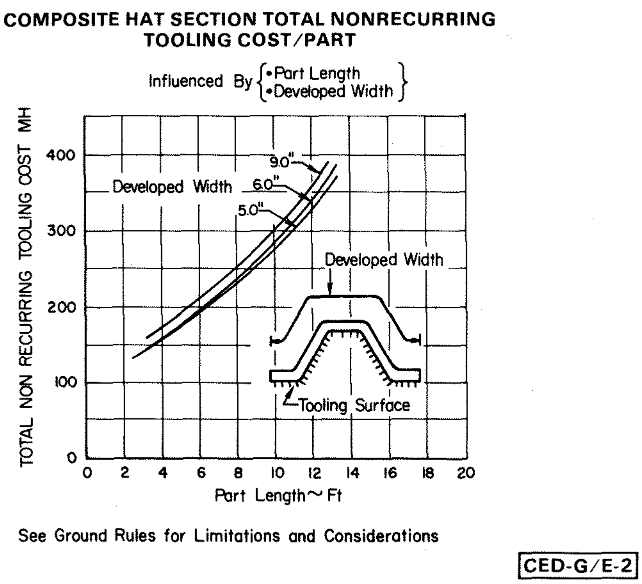


FIGURE 18. Cost of Tooling for Typical Composite Structural Section

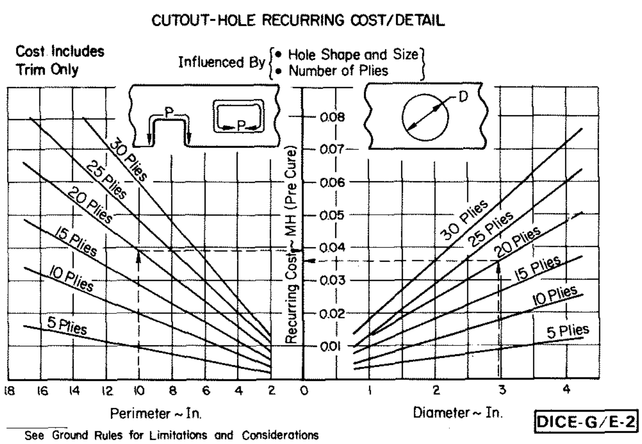


FIGURE 19. Manufacturing Man-Hours for Cut-Outs in Composite Element

The following are examples of cost-drivers in typical fabrication processes:

Forgings

- Forging processes
- Material
- Quality requirements
  - Tolerances
  - Metallurgical properties and NDT/NDE
- Quantity, lead-time, and lot releases
- Complexity
- Size.

Castings

- Casting process
- Material
- Quality requirements
  - Nondestructive testing
  - Destructive testing
  - Finished part tolerances and surface texture
  - Metallurgical properties
- Quantity
- Complexity
- Size
- Subsequent machining.

Sheet-Metal Forming

- Material type (formability)
- Complexity of configuration
- Size
- Tolerances
- Quantity
- Heat-treat conditions and other process requirements.

Surface Treatment

- Surface preparation
- Size
- Complexity
- Energy requirements
- Quantity
- Materials
- Tolerances.

Mechanically Fastened Assemblies

- Accessibility
- Jigging requirements
- Sequencing requirements
- Materials to be joined
- Sealing
- Quantity
- Stack-up of parts

- Number of parts
- Number and type of fasteners
  - Hand rivets
  - Drivematic rivets
  - Threaded fasteners
- Tolerances
- Assembly size.

Welding

- Material
- Welding processes
- Weld method
  - Manual
  - Mechanized
  - Automatic
- Type of joint
- Weld classification
  - Primary structure
  - Secondary structure
  - Non-load bearing, non-structural
- Size of assembly
- Length and number of passes
- Path complexity, e.g., straight, curved, irregular
- Pre- and post-weld processing (heat treatment and straighten)
- Tooling complexity
- Inspection
- Proof loading
- Weld repair.

Tolerances and Surface Texture

- Over-specification of dimensional tolerances
- Over-specification of surface textures
- Relative influence of dimensional tolerances in conjunction with surface textures
- Material types/machinability.

Advanced Composites

- Fiber types
- Part type and function
- Part size
- Number of plies
- Overlaps
- Gaps
- Lot size
- Resin systems
- Fiber mix (hybrids)
- Quality requirements
- Automatic versus manual lamination
- Curing method
- Facility requirements
- Tooling concept.

Test, Inspection and Evaluation Cost-Drivers

Considerable commonality exists in the cost-drivers attributable to test, inspection and evaluation (TI&E) for all manufacturing technologies. There is also a definite correlation between manufacturing and TI&E cost-drivers as a result of the design requirements established by engineering.

Quality control on TI&E costs varies greatly according to the product being produced, but in the aerospace industry range from 10-30% of the manufacturing cost.

The cost of achieving the required quality varies greatly, of course, according to the product. In airframe and engine manufacture, quality control costs range from 4-5% of total sales, or 8-12% of manufacturing costs. On some high performance aircraft components, such as high-speed constant drives, the inspection or quality control costs can be as high as 30% of manufacturing costs.

An analysis of the allocation of the quality-control or assurance costs for airframe and engine manufacture is approximately:

	Airframe	Engines
Prevention Costs	15.4%	20.3%
Detection Costs	57.3%	64.8%
Others	27.4%	15.0%

These values show that over half the quality costs are related to reviewing finished or partially finished articles for defects, that is, after the fact.

Quality-control or assurance costs, although necessary, evidently have a serious impact on the total cost, and as with manufacturing and other costs, can be alleviated if the cost-drivers can be identified and eliminated, or at least reduced.

Quality costs are influenced, not only by the product, but also by the responsibilities normally assigned.

As test, inspection and evaluation (TI&E) is frequently a cost-driver, guidance needs to be provided to, in particular, detail designers on the cost impact of design decisions on TI&E cost. A section of the MC/DG has been developed for TI&E for castings, composites, machining, sheet-metal assembly, and for some aspects of avionics. Quality control spans all phases of system development (Figure 20). Typical formats presenting TI&E cost-drivers and man-hours to designers are shown in Figures 21 and 22.

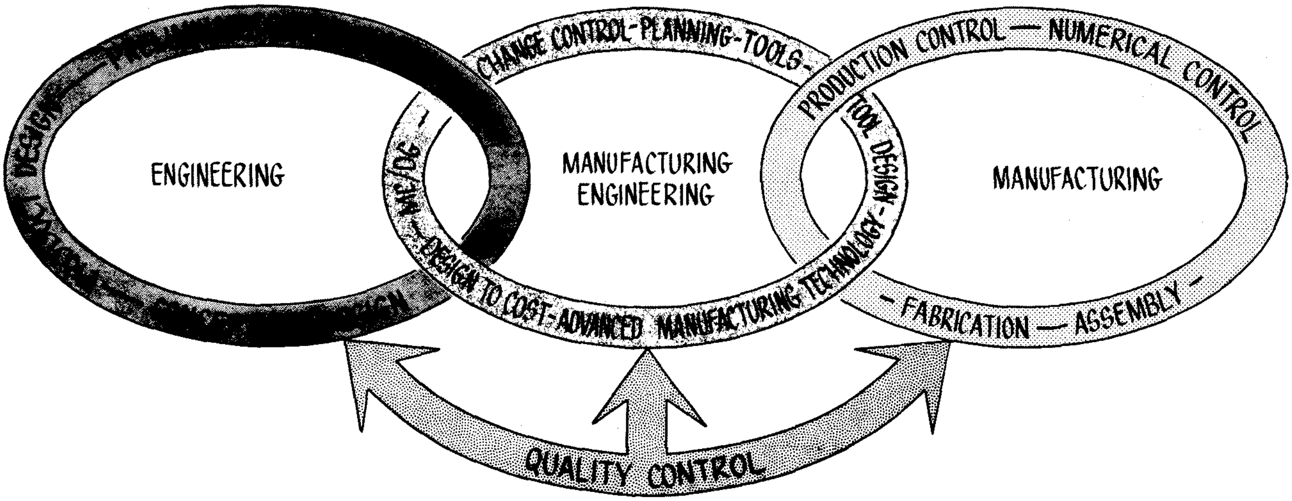


FIGURE 20. The Importance of Quality Control Throughout System Development

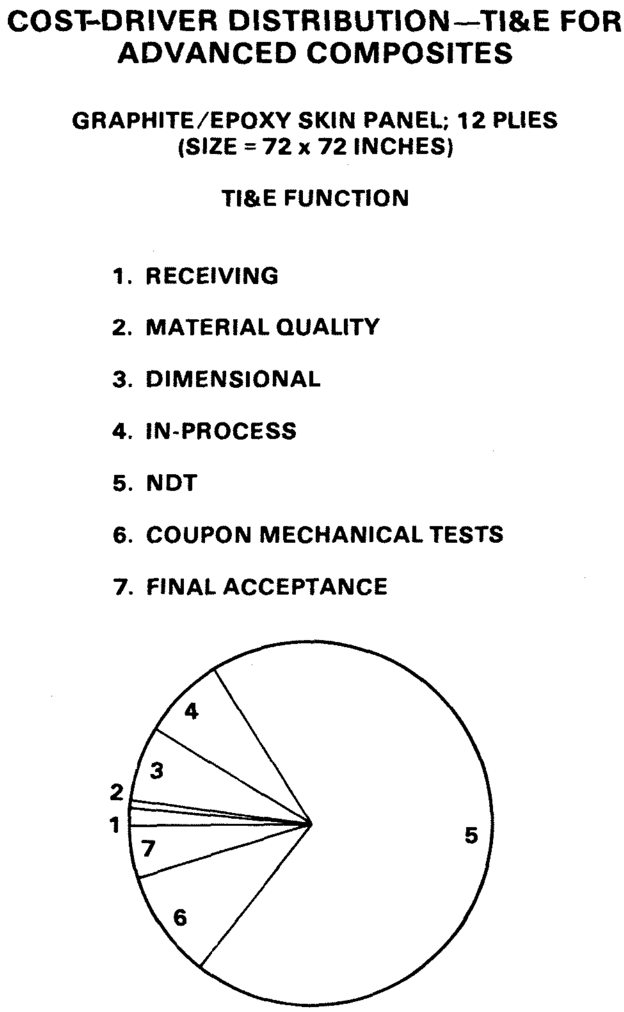


FIGURE 21. Approximate Distribution of Man-Hours for Test, Inspection and Evaluation for Composite Panel

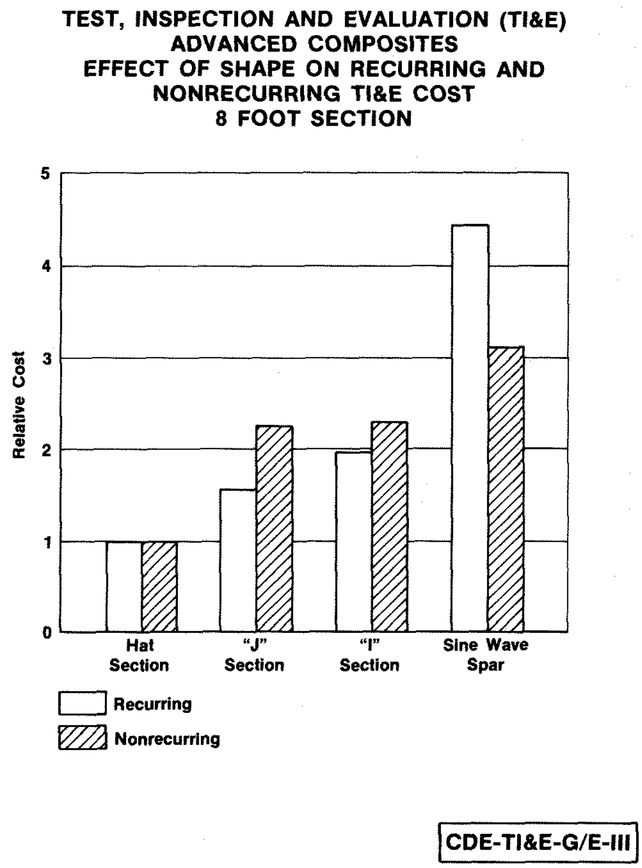


FIGURE 22. Typical Cost-Driver Effect (CDE) Format for TI&E of Various Sections

Designer's Worksheet

To determine the total program costs for both discrete parts and assemblies, a cost worksheet has been prepared for use by industry, Figure 23.

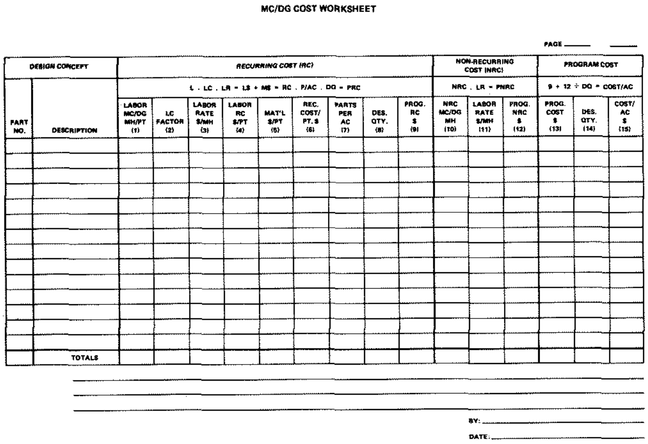


FIGURE 23. Design Guide Cost Worksheet

As experience and facilities vary across the industry, it will be necessary to utilize learning curve factors within each company using the guide. Examples of learning curve values are shown in Table 3.

TYPICAL AEROSPACE INDUSTRY LEARNING CURVES

MANUFACTURING CATEGORY	LEARNING CURVE VALUE
ASSEMBLY, CONTROLS	85%
ASSEMBLY, ELECTRICAL	80%
ASSEMBLY, HYDRAULICS, PNEUMATICS	85%
FUNCTIONAL INSTALLATION	65%
PLASTICS FABRICATION	85%
MACHINING — CONVENTIONAL	90%
MACHINING — NUMERICAL CONTROL	95%
STRUCTURAL ASSEMBLY — BENCH	85%
STRUCTURAL ASSEMBLY — FLOOR	75%
STRUCTURAL ASSEMBLY — FINAL	70%
SHEET METAL FABRICATION	90%

TABLE 3.

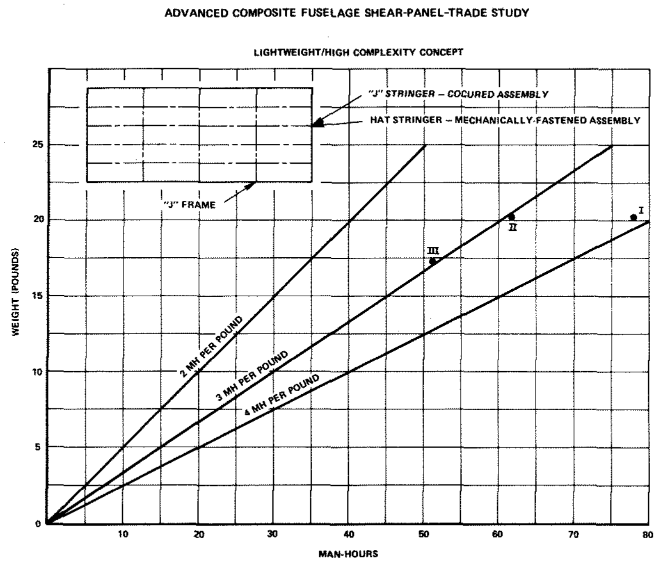


FIGURE 24. Typical Comparison of Concepts Studied for Advanced Composite Fuselage Shear-Panel

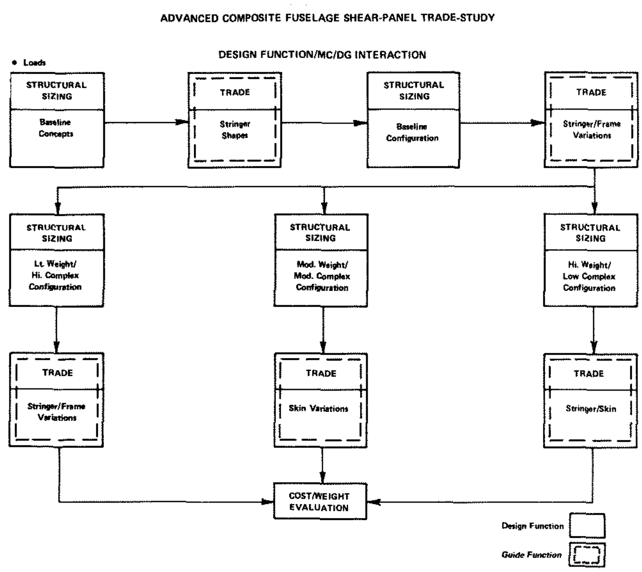


FIGURE 25. Trade-Study Flow for Advanced Composite Fuselage Shear Panels

The results are summarized by the designer for the various categories on configurations studies as indicated in Figure 24. Examples of the categories for a composite fuselage shear-panel are shown in Figure 25.

- Lightweight/high complexity
- Moderate weight/moderate complexity
- High weight/low complexity.

The conclusions of this trade-study are as follows:

- The trade-study successfully demonstrated use of MC/DG
- Manufacturing cost trade-offs were performed by the design discipline
- The MC/DG formats were utilized
  - By interpolation
  - With ease

- Recommended developments
  - Expand formats/data
  - Include further manufacturing methods
  - Include other structural configurations
  - Include other composite materials.

Each aerospace company has, of course, many sources of cost information. These sources are influenced by many factors which are suggested in Figure 26.

The Guide in Education

At the present time, it is difficult for the aerospace industry to recruit qualified design engineers. The shortage of engineers is caused by the fact that several new projects are currently underway in industry--both commercial and military. Because of this and other factors, university graduates will have to play an important role in the aerospace industry in the near future.

There was a large influx of engineers during World War II. The average age of designers is therefore approximately 55 years. Furthermore, many experienced engineers are considering early retirement. Unless some method is developed to transfer the vast amount of knowledge acquired by retiring designers over the years to less experienced designers, a valuable resource will be lost. The MC/DG is one means of documenting and retaining this experience thus achieving the needed transfer of design and manufacturing knowledge.

A further problem is that the industry has been generally disappointed by the lack of design understanding of graduates from our universities and colleges. This has resulted in industry having to conduct expensive and time-consuming training programs for new hires; to familiarize them with the design process employed in the aerospace industry. Because the recent graduate will be expected to become involved in design earlier in his career, tools are needed to help speed up the process of transitioning the graduates to the aerospace design team. The guide can be integrated into the university engineering curricula and industry training programs.

An important area in which the MC/DG can be used for training is in design-to-cost (DTC) programs. It introduces the designer to design-to-lowest cost objectives, cost-drivers, and methodologies seldom covered in his education. It not only introduces the designer to DTC, but it indicates how to achieve that goal by the airframe application examples contained in the MC/DG tutorials on the computerized system, and by the actual trade-studies conducted and included in the appendices to the MC/DG hard copy.

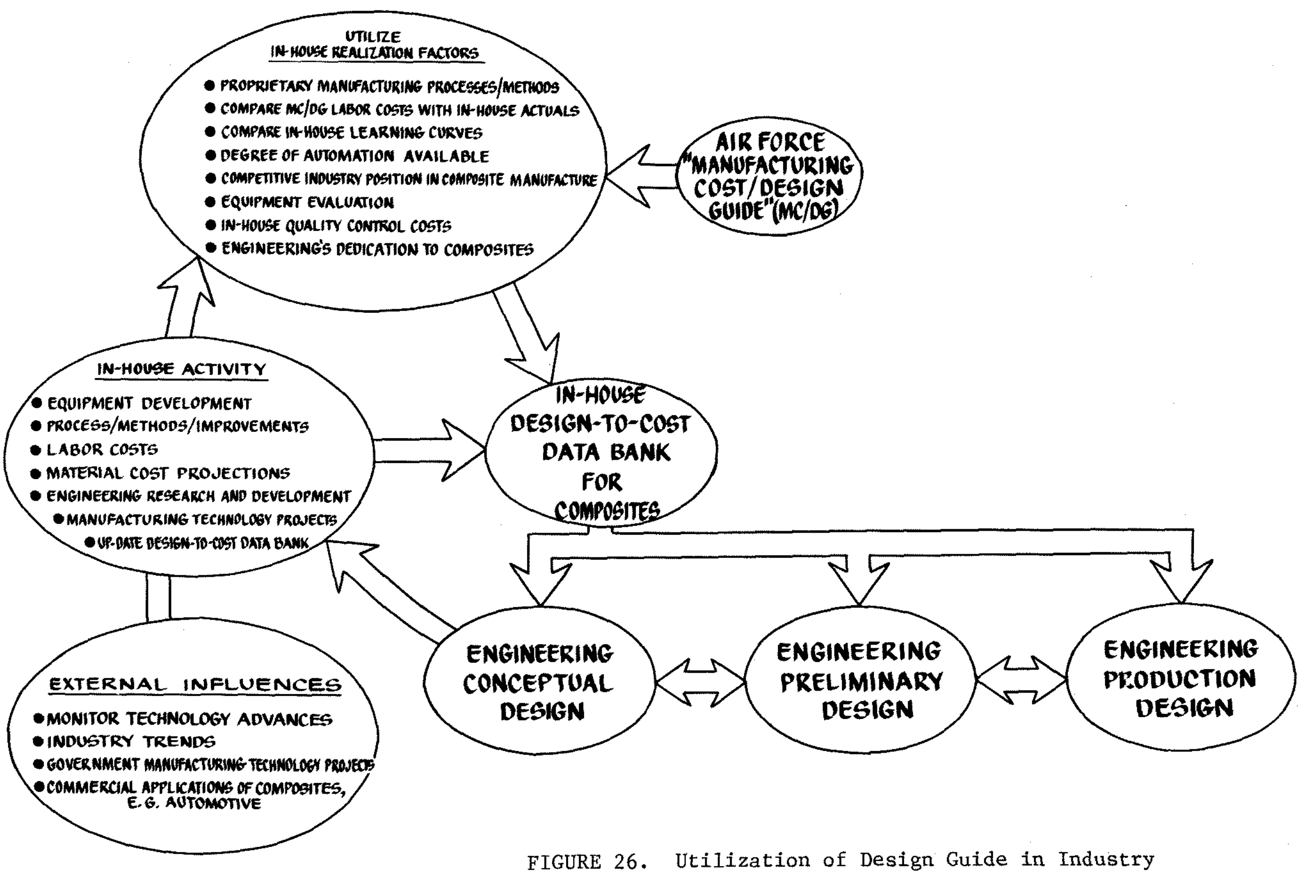


FIGURE 26. Utilization of Design Guide in Industry

The MC/DG introduces the less experienced designer to shop floor activities. The MC/DG provides an insight on how parts are manufactured and will help graduates design a part for lower cost manufacture. This information will improve communication between the less experienced designer and his co-workers, both in the design and manufacturing offices.

In the recent 67th Wilbur and Orville Wright Memorial Lecture, Mr. David S. Lewis stated that:

> "Members of design teams must have an understanding of several disciplines; the need will be for generalists much like the ones who started aviation on the road to success 75 years ago."

Benefits of the MC/DG in colleges and universities are summarized below:

To the Professor

- Provides a realistic, easy-to-use source of manufacturing cost information for aerospace discrete parts and subassemblies
- Provides generally applicable, up-to-date source of information, as opposed to specific information from the brochure of vendors
- Facilitates the alignment of theoretical courses to industry staffing requirements by enabling structural performance/manufacturing cost trade-studies to be conducted in the classroom
- The computerized MC/DG will provide an additional dimension to computer activities in engineering schools.

To the Student

- Introduces students to systematic methodologies for performing trade-studies
- Teaches students the impact of manufacturing technology selection, comparative costs, and manufacturing facility requirements
- Familiarizes students with the use of manufacturing cost data at all stages of the design process
- Aids students in the transition from the classroom or laboratory environment to industry.

Benefits of the Guide

The cost savings possible with future supersonic advanced aircraft, which will use larger quantities of steel, titanium, composites, castings, etc., are expected to be significant. With these advanced aircraft, the MC/DG will stimulate the designer to develop innovative structural configurations at the PD stage, which utilizes the lowest cost manufacturing technologies of both conventional and emerging categories. At present, only a limited number of cost studies can be accomplished on design concepts of aircraft types prior to production release, due to the time-consuming process of obtaining required cost information and estimates. This sometimes results in a more costly design being selected. If it is not possible to accomplish these studies prior to the initial release of the drawings and production go-ahead, the cost associated with making a change becomes so high that many of the cost reduction opportunities are lost.

The MC/DG will be used to support detail design decisions in selecting a design approach at the designer/group leader level. This will allow for relatively fast decisions to be made without the need for higher level direction. Decisions that can be supported with hard facts will be made at the design layout table. A greater breadth will be provided to the designer and the problem of the "point" designer selecting too narrow a scope, resulting in penalties in the program, will be minimized.

As discussed earlier, the MC/DG can serve as an important training document for young and less experienced designers. It can equip them to participate in design-to-lowest cost programs. It will also serve as course material for universities and colleges that are sometimes weak in teaching design synthesis and analysis responding to industry staffing requirements.

There are a number of additional potential opportunities to utilize the MC/DG data developed to stimulate design/manufacturing interaction towards lower cost. These are summarized as follows:

- Pocket-sized book illustrating the high cost-drivers representing 80 percent of airframe costs and cross referencing with MC/DG
  - To contain charts and serve as important tool on the plant floor in discussions on design/manufacturing interaction
- Pocket computer to enable selection of manufacturing processes which avoid or alleviate cost-drivers
- Forecasting tool
- For planning
- Justify acquisition of new equipment, for example, by indicating when equipment should be replaced due to the emergence of a cost-driver such as energy requirements.

Design Guide Computerization

The objective of the computerization of the guide is to provide the design engineer with a tool that will enable him to rapidly conduct trade-offs with respect to manufacturing costs. The computerized guide will:

1. Enable trade-off decisions to be made at the subassembly and component levels
2. Be capable of considering existing as well as emerging materials and processes
3. Allow for the establishing of standards

4. Provide a transition mechanism for design technology to be transferred throughout the aerospace industry.

The computerization program conducted at Battelle was essentially a concept validation study that serves as an example of how the final, full-scale computerized MC/DG system could perform. Therefore, the prime objectives of this concept validation study were:

- Short range--the construction of the sample system for concept validation; this also serves as an example of how individual aerospace companies might construct a computerized MC/DG system from presently available computer software components, and integrate it into company design manufacturing systems and information systems.
- Long range--the development of an implementation plan for a full-scale computerized MC/DG system which would be available for an aerospace company to install on its host computer.

The concept for developing a computerized guide is based on the following considerations:

- Aerospace designers will be primary users of the guide.
- A computerized system will be used in performing manufacturing cost/structural performance trade-offs on alternative design configurations.
- It will support the user in selecting appropriate manufacturing processes, man-hour (cost) data, displayed in the desired formats, to conduct trade-offs between alternative design configurations.
- This tool should be a real-time, interactive mode system designed to utilize state-of-the-art data management and graphics display techniques and the state-of-the-art computer resources.
- It should be implemented using standard languages and structure techniques to develop modular sub-systems suitable for installation on computers now utilized by the aerospace industry, and to provide for the transition to future hardware and software systems.

Designer Needs

The higher levels of the aerospace designer needs are as follows:

- Learn to Use the System. The most immediate need for use of any new system is training. Instructional media needed are a written user guide, classroom reinforcement of concepts, and on-line (computer-aided) tutorials. The computer-aided tutorials should be packaged in the high-level (macro) procedural language required to support general user needs.
- Selection of Parts/Subassemblies (Including Cost/Weight Trade-Studies for Alternative Designs).

  These involved the need to:

  - Retrieve Cost-Driver Effects (CDE) and Cost-Estimating Data (CED): To accomplish retrievals, the user needs to simplistically initiate the use of standard macro procedures for common retrievals and to perform nonstandard index term, numeric range term, and sequential search. Also, when more than one retrieval is performed, either searching or retrieval set Boolean operations must be performed to isolate the unique set of data desired.
  - Display Data in Tables and Graphs: To display data, the user needs to simplistically initiate the use of standard macro procedures for common tables and graphs. For specialized tables, the user needs the ability to conveniently and easily specify the composition of tables; for specialized graphs and charts, the user also needs a convenient and simple method to specify the composition of graphs and charts. Display and analysis (trade-study) results, as well as retrieved data, are needed.
  - Perform Analysis (Trade Studies): To perform analyses, the user needs a wide variety of simplistically invoked stanard macro procedures for common trade-studies. For specialized analyses, external program modules will be needed. For specialized analyses, the user also needs to evaluate analytic expressions involving retrieved (and analyzed) data. The ability to save the analysis results for further analysis is needed.
- Store Procedures and Data Analysis Results: The user needs the ability to simplistically create and save unique procedures. The procedures may be for specialized retrievals, displays, or analyses. Also, the user needs the ability to save the results of analyses in a temporary user-assigned storage.

One possible use of a "dynamic" computerized guide would be to determine the impact of material price fluctuations. With inflation and advanced material production methods contributing to change the cost of materials, the ability to use current and projected material costs is a vital need in all phases of design. This is especially true of conceptual and preliminary designers attempting to incorporate a greater percentage of composite materials into future aircraft. These designers are faced with constantly changing material costs, influenced, for example, by increasing use of the materials. These factors can result in a trade-study becoming obsolete almost overnight. Without a dynamic computerized guide, the number of trade-studies performed would be severely limited, and optimized application of, for example, composite materials would not be possible.

Labor rate fluctuation can be handled in much the same way as the material price variations. As labor rates increase, the need to design a part that can be manufactured with the least amount of hands-on labor will become more important. With the computerized guide, the designer could use projected labor rate values for the proposed time period of production in his trade-study, to determine if the labor rate would cause a major problem in the cost of the project. A format, consistent with previously developed formats, needs to be developed to display the effect of the labor rate (or material price) fluctuations.

The determination of the impact of the position on the learning curve needs to be included into the trade-studies, determined by aircraft buy quantity. It is also a potential use for a computerized guide. The current data are based on a unit 200 learning curve, but a prototype development of maybe five aircraft would have higher values on the learning curve. At the other end of the scale, a very large production contract would have a much lower value. The impact of this learning curve value could be a major factor in management decisions to determine if a bid should be presented for a potential contract. With a computerized guide, the designer could quickly determine the point at which it would be practical to submit a bid (given a target by management).

A "dynamic" computerized guide would also be of use in determining the impact of lot release size, especially for lot sizes of less than 25 units. Beyond 25 units, the impact of lot size is sometimes negligible for trade-study purposes, but as the lot release size decreases below 25 units, its impact increases dramatically. With a computerized guide, the designer, in cooperation with production planning personnel and management, could perform trade-studies to determine an optimum design for various lot release sizes.

The computer would be an invaluable aid in extrapolating and interpolating dimensional data of parts and assemblies. This function of the computerized guide is, in reality, more of a necessity than a convenience, because the data base could not contain all possible combinations of dimensions for aerospace parts. In order to conduct a trade-study, the designer must be able to input the part dimensions and have the computer return the desired data.

Another helpful feature of a computerized guide would be the ability to retrieve earlier design trade-off data in a readily usable and recognizable form. This would allow the designer to quickly evaluate past designs and determine what features would be applicable to his particular problem, and what to avoid. This retrieval feature would also be helpful to designers in preparing presentations to management detailing how the chosen part configuration was developed, thus providing both the designer and management with confidence that the best possible part configuration had been chosen, within the constraints provided.

Conclusions on Airframe Cost-Drivers

Airframes frequently represent over 50 percent of total aircraft manufacturing costs and utilize the most diversified manufacturing technologies. Almost all manufacturing processes, methods, and materials which are used in the other subsystems are utilized in airframe manufacture.

Airframe manufacture is generally referred to in industry as:

- Primary structure
  - Fuselage (longerons, skin, formers)
  - Bulkheads
  - Wing-box (ribs, spars, covers)
- Secondary structure
  - Fairings
  - Doors
  - Control surfaces
  - Removable panels
  - Windshields, canopy, etc.
- Assembly
- Installation
  - Equipment
  - Wiring
  - Tubing
  - Rigging/check-out.

Aluminum (sheet, plate, forgings, castings, extrusions, etc.) is the most common material, with titanium and steels, and also composites, playing an ever-increasing role.

Cost-drivers are frequently common to both primary and secondary structures, with the primary structure containing a major percentage of machined parts and the secondary structure containing primarily sheet-metal or composites.

The following are observations from this program:

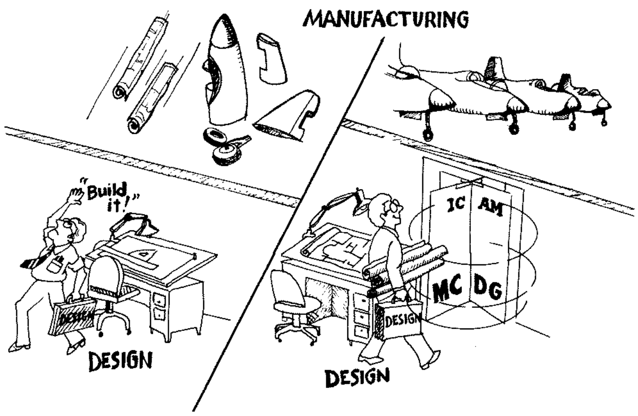
- In aerospace, airframe manufacturing provides the most potential for the maximum return-on-investment with manufacturing technology projects.
- Airframe manufacturing is the most favorable environment for the introduction of advanced materials, processes, and methods due to the full range of manufacturing operations and technology required in airframe manufacture. Investments in technology could be readily transferable to other subsystems.
- This is an indication that we are manufacturing today's airframe with yesterday's technology. Much of the equipment in use is becoming obsolete and little major equipment has been developed over the past 20 to 30

years (with the exception of N/C applications and higher tonnage stretch presses, bladder presses, etc.).

- The airframe design engineer has made excellent progress in providing increased performance, but the manufacturing technology has not kept pace, resulting in attempts to develop technology in conjunction with production.

- A major cause of escalating manufacturing costs is the spiralling cost of labor, material, and the lag in bringing manufacturing technology and equipment "on-stream".

- The possibilty of introducing new manufacturing technologies on a production program is minimal due to the cost of redesign, retesting, and retooling, plus the "form, fit, and function" requirements, but opportunities remain to reduce present costs without major redesign using existing proven approaches.



MC/DG IS THE BRIDGE BETWEEN CAD AND CAM