

## A Unified Approach for Composite Cost Reporting and Prediction in the ACT Program

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### Abstract

The Structures Technology Program Office (STPO) at NASA Langley Research Center has held two workshops with representatives from the commercial airframe companies to establish a plan for development of a standard cost reporting format and a cost prediction tool for conceptual and preliminary designers. This paper will review the findings of the workshop representatives with a plan for implementation of their recommendations.

The recommendations of the cost tracking and reporting committee will be implemented by reinstating the collection of composite part fabrication data in a format similar to the DoD/NASA Structural Composites Fabrication Guide. The process of data collection will be automated by taking advantage of current technology with user friendly computer interfaces and electronic data transmission.

Development of a conceptual and preliminary designers' cost prediction model will be initiated. The model will provide a technically sound method for evaluating the relative cost of different composite structural designs, fabrication processes, and assembly methods that can be compared to equivalent metallic parts or assemblies. The feasibility of developing cost prediction software in a modular form for interfacing with state of the art preliminary design tools and computer aided design (CAD) programs will be assessed.

### Introduction

Boeing Commercial Airplane (BCA) Group and Douglas Aircraft Corporation (DAC) use approximately 400,000 pounds of composites per year in spoilers, rudders, elevators, doors, and other secondary structure. The rate of application of composites to empennage, wing, and fuselage commercial airframe primary structure has been disappointingly slow. Composite materials are an obvious choice for performance optimization, corrosion resistance, and fatigue suppression, but before a bold leap toward more extensive use of composites can be expected in commercial applications, accurate cost prediction methods and confidence that production costs can be predicted accurately must be demonstrated. The Advanced Composite Technology Program's goal is to establish design concepts, develop manufacturing approaches, and demonstrate the structural integrity and cost effectiveness of innovative low cost composite assemblies, providing confidence for production commitment to primary structure by the turn of the century.

The need to unify cost reporting and prediction methods for the Advanced Composites Technology (ACT) program has been identified by industry participants during program reviews. A [REDACTED] considered a high priority issue to assure a valid comparison of cost effective structural concepts, material forms, and assembly methods being developed by the participants. The Structures Technology Program Office (STPO) has hosted two workshops with representatives from the commercial airframe companies to define

- (1) a standard cost tracking and reporting format, and
- (2) a development plan for a conceptual and preliminary design cost prediction model.

The preliminary design process has been identified as the most critical period of opportunity for substantial cost reduction during an airframers hardware production cycle. Boeing has experienced that 70% of airplane fabrication costs are fixed by the time the design is frozen and that the influence of engineering on fabrication cost reductions is significantly reduced once the design is completed. Concurrent engineering interdisciplinary teams are emphasizing cost evaluation at the early stages of the development cycle in the preliminary design process. The advent of CAD/CAM on powerful work stations provides the designer with the possibility of including cost as a complementary variable in the design process. A comparative cost algorithm, which can function purely as an engineering design tool to evaluate different design concepts, would be exceptionally valuable to concurrent engineering teams. As part of the overall NASA effort to improve the economic viability of composite structures, the STPO plans to implement two activities related to composite costs:

1. Reinstigate and automate the collection of composite part fabrication costs in a format similar to the DoD/NASA Structural Composites Fabrication Guide (Fab. Guide) (Ref. 1).
2. Determine the feasibility for development of a universally accepted academically rigorous theoretical method for predicting the relative cost of different composite structural designs in the preliminary design process.

### **The NASA-Industry Workshops**

The first workshop on cost reporting and prediction (Ref. 2) was held in Norfolk, VA in December 1989. The purpose of the workshop was to

1. Determine the procedures currently used by the industry to predict the production cost of composite components and to determine if there was a need to develop or modify existing methodology to account for new composite manufacturing processes such as tow placement, resin transfer molding, and filament winding.
2. Establish a uniform procedure for reporting the costs of parts developed in the ACT program.

Participants at this workshop were divided into cost reporting and cost prediction committees and concluded that

1. Development of standard cost reporting and prediction methodologies were desirable.
2. Each company would identify representatives to serve on a steering committee to draft a plan.

3. The STPO should strive for implementation of unified reporting and prediction methods by the last quarter of 1990.

The second workshop (Ref. 3) was held at Douglas Aircraft Corporation in Long Beach, CA in February 1990. The purpose of the second workshop was to

1. Establish standard forms for cost collection and reporting.
2. Establish written requirements for a conceptual and preliminary designers' cost prediction model.

Participants at this workshop were divided into cost reporting and cost prediction committees and requested to report their recommendations to STPO by July 15, 1990. L. E. Meade (Lockheed Aeronautical Systems Co.), chairman of the cost reporting group, indicated that representatives of the three commercial companies agreed that the Data Abstraction Form developed for the Fab. Guide adapted to a Lotus 123 spreadsheet format would be an acceptable form for the ACT program.

G. Swanson (BCA), chairman of the cost prediction group, prepared a committee report (Ref. 4)\* with the following recommendations:

1. NASA should take an active role in updating the composites data base with current state-of-the-art cost data and manufacturing processes. A "subscriber" approach, wherein contributors to the data base would have access to it, was suggested as one approach for obtaining data in addition to the ACT program participants' hardware cost results.
2. NASA should ensure that the data base be kept current with long term support.
3. NASA should develop a producibility guide to assist design-build teams in making decisions on a design concept. This document would supply information on selected manufacturing processes and provide information to the designer on types of design details to avoid that would adversely affect cost. At the same time, large cost drivers would be delineated. An implementation plan to address CAD interfaces would be required to accompany the development of the producibility guide.
4. NASA should establish standard material costs (including future costs) to be used for comparative costing studies and include them in the data base.

### **Cost Tracking and Reporting**

As part of the ACT program, various airframe manufacturers will be designing and fabricating composite components that are more cost effective than previous composites or equivalent aluminum structure. The components, of various sizes, will be made using low cost and automated fabrication processes. In order to assess the cost effectiveness of the designs and their fabrication processes, cost information must be acquired on the fabrication process. As noted above, the workshop committee suggested that the form originally developed for the Fab. Guide included all the essential information and was familiar to the industry. Most Government programs on composite

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\*(Letter Report. See Ref. 4)

structure development during the 1970's and the early 1980's included requirements for the completion of the "Fabrication Guide Data Abstraction Form". The effort to collect fabrication information ended about 1983. More recent contracts have not had that requirement.

In revitalizing the data collection activity, STPO will attempt to automate and simplify the process. A standard, unified cost collection Data Abstraction Form will be implemented via a software module that easily allows the relevant manufacturing data to be collected and formatted for subsequent inclusion in a fabrication cost data base.

The proposed cost tracking program will proceed in two stages:

1. The procedure for entering data will be standardized to a user friendly software interface which is MS-DOS<sup>®</sup>, Macintosh<sup>™</sup>, and UNIX<sup>™</sup> compatible.\*
2. A data base with an appropriate data base management system (DBMS) will be established to store the existing fabrication data as well as data acquired in the current programs. The DBMS will be selected so that the data base can be easily updated and sorted to provide a variety of forms, charts and graphs. The data base will be accessible to companies that contribute fabrication data.

The first task is essentially an evolution in the technology of the Fab. Guide Data Abstraction Form (DAF). Interactive software will be developed to run under MS-DOS, Macintosh, or UNIX systems. The software will be "intelligent" enough to prompt the user for only required input, and present the user with a flow diagram of a composite structure manufacturing process. Figure 1 shows the hierarchical structure of the DAF. The diagram will be displayed to the user and boxes

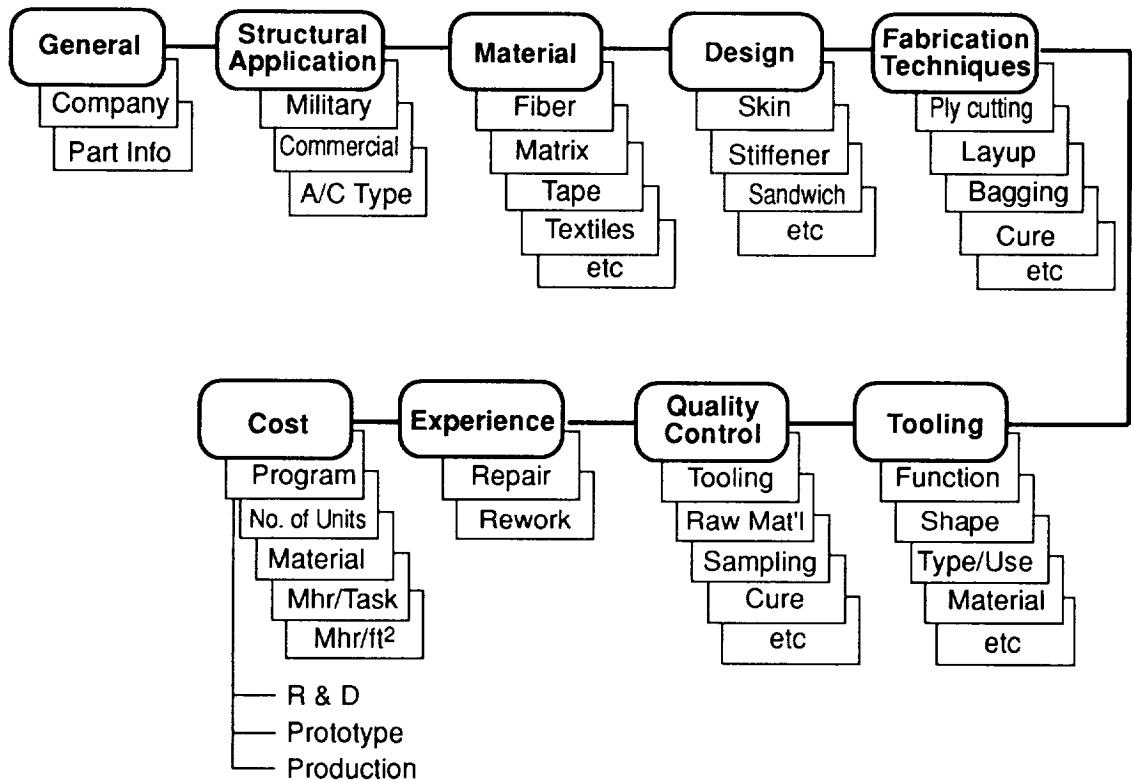


Figure 1. - Hierarchical structure of data abstraction form.

will serve as menus and "buttons" that allow the user to move directly to any section of the form. Figure 2 shows screen images of a demonstration version of a portion of the data input form which runs under HyperCard™\* on the Macintosh. The program is configured so that the cursor moves to the next appropriate field after input has been entered.

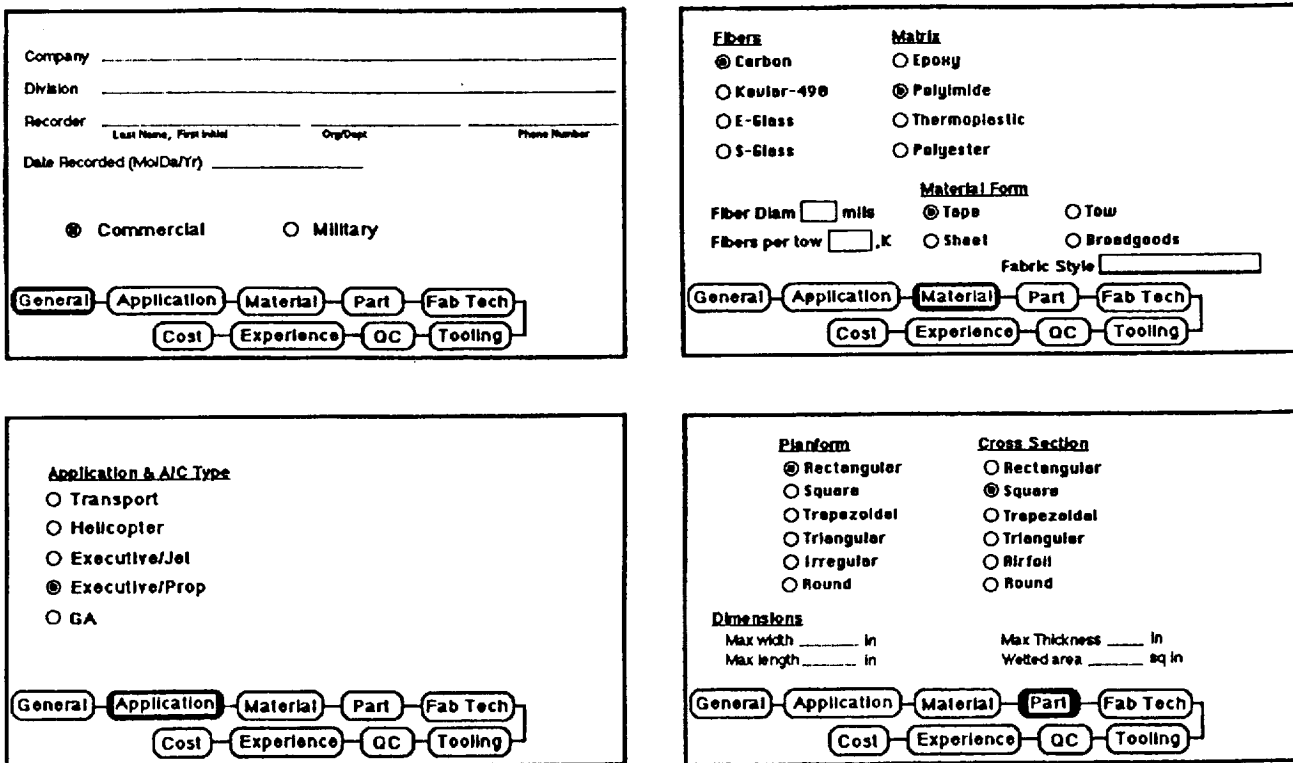
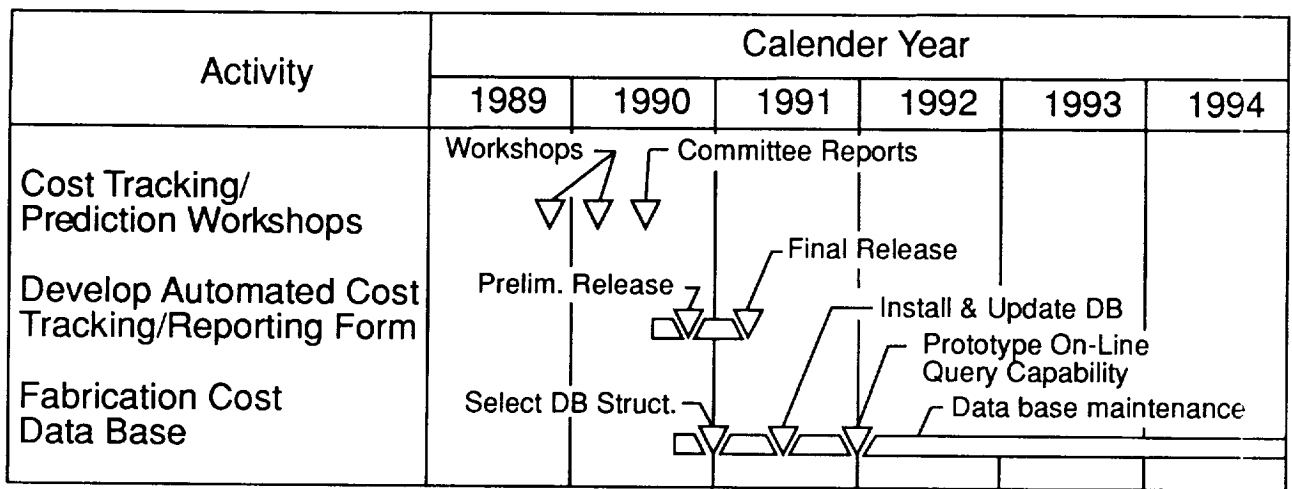


Figure 2. - Screen images of automated Data Abstraction Form.

After the software form has been filled out, the user will have the option of electronically transmitting these data to a NASA host mini-computer via an electronic mail system, by calling an 800 number to log in directly, or by mailing a disc.

Another software module that will be resident on the host computer will be a data input parser (checker). This will verify that the user inputs are within "reasonable" and "acceptable" ranges. Once developed, this software could be made available directly to the user. It will also be available for interactive use when the data is directly transmitted to the host computer. Companies will not interface with the data base directly, but only with a host data collection file. Data will be entered into the data base by NASA only after the source and the acceptability of the data are verified.

The last software module that will be developed will be one which allows a user to interface with the fabrication cost data base in a "read only" mode. A user friendly interface is envisioned that will allow the user to extract information based on specified queries such as "provide the labor hours required for manufacturing hat stiffeners of any composite material by all manufacturing processes." A schedule for the development and distribution of the data abstraction form and the establishment of the data base is given in figure 3.



**Figure 3. - Fabrication cost data base development.**

The selection of a DBMS requires careful attention in order to ensure that it is both user friendly and versatile. The user interface must be structured so that the user will not have to learn and understand details of the data base structure in order to access it and obtain information from it. A survey will be made of the DBMS packages available on the market with the following attributes:

1. Wide acceptance/use in the field.
2. UNIX based or demonstrated on a number of platforms.
3. A demonstrated MS-DOS and Macintosh interface capability.

For the future, one can envision including additional information in the data base such as tables of available material forms and their current costs, manufacturers' property data, digitized drawings and images of parts, contractor reports, video images, audio reports, etc.

### Composite Cost Prediction

"All costs are based on facts that may or may not be true" (Ref. 5). The word "cost" has a variety of meanings to different disciplines. Designers, accountants, estimators, managers, manufacturing engineers etc. are interested in different levels of detail and economic conditions that imply a numerical value to the term "cost". Often price is confused with cost. This lack of uniform, concise description of the elements and time-valued rate constants that make up recurring cost, nonrecurring cost, etc. leads to confusion and debate. Unifying the way the composites community represents hardware cost for composites and metallics is perhaps as much a communication problem as it is a demanding engineering challenge. This program will determine the feasibility of establishing theoretical cost functions that relate geometric design features to summed material cost and computed labor content in terms of process mechanics and physics.

Figure 4 provides a flow chart form of the detailed cost bookkeeping elements that should be considered when comparing composite aircraft cost to a metallic equivalent. The ability to fabricate very large one piece composite structure to eliminate thousands of fasteners in equivalent aluminum hardware requires assembly level cost estimating to establish a fair comparison during preliminary design. The exceptional fatigue life and resistance to environmental degradation of composites should be considered since they provide favorable maintenance and supportability comparisons.

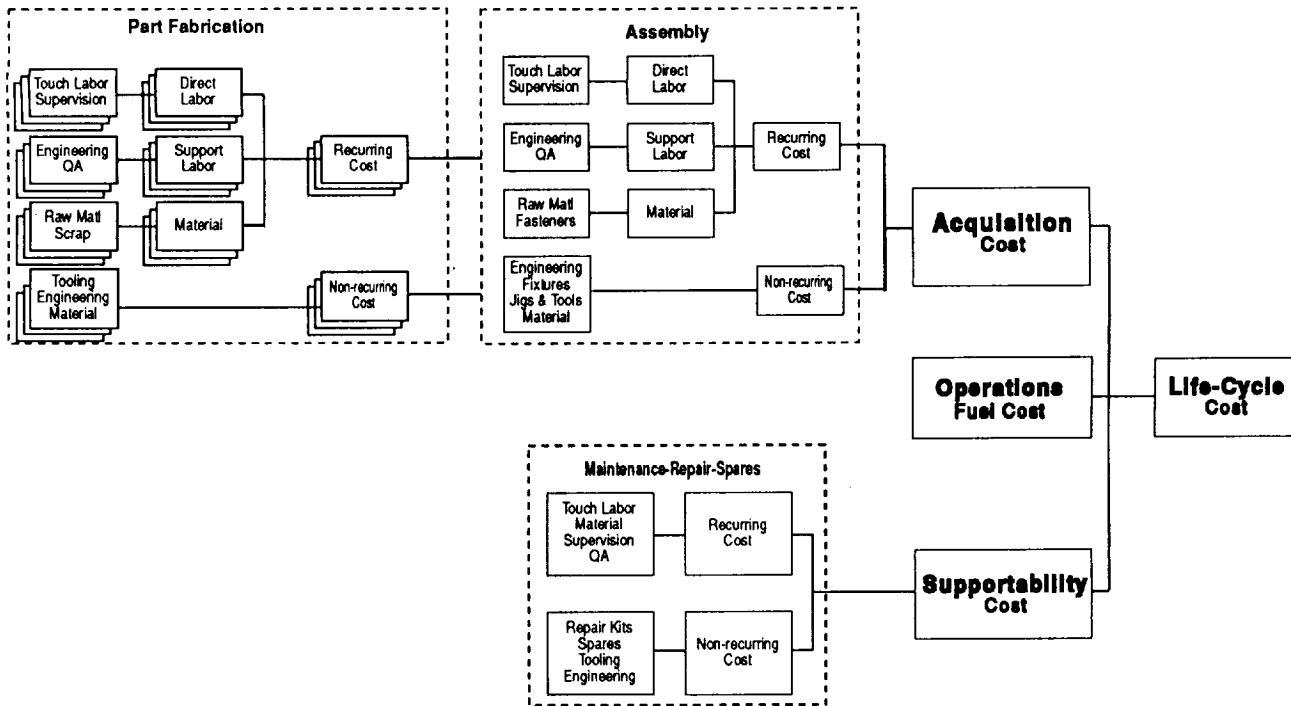


Figure 4. - Detailed cost bookkeeping elements.

Large weight savings associated with extensive use of composites in wing and fuselage structure would result in significant fuel savings over the operational life of each aircraft. Ideally the designer should be aware of the cumulative effects of operational and supportability cost savings, but his influence on lowering the acquisition cost generally dictates the success of a replacement part or new design being committed to a production application.

STPO's objective in attempting to develop a designer's cost model is not to replace company accountants or estimators, or to develop more efficient bookkeeping tools, but rather to develop a cost model to provide the designer with a user friendly tool that relates cost to terms the designer normally uses. The cost related issues a designer can influence usually are related to selections of materials, tolerances, simple versus complex shape or geometry, and process dependent features that contribute to automation potential and tooling complexity. The designers model should provide definitive assistance in identifying the cost implications of these choices, but it should not be expected to replace the professional cost analyst that has to interpret company policy and historical pricing practices. Managerial decisions affecting actual program costs related to availability of land, unused company facilities, future labor rates, return on investment, etc. are not issues the designer can be expected to consider. The primary goal for a design-with-cost model is to provide the designer with a producibility data base and theoretical cost model that relates a new composite design to an equivalent aluminum structure using elements of the design process that the designer can realistically influence.

Figure 5 illustrates the standard methods used for cost/price estimating. Variations of these methods are used routinely by estimators and price analysts to forecast or compare the relative value of materials, automated processes, and projects. Figure 6 shows four state of the art cost models used for estimating composite hardware program requirements. The current state of the art models

Estimating Methods	Technique	Resource Category
Parametric	<ul style="list-style-type: none"> <li>• Correlates design and historical cost data</li> <li>• Estimates applicable at the component and subsystem</li> </ul>	Conceptual Preliminary design
Factors	<ul style="list-style-type: none"> <li>• Used when details of item are not available</li> <li>• Compares new item to a prior similar item and then factors historical cost</li> </ul>	Conceptual Preliminary design
Analogous	<ul style="list-style-type: none"> <li>• New item very similar to a current item in production. Specific analogies are drawn as the basis for defining the cost of the new item</li> </ul>	Conceptual Preliminary design
Trend Analysis	<ul style="list-style-type: none"> <li>• Use historical production trend data to estimate future production costs</li> </ul>	Conceptual Preliminary design
Identical Units	<ul style="list-style-type: none"> <li>• Actual cost of the item is known. Units are in production for other applications.</li> </ul>	Design Development Production
Detailed	<ul style="list-style-type: none"> <li>• Estimates accomplished by defining tasks, characteristics, manhours, material costs for specific work packages</li> <li>• These types of estimates are based on previous detailed labor/material history</li> </ul>	Design Development Production

Figure 5. - Summary of estimating methods.

<ul style="list-style-type: none"> <li>• An interactive spread sheet to include cost</li> <li>• Starts with basic part of a simple form then adds: <ul style="list-style-type: none"> <li>• Palate of manufacturing methods</li> <li>• Builds up discrete parts to give airframe structure</li> </ul> </li> </ul>
<p>Advantages:</p> <ul style="list-style-type: none"> <li>• Allows both metal and composite technologies</li> </ul>
<p>Disadvantages:</p> <ul style="list-style-type: none"> <li>• Requires a mainframe and does not have user friendly data base or CAD interface</li> </ul>

(a). - Battelle Manufacturing Cost/Design Guide

<ul style="list-style-type: none"> <li>• A detailed breakdown of the production process into its component parts based on a time and motion study conducted in 1976</li> </ul>
<p>Advantages:</p> <ul style="list-style-type: none"> <li>• A data base of limited production processes for Al and composites</li> <li>• Each production process is based on the average labor time, average productivity factor, QC, etc.</li> </ul>
<p>Disadvantages:</p> <ul style="list-style-type: none"> <li>• Requires a mainframe and does not have a user-friendly data base or CAD interface</li> </ul>

(b). - Northrop ACCEM & FACET

<ul style="list-style-type: none"> <li>• Lotus 123 spreadsheet models for many composite processes</li> </ul>
<p>Advantages:</p> <ul style="list-style-type: none"> <li>• Production methods compared &amp; evaluated on the basis of cost of materials, scrap, QC, tolerances, &amp; overhead</li> <li>• Econometrics module available</li> </ul>
<p>Disadvantages:</p> <ul style="list-style-type: none"> <li>• Can only handle parts, not assemblies</li> </ul>

(c). - MIT/IBIS model.

<ul style="list-style-type: none"> <li>• A commercial model with nation-wide subscribers</li> <li>• Resident on a mainframe</li> </ul>
<p>Advantages:</p> <ul style="list-style-type: none"> <li>• Includes extensive mathematical methods for manufacturing cost estimation</li> <li>• Includes standard risk models</li> </ul>
<p>Disadvantages:</p> <ul style="list-style-type: none"> <li>• Requires a highly expert user with a large training time investment</li> <li>• Code and equations practically unavailable</li> </ul>

(d). - GE PRICE model

Figure 6. - State of the art cost estimating models used for composite structures.



used to estimate the cost of composite fabrication for hand layup and automated tape laying are the ACCEM (Ref. 6) and FACET (Ref. 7) programs. Northrop developed the ACCEM program in 1976 based on a time and motion study of different composite material manufacturing processes. Equations were developed to estimate recurring composite part manufacturing costs. FACET has been developed as a Fortran language mainframe computer program that evolved from ACCEM with updated Air Force project data bases. New material forms and manufacturing processes that can be evaluated for production of the most cost effective structure are considered in the MIT/IBIS model (Ref. 8). These spreadsheet models estimate individual cost elements and enforce consistent accounting assumptions. The G.E. PRICE H (Ref. 9) model is very complex and requires extensive training with terms and concepts that best suit the needs of a cost analyst or accountant.

The Boeing, Douglas, and Lockheed workshop participants all currently use a preferred composite fabrication cost estimating methodology. Boeing estimators rely heavily on the G.E. PRICE Model, the only model that cost analysts from all three companies use routinely. Lockheed uses both ACCEM and FACET and has developed parametric equations based on in-house fabrication experience. Douglas is developing an expert system model based on the GURU (Ref. 10) artificial intelligence program and in-house experience. None of the current cost models used by the airframers contain information on newer fabrication processes (e.g. RTM, pultrusion, filament winding, braiding and stitching). All of the available composite cost models appear best suited for fabrication experts, and none are independently used by designers. The tools that are available are not suitable for preliminary and conceptual designers who will not spend their time filling out forms and collecting material or process specific data that must be input to existing cost models. Modifying existing models has been considered. Establishing accounting consistency with Lotus 123 (or equivalent) spreadsheet forms and contractually requiring all ACT program participants to uniformly report with these forms has been discussed. Holding an additional workshop to develop unified equations, factors, and standard constants to be used in the G.E. Price model also has been considered. The major concern for these approaches is that designers will not use a tool that is unfamiliar and unrelated to the design process. If a cost estimating system is to be useful to the designer, and helpful in the selection of design concepts with their associated fabrication processes, the system must be relatively transparent to the designer. A model for designers must be structured to have input that can be coupled directly to a preliminary design module. Such input relates cost to panel thickness, stringer spacing, stiffener height, laminate ply orientation stacking sequence, etc.

The primary thrust of the designers' cost model development would be to use a first principles approach to establish building block unit cell elements (e.g. prepreg tow, 12" prepreg tape, cloth, etc.) that represent different material forms, and to use basic principles (mechanics, dynamics, physics, etc.) to describe labor content in terms of machine feed rates, accelerations, and material deposition efficiencies that characterize processes and the effectiveness of automation. Modeling concepts of cost per inch, materials cost per cubic inch, and layup man hours per square inch for a unit cell representative of each material form are concepts that would suit the designers' needs. Engineers customarily express cost comparisons as \$/pound or man-hours/pound. Ratioing comparisons with respect to geometric properties and dimensions of length, area, or volume would provide a means of incorporating geometric complexity in the comparison. Complexity factors determined as theoretical relations for radii of curvature, degree of double curvature, tight dimensional tolerances, number of stiffening elements, etc. would provide equations to uniformly express theoretical cost of materials and labor for simple or difficult to fabricate designs. The designer employs laminated plate theory to sum lamina properties that are experimentally determined through the thickness of a

laminate to develop smeared stiffnesses that account for ply orientation and stacking sequence. A similar approach for treating cost as a lamina material property (\$/square inch) that's summed through the thickness, accounting for material length associated with part topography and process dependent scrap of off angle plies, would allow development of a totally theoretical cost representation. Panels could be designed to calibrate the labor content of automated processes by measuring man hours per square inch to apply lamina to a simple and complex shape mandrel providing process dependent coefficients similar to the lamina modulus measurements now used to evaluate composite materials.

Assemblies could be considered by describing the material and man hours associated with fastener installation and added structural joint complexity. A metallic structural part or assembly cost could be used for comparison to provide ratios (index of value) that nondimensionalize the cost representation and remove issues of proprietary labor rates, time value of money, etc. Initial efforts should concentrate on recurring costs which are most amenable to a detailed breakdown and are directly related to design features. Recurring costs should be a function of the physical description of the part and the fabrication process related to the part. As the term "recurring costs" implies, these costs are incurred for every part made and should be consistent from part to part. Since the recurring cost elements of a fabrication process are amenable to a time and motion study, equations can be developed that predict cost from material volume, part geometry and the physics that describes the time and resources required to perform each step of the of construction, machining, and assembly with fasteners or adhesives. This approach would provide designers with an technically sound, academically rigorous, and universally accepted model to describe a theoretical material cost and labor content for comparison of their designs. These models could be calibrated with actual corporate experience to provide bounds of theoretical versus actual process efficiencies. Ideally the model can be a module to existing design software that will compute cost from the geometric features derived from design software, geometry generator programs and, eventually, CAD programs. Such a model would allow the designer to use cost equations as minimization functions in optimization models now used in designing to minimum weight. Figure 7 provides a flow chart for a prototype designers' theoretical cost optimizer concept with emphasis on the data base elements that must be developed.

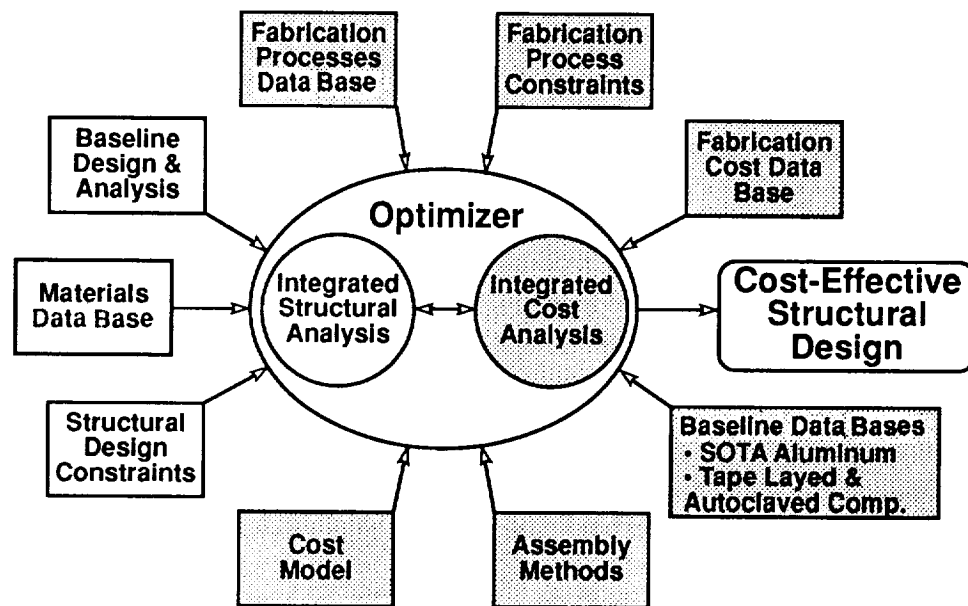


Figure 7. - Optimization of design process with cost as a design variable.

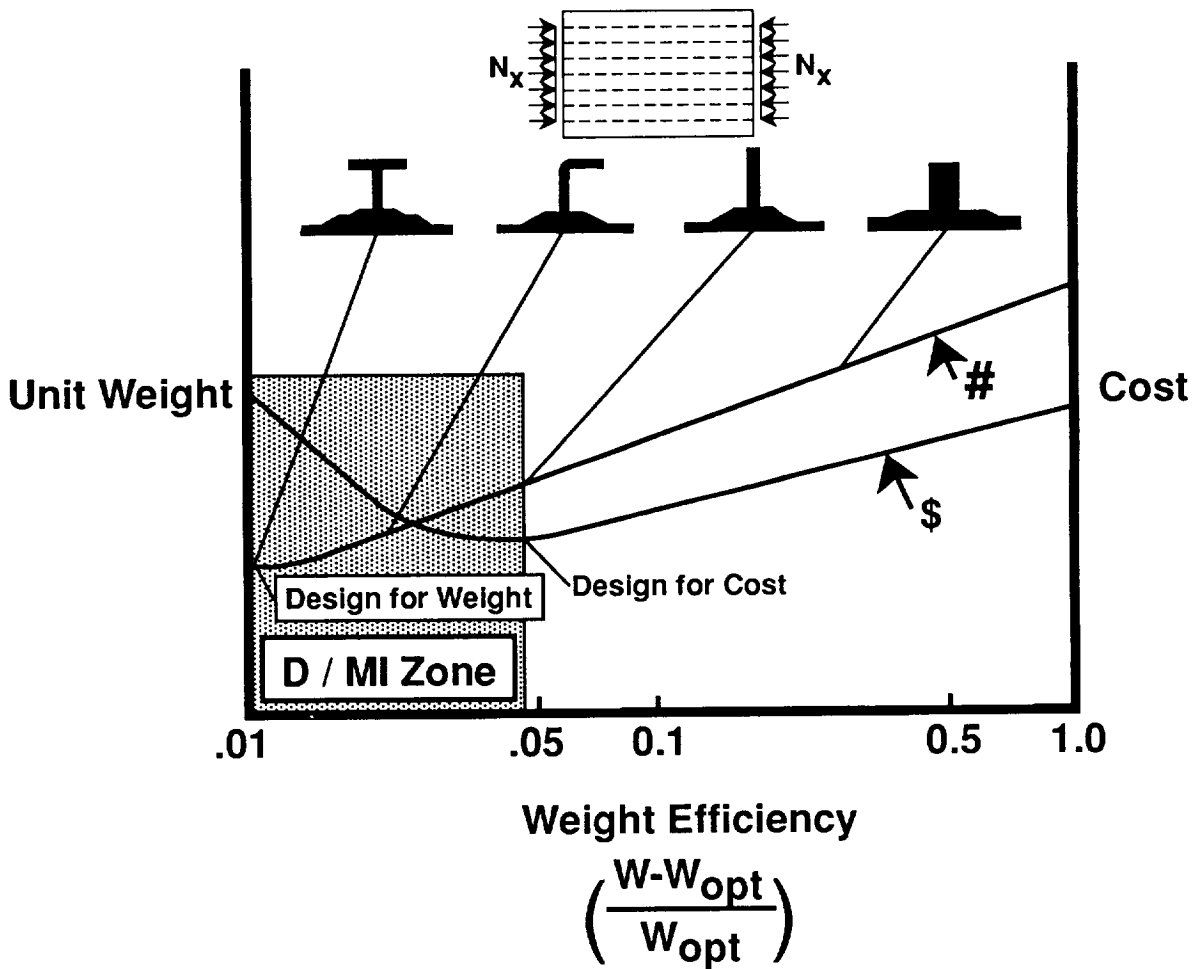
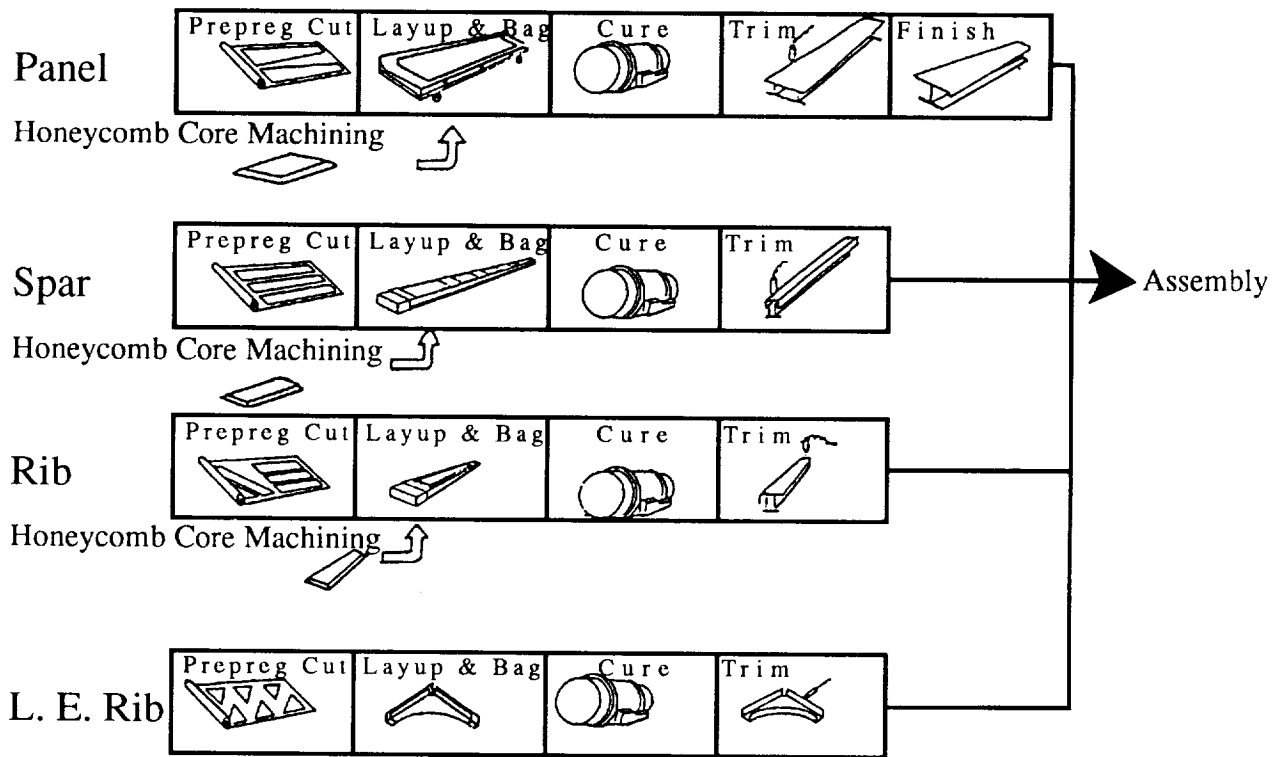


Figure 8. - Influence of design/manufacturing integration (D/MI).

The designers' cost model must have sufficient fidelity to distinguish between concepts if the concepts have significantly different costs. This fidelity implies the need for adequate detail in both the description of the part and the associated cost methodology. Figure 8 provides a schematic of the results of the design-with-cost process for a simple stiffened skin compression panel. The influence of design concept on cost and weight is the product of this process. The D/MI zone permits the designer the opportunity to increase weight efficiency with cost as a primary variable. A cost methodology that sums the cost of each element of the fabrication process and allows for parallel as well as serial operations may be required to achieve the needed fidelity. Figure 9 shows a flow chart for manufacturing an elevator including panel, rib, and spar details. Developing equations representing economic relationships in terms of energy, power, thermodynamics, mechanics, process physics, etc. for each step would sum to a theoretical cost for performing each operation. Statistical bounds applied to each operation could establish theoretical maximum and minimum cost values. One model concept would be to treat cost as a control theory or chemical engineering process problem where time dependent cost functions were inputs to be integrated through process steps to completion as a part or assembly. Participants in the ACT program will be generating cost data related to new processes and the state of the art for manufacturing large composite structures, providing the required data base to formulate a theoretical cost model approach and the coefficients and constants necessary to calibrate or verify the model.



**Figure. 9 - Elevator manufacturing flow.**

Nonrecurring costs are important since the need to build new tooling often adds large start up expenses to a project. Tooling costs should be considered because they vary according to the selected design concept or fabrication process and are therefore an element of cost that is directly related to design. Tooling cost should be predictable in relation to the physical, dimensional and geometric complexity of the part to be made. Tooling costs are a function of the production rate and the total number of parts to be made. A program that includes tooling costs should have the flexibility to consider changes in production rate and the total number of units over which the costs of tooling will be amortized. The feasibility of a theoretical tooling cost model related to tool material type and geometric complexity of the part to be made will be evaluated.

### Conclusions

The remarkable advances in computer hardware and commercial software technology have led to low cost data storage and sophisticated data base management systems. These developments make it economically feasible to track the cost history of numerous projects and provide the historic opportunity for bringing cost into the preliminary design process as an engineering variable.

Recommendations of the cost reporting and cost prediction workshop committees will be implemented by

1. Continuing an established task with AS&M to develop an electronic data base that will unify formatting and automate the collection of composite part fabrication costs provided by ACT program participants. A "subscriber" approach, wherein contributors to the data base would have



access to it, will be implemented. The data base will include standard material costs (including future costs) for consistent comparative costing studies. The database will be kept current through the duration of the ACT program and methods for long-term maintenance will be considered.

2. Development of an academically rigorous model for predicting the cost of different composite designs during the preliminary design process will be initiated. This effort will include development of a producibility guide (a manufacturing data base software module) to provide the designer with information on selected manufacturing processes and types of design details that adversely affect cost. Large cost drivers will be identified and software approaches to couple the data base to design optimization and CAD interfaces will be pursued.

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