

DESIGNERS' UNIFIED COST MODEL

W. Freeman, NASA Langley Research Center ✓
L. Ilcewicz and G. Swanson, Boeing Commercial Airplanes
T. Gutowski, Massachusetts Institute of Technology

3000
11/15/11
52-24
51342
P-20

Abstract

The Structures Technology Program Office (STPO) at NASA Langley Research Center has initiated development of a conceptual and preliminary designers' cost prediction model. 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 programs is being evaluated.

The goal of this task is to establish theoretical cost functions that relate geometric design features to summed material cost and labor content in terms of process mechanics and physics. The output of the designers' present analytical tools will be input for the designers' cost prediction model to provide the designer with a database and deterministic cost methodology that allows one to trade and synthesize designs with both cost and weight as objective functions for optimization. This paper presents the team members, approach, goals, plans, and progress to date for development of COSTADE (Cost Optimization Software for Transport Aircraft Design Evaluation).

Introduction

The preliminary design process has been identified as the most critical period of opportunity for substantial cost reduction during an airframer's hardware production cycle. Boeing has experienced that 70% of airplane fabrication costs are fixed by the time the drawings are frozen, and the influence of engineering on fabrication cost reductions is significantly reduced once the detailed design is completed. Concurrent engineering interdisciplinary teams are now emphasizing cost evaluation during early stages of the development cycle in the preliminary design process, and the advent of powerful low-cost work stations now provides the designer with the possibility of including cost as a complimentary 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.

Accurate cost prediction is considered a high-priority issue to assure a valid comparison of cost-effective structural concepts, material forms, and assembly methods being developed by the Advanced Composites Technology (ACT) program participants. The Structures Technology Program Office (STPO) has initiated the development of a conceptual and preliminary designers' cost prediction model based on workshop results and objectives that are detailed in Reference 1. Affordable composite technology for pressurized transport fuselages is currently being developed under Boeing's Advanced Technology Composite Aircraft Structure (ATCAS) contract NAS1-18889. The ATCAS contract was modified to initiate development and verification of the designers' cost prediction model. The model software acronym will be COSTADE (Cost Optimization Software for Transport Aircraft Design Evaluation). This software will be written to incorporate the cost model, appropriate mechanics constraints, and optimization capabilities. Cost and mechanics modules will be self-contained, allowing the user to run them separately or in combination with the optimizer.

This paper is divided into four main sections describing the proposed development and verification of a designer's cost prediction model. The first section reviews the goals, requirements, and applications for such a model. The next section describes an integrated approach involving industry, university, and government. The third section describes major technology issues and outlines the detailed plans which will be used to solve these issues. Progress to date and conclusions are highlighted in the final section.

Designer-Specific Cost Prediction Model Goals, Requirements, and Applications

"Designers, accountants, estimators, managers, manufacturing engineers, etc. are interested in different details and economic conditions that imply a numerical value to the term "cost." Unifying the way the composites design community represents hardware and assembly 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 design variables (size, shape, tolerances, geometric complexity, and material properties) to summed material cost and computed labor content in terms of process mechanics and physics. STPO's objective in attempting to develop a designer's cost prediction model is not to replace company accountants or estimators, or to develop more efficient bookkeeping tools that are now used by estimators, but rather to develop a cost model that will provide the designer with a user-friendly tool that relates cost to terms the designer normally uses. 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 cost-related issues a designer can influence usually are related to selections of 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 and have sufficient fidelity to distinguish between concepts that have significantly different costs. This fidelity implies the need for adequate detail in the description of the part/assembly labor and material cost at any stage of the fabrication and assembly process. A cost methodology that sums the cost for each element of the fabrication process and allows for parallel as well as serial operations may be required to achieve the needed fidelity. One goal is to provide the designer with the ability to relate the value of a new composite design to an equivalent aluminum structure at similar stages in the fabrication or assembly process.

The ability to fabricate a 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. Large weight savings associated with extensive use of composites in wing and fuselage structure would also 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.

After the designer has screened a multitude of concepts and fabrication/assembly methods employing the COSTADE model, he would forward the details and drawings of final design trades to the professional cost analyst who has to interpret company policy regarding labor rates, return on investment, capital equipment purchase, etc., for a management accepted cost estimate/comparison.

Figure 1 illustrates how technology for advanced composite transport primary structures has evolved at The Boeing Company in past years. Developments during the 1980's were performed by co-located engineering and manufacturing personnel. Despite co-location, 1985 technology development efforts occurred in series, and the relationships between design, performance, and manufacturing costs were not understood. Early supporting technology efforts included process trials, analysis development, database

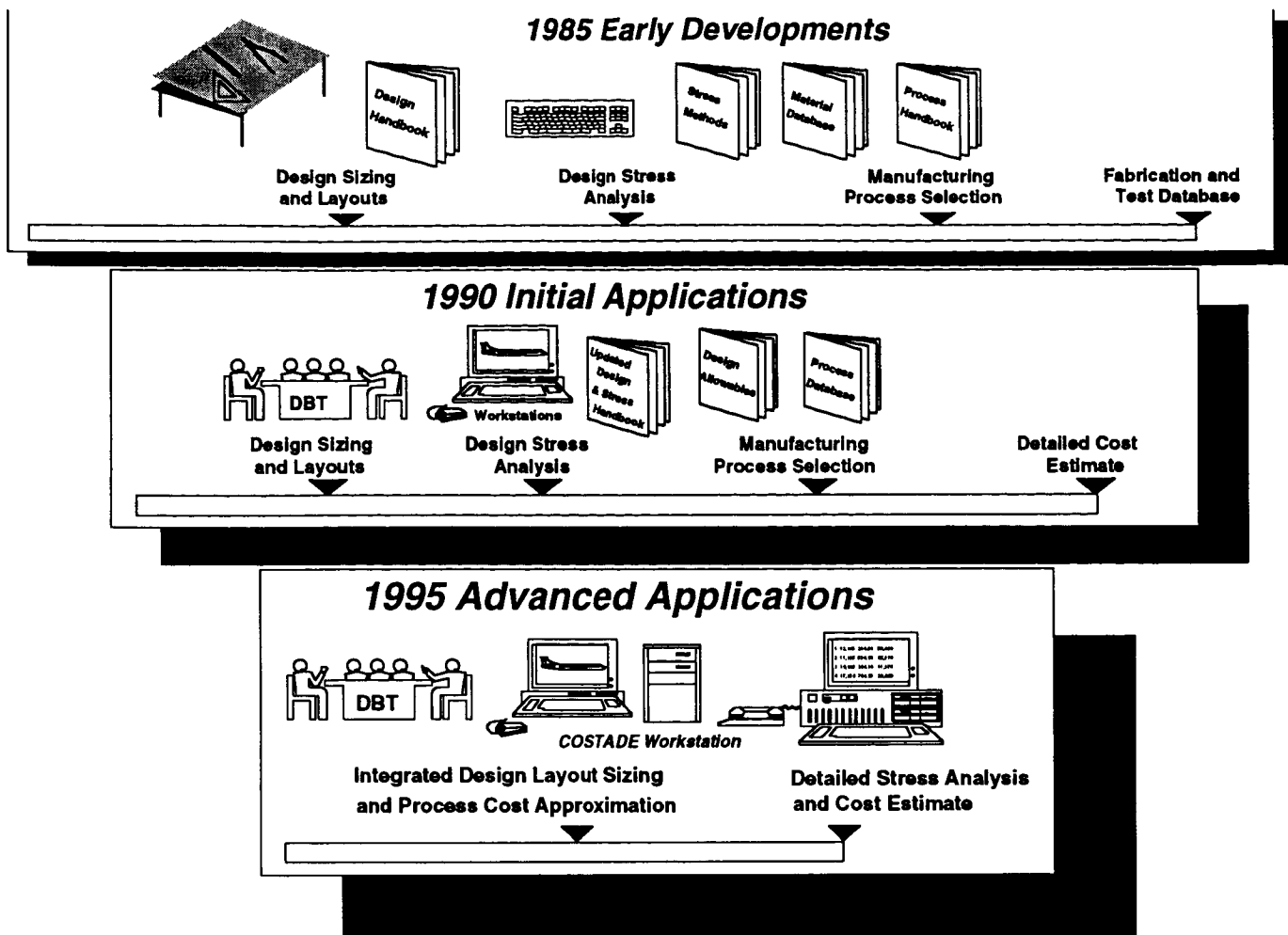


Figure 1: Evolution of Design Tools and Advanced Composite Technology Timelines for Primary Transport Structures

generation, and the documentation of design and process guidelines. By 1990, a concurrent engineering design/build team (DBT) approach was adopted to allow various engineering and manufacturing disciplines to influence decisions made early in the design process. The 1990 DBT consisted of many individuals with composites experience; however, rigid schedules and the continued lack of comprehensive databases limited cost and weight optimization efforts.

Figure 1 also shows an estimated timeline for 1995 advanced DBT activities that are supported by a computing workstation incorporating COSTADE software. The COSTADE design tool is expected to substantially reduce the DBT time needed to select concepts by integrating sizing exercises and cost approximation. This will enable the DBT to give early consideration to details which have traditionally lead to design changes and increased cost. As in current design practices, more detailed stress analyses and cost estimates will still be used to validate the selected concepts.

The COSTADE design tool is intended to be suitable for several applications. First and foremost, it must give timely support to a DBT by efficiently projecting the effects of preliminary design decisions on manufacturing and assembly costs. Calculations performed during sizing exercises will be matched with an approximation of the effect of structural details on process costs. The model is intended to help the DBT quickly trade cost and weight of numerous design details prior to concept selection. This would enhance the DBT's ability to select design variables (e.g., stiffener spacing, material type, skin gage) that:

(a) are cost effective for available manufacturing processes; and (b) meet performance requirements for the particular application. As with any model, the accuracy of COSTADE predictions is dependent on data input by the DBT; therefore, the cost and weight savings potential will increase as composite databases grow.

Additional applications for the designer's cost model would include trade studies to guide research and development (R&D) programs in manufacturing, structures, and materials. Relationships between structural design guidelines, criteria, and manufacturing cost can be used to judge which areas should be studied in greater detail to avoid the unnecessary costs associated with overly restrictive design rules. Trade studies with the model may also be used to estimate when added material cost is acceptable for enhanced performance.

Approach

In early 1991, the Boeing ATCAS contract was modified for development and verification of a design technology tool for assessing the cost and weight of transport aircraft structures. Deliverables described in the modified work statement include: (1) theoretical formulations of structural design relationships to manufacturing cost; (2) design analysis methods to estimate structural performance and constrain design decisions affecting manufacturing tolerances; (3) software for predicting design performance, cost, and weight; (4) optimization algorithms to efficiently perform trade studies; and (5) documentation on design tool usage, including results from applications to composite aircraft structures.

Several requirements for the design cost model have been established. The proposed four-year effort will be closely tied to existing NASA ACT contracts with progress reviewed annually at cost workshops. Recommendations from other ACT contractors will be solicited to help guide model development and integrate technologies (e.g., design sizing methods, databases, and manufacturing cost relationships) developed and validated during the course of the NASA ACT program. Formulation of the theoretical cost model will be general enough to simulate the design/cost relationships of new manufacturing technologies as they evolve. Finally, all data considered sensitive by industry will be treated as user inputs to the model, allowing the user to retain proprietary rights.

The ATCAS DBT approach for global/local design optimization was described in detail in References 2 and 3. To date, this approach has been successfully used to select (Refs. 2 and 4) and optimize (Ref. 5) fuselage crown panel concepts that are projected to have both cost and weight savings relative to 1995 metals technology.

The upper left portion of Figure 2 shows the global concept evaluation steps used for selecting a design family. Design families arose out of the DBT's desire to efficiently perform cost and weight trade studies. Each design family consisted of concepts having unique features from a manufacturing perspective. For example, in the ATCAS global evaluation exercise (Ref. 2), Family A differed from Family B in that stiffeners were mechanically attached for A and bonded for B. During global evaluation, concepts representing a limited number of families are analyzed and the results are used by the DBT to select a family having the best potential for cost and weight savings.

The ATCAS program is considering large integrated composite panels for potential cost savings in fuselage applications. Large integrated panels will reduce assembly labor and joint complexity which has traditionally been identified as a cost center for aluminum structure. Large panels will facilitate composite automation and greatly reduce the number of fasteners required compared to metallic assemblies (Refs. 6-9).

In order to project the cost and weight of large curved composite panels, a labor intensive screening process was adopted for global evaluation. The bottom of Figure 2 shows the schedule which was used for crown global evaluation, resulting in more than 12,000 manhours of effort. Two concepts for each of three families were evaluated (Refs. 2 and 4). The six concepts had different materials, processes, and design details, allowing trades to be performed down to the element level. An exhaustive study was deemed necessary due to the lack of experience in designing and manufacturing composite transport fuselage structure. Detailed drawings were used to develop a manufacturing plan of the process steps needed to fabricate and install a 15-ft. by 31-ft. crown panel for a fuselage with a 20-ft. diameter. A factory of the future, capable of producing five shipsets a month, had to be envisioned. Finally, detailed cost estimates were used to project manufacturing costs.

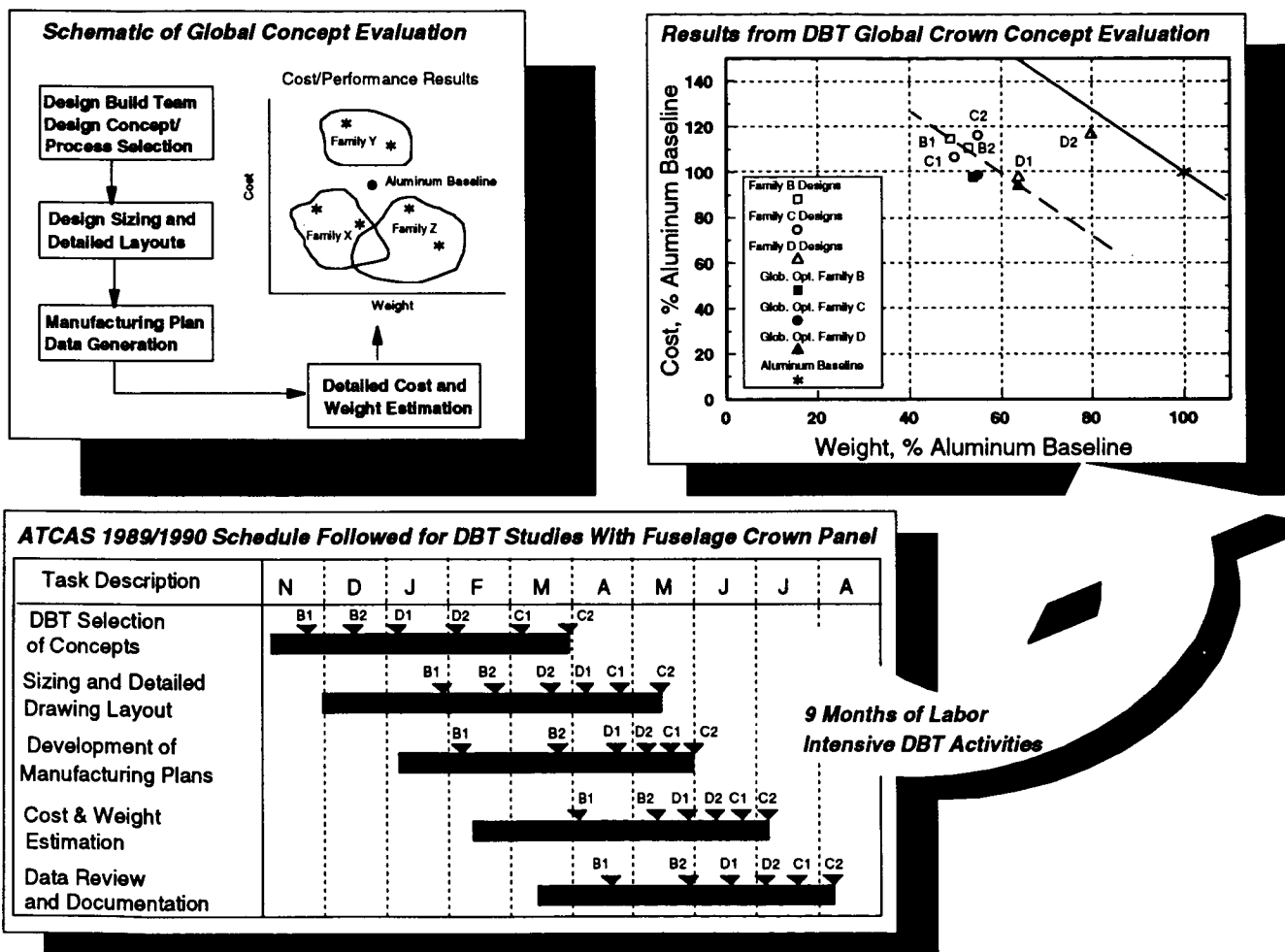


Figure 2: Results from Global Evaluation of ATCAS Fuselage Crown Concepts

The upper right portion of Figure 2 shows results from global crown evaluation. A sloped line is drawn through the aluminum baseline to represent an acceptable added cost per unit weight savings. Since all composite concepts fall below this line, each would be considered to have advantages in crown applications. After considering the design, material, and process trades performed at the element level, globally optimized concepts were selected for each family (marked by filled symbols in Figure 2). Family C was selected for local design optimization, fabrication, and test as described in References 2 and 4.

The DBT activities supporting ATCAS global evaluation will be used to help develop the design cost model. As discussed earlier, the model is required to be general enough to account for emerging

technologies. By projecting the layout and costs of future factories capable of producing advanced composite fuselage structures, ATCAS studies will provide insight on the theoretical formulation needed for a general designers' cost model. With this foundation, methods will exist for converting fabrication data into suitable input data for the design cost model as new technologies emerge in the factory. A large database relating design, material, and manufacturing variables to the cost of fully assembled structure was initiated for the crown. Cost centers for fuselage crown panels were identified in this effort. Future ATCAS global evaluation studies for keel and side panels will provide results for additional fuselage design details (e.g., large cutouts) that affect manufacturing costs.

Local optimization in ATCAS is used to focus design efforts. After using global evaluation to select a design family, the cost and weight relationships within that family are analyzed in greater detail during ATCAS local optimization. As shown in Figure 3, local optimization includes several activities, one of which is directly associated with the application of a design cost model. Initial ATCAS efforts with crown panels used a computer program called UWCODA which was developed in cooperation with an ATCAS subcontract to the University of Washington (Ref. 10).

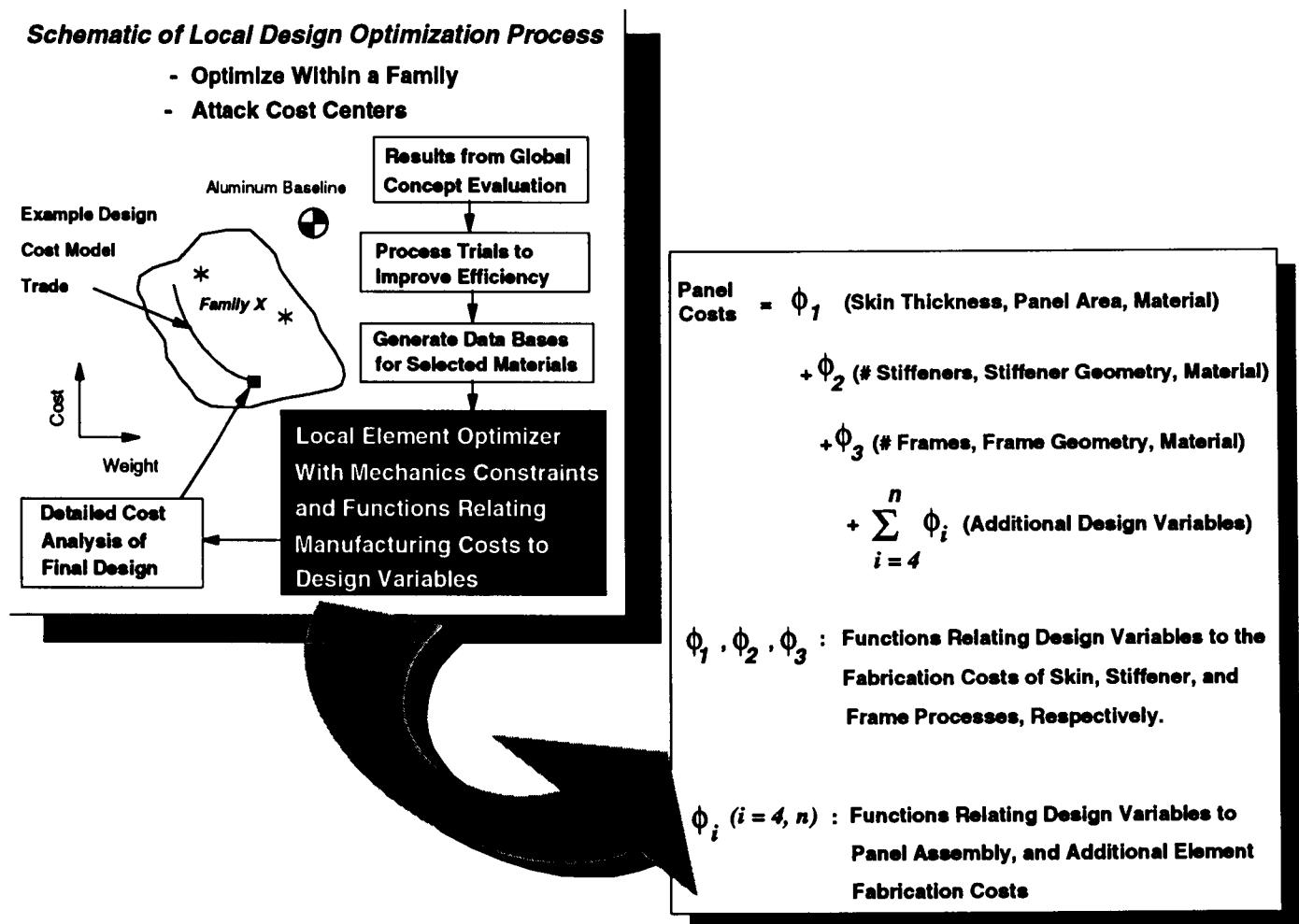


Figure 3: Role of Design Cost Model During Local Optimization of ATCAS Fuselage Concepts

Functions relating manufacturing costs to design variables for crown structures were developed and added to UWCODA in order to perform cost and weight optimization (Ref. 5). As shown schematically in Figure 3, the functional form of these equations treats design parameters as independent variables. Constants in the equations characterize the manufacturing cost relationship for a specific set of processes.

Separate functional relationships quantify fabrication and assembly components of the cost; however, it is important to obtain the sum to judge how complex interactions (i.e., design variables that affect several components of cost) affect total costs (Ref. 6).

Results from applying UWCODA to crown local optimization are documented in Reference 5. Some of these results will also be discussed later in this paper. The crown design cost relationships and UWCODA serve as a starting point for COSTADE. Generalizations are needed to develop the design cost model suitable for analyzing other fuselage structures and manufacturing processes.

The ATCAS global/local DBT approach is currently being applied in a research and development mode. From a hardware program perspective, the global evaluation step could be used during product development to help make major economic decisions (e.g., composite versus metal, equipment purchase, factory and manpower needs). Local optimization would be applied during detail design to ensure that an existing factory is utilized efficiently. A design cost model would directly support local optimization; however, parametric studies could be performed with such a tool to globally evaluate different factories.

The designer's cost prediction model development and verification tasks will interface with the ATCAS global/local DBT in two ways. First, global evaluation of future factories will support design cost model development by helping to generalize the theory for emerging technologies. Second, the model will be verified during ATCAS local optimization.

A collaborative effort involving industry, university, and government will be used to develop and demonstrate the capabilities of COSTADE. Subcontracts are currently planned to include Massachusetts Institute of Technology (MIT), University of Washington, Sikorsky Aircraft, Dow-United Technologies Composite Products Inc., and Northrop Corporation. Figure 4 shows these team members and some of their responsibilities.

Issues and Plans

Several technical issues will be addressed during the course of designers' cost prediction model development and verification. Table 1 lists seven objectives for solving the major technical issues.

-
- 1.) *Develop an Understanding of Design Details Critical to Manufacturing Costs*
 - 2.) *Develop a Theoretical Framework, General Enough to Model Design/Cost Relationships for Both Current & Evolving Processes*
 - 3.) *Incorporate Design Constraints in the Model to Help Ensure that Concepts Analyzed for Cost Are Also Structurally Sound*
 - 4.) *Develop Methods to Analyze the Effects of Design Details On Manufacturing Tolerances and Add Appropriate Model Constraints*
 - 5.) *Develop & Adapt a "Blending Function" Which Enables the Model to Cost-Effectively Blend Design Details Over Variations in Load*
 - 6.) *Combine Design Cost Model Technology as Software (COSTADE) Suitable for Performing Design Trade Studies in a Timely Manner*
 - 7.) *Verify the Design Cost Model and COSTADE With ACT Fabrication Data, Detailed Estimates for Future Factories, and Past Databases*
-

Table 1: Technical Issues to Solve, Expressed as Objectives for Design Cost Model Development and Verification

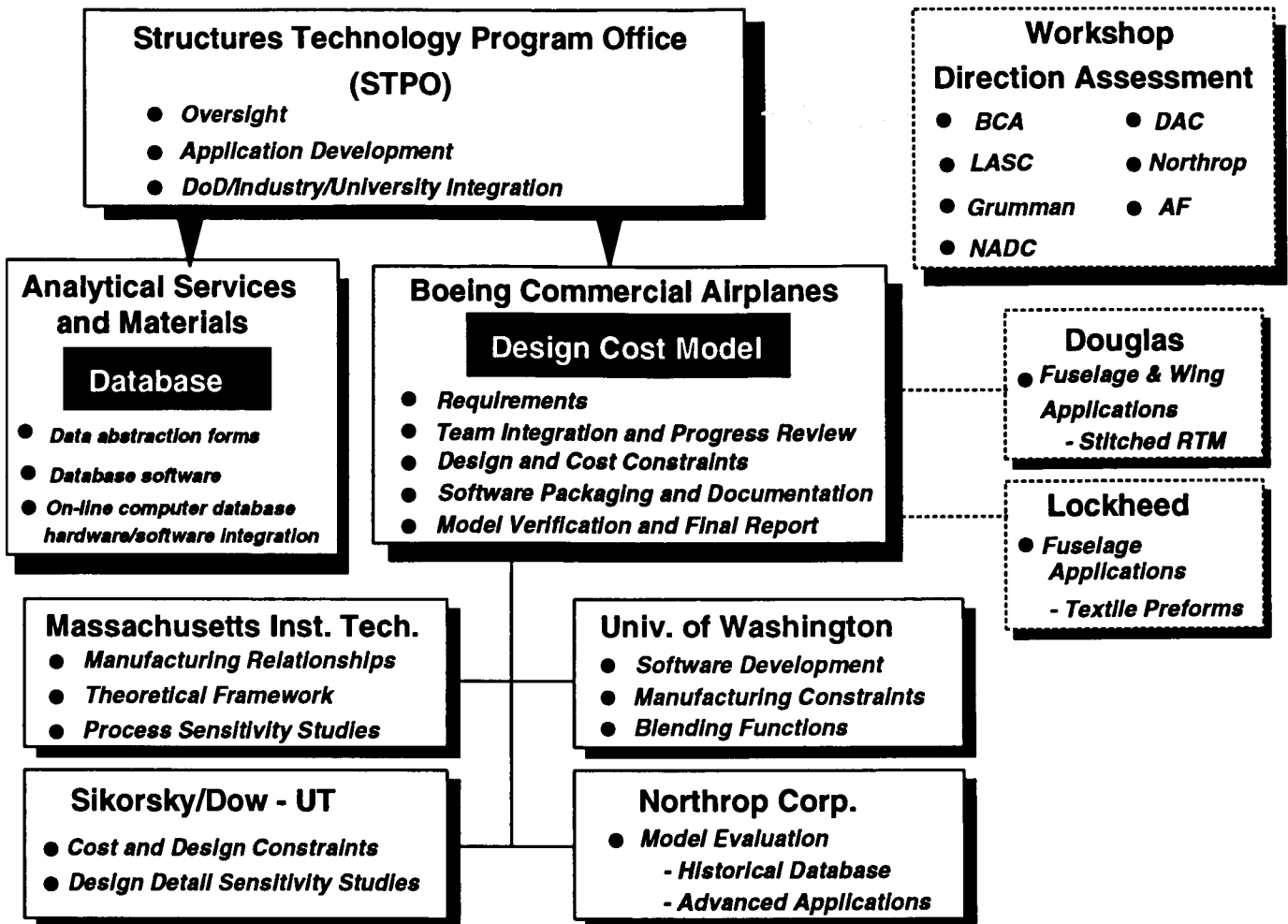


Figure 4: ACT Team Interactions for Database and Design Cost Modeling Tasks

The plan developed to achieve objectives listed in Table 1 involves four main areas of work. These include cost model development, design constraints, software development, and cost model verification. Tasks associated with each area of work are shown in Figure 5. This figure also shows the interactions between individual tasks and a critical path to achieving goals. The objective numbers from Table 1 that relate to specific tasks in Figure 5 appear in the associated flow chart symbols.

Figure 5 shows that the theoretical formulation will make use of existing database and process experience. Data considered to be of a proprietary nature may be used for model development, but won't be included in documentation that demonstrates the model. Despite the link with past data, the design cost model must have a theoretical framework based on scientific principles. Such a formulation will be derived based on process modeling and industrial engineering, as opposed to purely empirical relationships with data from existing factories. An empirical approach would not meet the requirement for a general model that can be used for emerging technologies. Since the primary focus of the ACT program is composite primary structures for transport aircraft, reliable data for an empirical approach is also not likely to be available for several years.

Model verification will include comparison of the model predictions with detailed cost estimates and fabrication trials from the ACT program. The "ACT Costing Groundrules" (Refs. 1 and 2) will be adopted as default values to portray how the model is utilized. The remaining tasks will incorporate design criteria, material databases, manufacturing tolerances, and mechanics constraints. These tasks

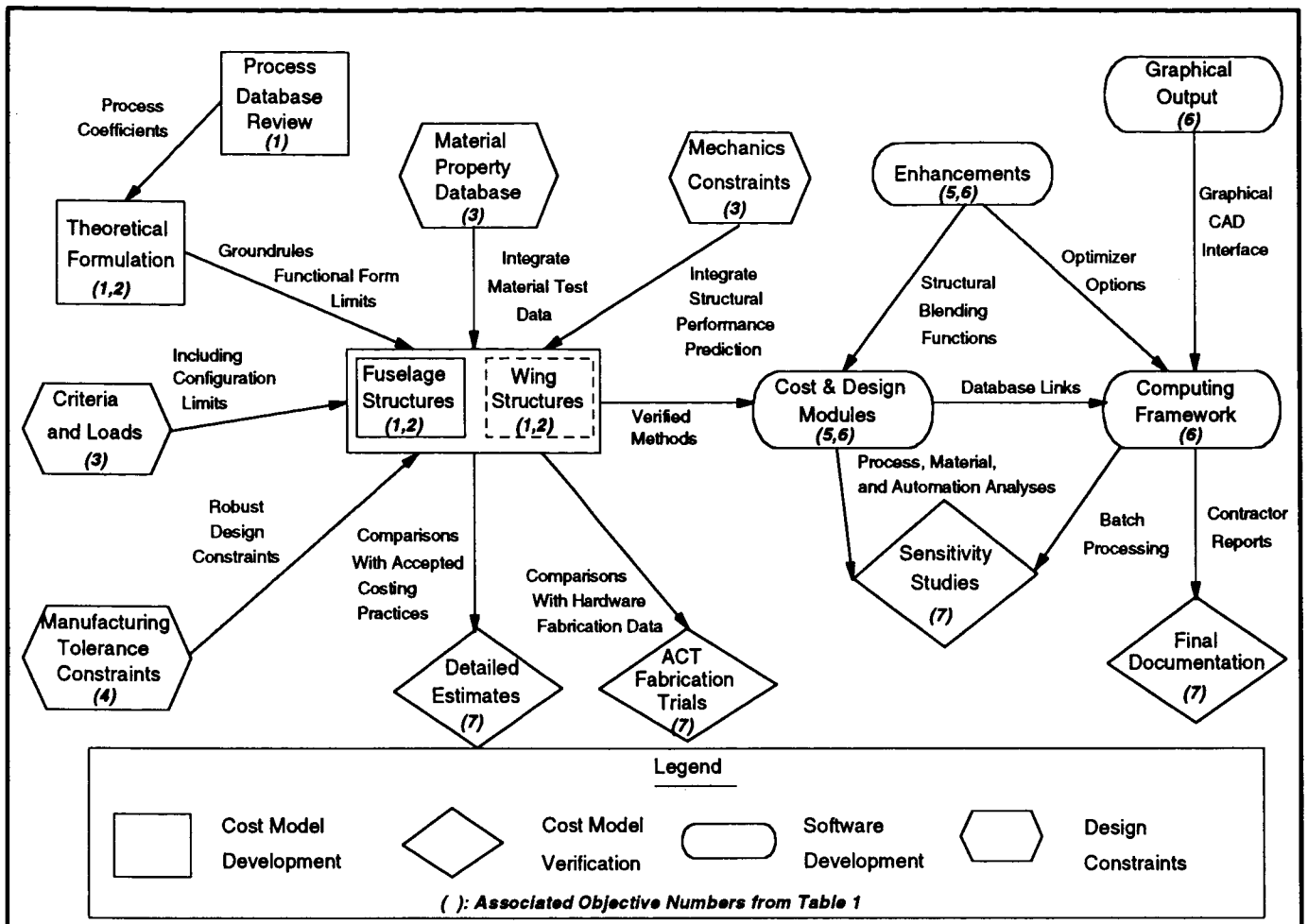


Figure 5: Critical Path Flow Diagram for the Design Cost Model

include integrating ACT technologies including automated tow placement, textile preforms, resin transfer molding, etc. An additional major task will involve development of the computer program, COSTADE.

Theoretical characteristics of the model will be determined in coordination with team members during the first year of work. The model will be capable of relating design features (e.g., material type, skin gage, stiffener spacing, etc.) and processing parameters (e.g., material cost, ply lay-up speeds, tooling costs, etc.). Initial efforts will concentrate on design details for fuselage structures. The model will also be generalized for wing structures with the help of other ACT contractors. A number of composite fabrication methods and material forms which are suitable for the various hardware elements will be studied. These will include automated tow placement, resin transfer molding, textiles, and conventional hand lay-up.

Inputs to the cost model will need to be predetermined in a manner analogous to material moduli for a solid mechanics analysis. For example, cost data may be used to determine the coefficient relating stiffener fabrication cost to stiffener geometry; whereas, a mechanics model requires coupon tests to determine a material property that relates tensile stress to strain. In each case, a combination of simple relationships (i.e., process/design cost equations or material constitutive laws) is used to determine more complex behaviors (i.e., total structural cost or stiffness, respectively).

One prerequisite for a cost-effective design is that it is also a structurally sound design. Most cost models which compare different processing methods for a structural element have made the assumption that design performance and the manufacturing process are uncoupled. This is clearly not the case in the real world where structural properties can vary depending on process and material form (e.g., filament winding with oven cure and hand lay-up with autoclave cure will not generally produce panels having equivalent performance characteristics). In order to perform efficient cost and weight trades for numerous designs, the designer must have tools that enable him to quickly evaluate both performance and cost. As shown in Figure 5, design criteria, loads, and mechanics constraints will be linked to the design cost model to facilitate trade studies. Process-related properties will be included in supporting material databases.

Another interface between product cost and performance comes in the form of design decisions which affect manufacturability. For example, it is crucial to limit a designer from tailoring part geometry and skin gage such that they have a severe effect on factory automation and efficiency. In addition, designs which are not robust (e.g., those tending to warp or are sensitive to manufacturing tolerances) may lead to additional costs during assembly. Methodologies will be developed that help constrain design selection and avoid designs prone to assembly problems.

As shown in the software development symbols of Figure 5, COSTADE software will be written to incorporate the cost model, appropriate design constraints, and optimization capabilities. Advanced optimization modules, capable of blending design details over variations of load, will be developed and added to COSTADE. Cost and mechanics modules will be self-contained, allowing the user to run them separately or in combination with the optimizer. The COSTADE design modules will also evaluate whether a design is robust for assembly by analyzing the combined effects of manufacturing tolerance variations for individual details. Sensitivity studies will be used to check software and to identify critical variables affecting cost. The computer code entitled UWCODA (Refs. 5 and 10), which was developed as a design optimization tool for Boeing's ATCAS program, will be used as the initial basis for COSTADE.

The diamond-shaped boxes in Figure 5 show four tasks supporting cost model verification. The cost data collected for ACT fabrication trials will provide some verification, although none of the hardware currently planned will allow a direct comparison for full-scale structures fabricated with the production rates of a dedicated factory. Detailed estimating, which is an approach currently used to forecast the costs of future composite structures, will help to evaluate the model for future factories. The final two verification tasks, sensitivity studies and documentation, will be used to screen for critical factors and report results.

Figure 6 shows a schedule of major milestones for the design cost model. Discussions with individual groups to support this effort are currently underway. As shown at the top of Figure 6, workshops are planned during each year of cost model development and verification.

Cost model development: Work in this area will concentrate on the formulation of analyses to relate design variables and manufacturing costs for transport aircraft composite structures. Groundrules for this effort will be determined by team member meetings and through a consensus reached at a future NASA ACT cost workshop. The theoretical basis for relating design variables and manufacturing costs will be established by the end of 1992. This will include documentation of a functional form for the theory that, in general, will allow nonlinear interactions between design parameters and cost components. During the following year, specific design/cost equations will be formulated. Documentation will be required to give variable and coefficient distinctions to each parameter in the equations. A theoretical framework is scheduled to be completed by early 1993. The capabilities and limits of the theory will also be documented at that time.

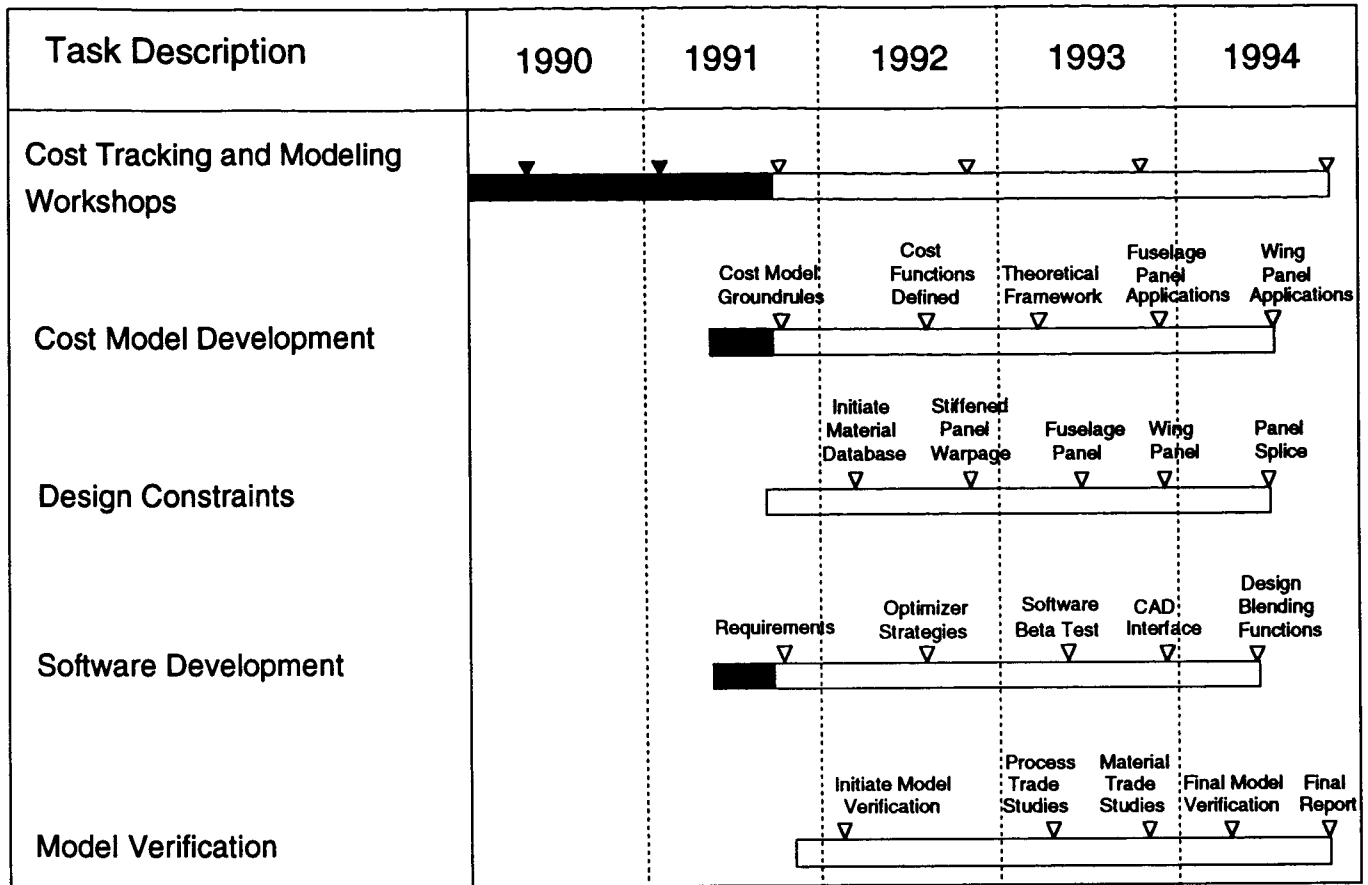


Figure 6: Schedule of Major Milestones for the Design Cost Model

The design model will allow for manufacturing cost components such as material, fabrication labor, assembly labor, and tooling. As shown in Figure 4, MIT will take the primary role in understanding the manufacturing relationships and in developing the design/cost theoretical framework. Relationships developed will allow evaluation of the effect of design variables on fabrication cost for both an individual component and the fully assembled structure. Close collaboration between MIT and industry team members will be needed during model development since a perception of assembly and tooling relationships is not readily available outside industry.

Fuselage structures will be the primary focus for design/cost model development and verification in ATCAS. As discussed earlier, much of the fuselage cost constraint data needed for such a model will become available during the course of global evaluation studies involving ATCAS quadrants (i.e., crown, keel, and side). This data includes the identification of cost centers and critical design variables. The schedule for applications of the design/cost model to each fuselage quadrant will trace ATCAS local optimization activities.

The ATCAS fuselage study section is directly aft of the wing to body intersection (Refs. 2 and 3). Loads in this area include internal pressure and additional axial tension, compression, and shear-for-flight maneuvers that induce body bending. Development of methods for analyzing design/cost relationships for crown, keel, and side quadrants of the ATCAS study section will result in capabilities for most of the

fuselage shell. Much of the crown quadrant consists of the minimum gage panels also representative of upper and lower regions of barrel sections located away from the wing-to-body intersection. The keel quadrant is characteristic of heavily loaded compression panels found at the bottom of the fuselage, in sections directly forward and aft of the wing-to-body intersection. Side panels include design details for door and window cutouts found along the full pressurized length of the fuselage.

The design cost model will be generalized to include wing structures with the help of other ACT programs. Activities in this area will be initiated at the design/cost model workshop scheduled for the end of 1992. Model developments for wing panel applications will be completed by mid-1994.

Design Constraints: Work in this area will integrate the tools that a designer needs to efficiently consider multiple design concepts during COSTADE analysis. As shown in Figure 6, the information needed in a material database for transport fuselage and wing applications will be identified first. One objective of the ACT program is to establish a database of properties for advanced material forms processed with low-cost manufacturing methods. Results from such activities will be used with design and cost constraints to evaluate cost/performance relationships. The process/material property database used during model verification will be reviewed periodically at workshops.

The loads, design criteria, and limits on structural configuration will be established as guidelines for development and verification of the COSTADE tool. Sensitivity studies will be performed with the cost model in order to judge how criteria (e.g., damage tolerance, defect allowances) affect the cost of composite structures. Results from such studies will be reviewed at workshops.

Design and mechanics constraints will be added to the design cost model to analyze transport fuselage and wing structures. Most of this sub-task will concentrate on integrating design sizing methods that exist or were developed in other ACT activities. Typical mechanics constraints include stiffness requirements, panel stability, crippling, damage tolerance, bolted joints, cutouts, combined load criteria, and load redistribution guidelines. All constraints used for this effort will be suitable for screening multiple designs. Constraints for fuselage zones characteristic of ATCAS crown panels will be established during the first year. Methods for other fuselage and wing locations will be added, resulting in more complete capabilities by the end of 1993. The final mechanics constraints generated will relate to panel splice details.

Manufacturing tolerance constraints will be developed to address the effects of design decisions on costs associated with manufacturing tolerances. The constraints will be added to COSTADE to help the designer in developing robust design concepts that avoid assembly problems. An analysis method will be developed to evaluate the effects of element design details (e.g., geometry and lay-up) on co-cured/co-bonded panel warpage. The effects of cured panel manufacturing sensitivities such as resin content tolerances, resin content distribution, and ply misalignment tolerances will be considered in this effort.

Software Development: The computer program COSTADE will incorporate design and cost constraints that enable a DBT to efficiently perform cost and weight trade studies. Most of the work on this task will be performed at the University of Washington and Boeing. Software and hardware requirements will be established first. Software decisions on language, framework, and computational architecture will be subject to approval by NASA and participants at future cost workshops. Hardware compatibility requirements will be set after identifying which computing tools are projected to be used by designers in future years.

A modular programming style will be used for COSTADE. The software will be written to allow links with databases for input parameters related to process cost, material properties, and mechanical performance. A number of input/output options will be added including: (1) switches to run cost and

mechanics modules with or without optimization features; (2) user-written subroutines for performing sensitivity studies; and (3) macros for batch job processing and output data reduction. A software manual will be created that includes case studies.

Initial software for cost and design modules is planned for completion after associated *cost model development* and *design constraint* activities. The proposed timeline to develop the cost model and to integrate design constraints was set based on availability of input from current ATCAS schedules. Cost and design software modules developed for each area of the aircraft will have features that allow improvements to be made as technology matures (e.g., innovative design concepts).

A number of optimization capabilities will be developed for COSTADE and made optional to the user. These enhancements will help to trade a larger range of design details and consider possible interactions. Although current structural guidelines limit the number of composite variables considered by designers, a properly constrained optimization scheme is still an advantage. As composite technologies mature and databases expand, additional cost and weight savings will be possible by removing unwarranted constraints. Some cost and weight optimization capabilities have already been established for the original code, UWCODA (Refs. 5 and 10). The ability to perform cost/weight optimization will be added. This feature will require an input from the user to determine the cost he is willing to pay per unit weight savings.

Other optimization capabilities which will be developed for COSTADE include "panel and splice blending functions." Currently, designers apply point analyses to size each portion of the structure and then make changes in design details to meet requirements for compatibility at adjacent points. This activity, referred to as blending, results in continuity for an entire configured panel. The key to a blending function algorithm is to model how design details selected at one point of the structure affect the requirements at neighboring points. The desired result is a tool that performs cost/weight optimization for a complete fuselage or wing panel.

The cost of a configured structure depends on the success of a blending scheme, manual or otherwise. Considering the large panel sizes that are projected to be cost effective for composites and the complex nature of anisotropic materials, the task of blending a composite structure can be laborious when performed manually. In the past, the time needed to blend a composite design has often limited trade studies and resulted in increased cost because schedule-driven design selections result in costly details. For example, local laminate lay-up and thickness tailoring may be adapted to meet performance or weight requirements, at the penalty of an adverse effect on manufacturing automation.

Panel blending functions will be developed as enhancements for optimization performed with COSTADE. These functions will enable a designer using COSTADE to minimize total costs while considering a design space with variable load distribution and design criteria. Without the blending module, COSTADE will still be able to analyze the relationship between local design details and total structural costs. The addition of a blending function will enhance this capability by guiding the selection of local design details to minimize total structural costs.

The effects of splice design details will initially be programmed in COSTADE as design constraints. The "splice blending function" will be added as an option to combine panel and splice optimization schemes. This is scheduled to be added after work is completed on adding splice modules to the cost and mechanics models.

A visual presentation of ideas and results from design trade studies can often help members of a DBT make decisions. This is true provided the graphics can be produced in a timely manner. An effi-

cient method of creating graphics from COSTADE results will be considered in the form of a computer-aided design (CAD) graphics interface. The first step in this effort is to define the industry CAD which will be most suitable. Most the work on a CAD interface will occur after other software developments have been completed.

Model Verification: The overview schedule shown in Figure 6 indicates that cost model verification milestones are dispersed throughout the four-year plan, yielding direct measures of the success of cost model developments as they evolve. Since verification occurs continuously, each step of cost model development will benefit from previous findings. Industry team members (Boeing, Northrop, and Sikorsky/Dow UTC) will take a lead role in model verification. As was the case with many work tasks on *Design Constraints*, results from current ACT contracts will also be used to support some of the model verification tasks. Contractor proprietary data will not be included in the deliverables documenting model verification and demonstration; however, such data will be useful when individual companies evaluate the model.

Sensitivity studies will be used to demonstrate the cost model capabilities. Such studies are crucial to checking sensitivities to input data used for simulating process relationships (Ref. 7). This is particularly critical to interpreting the results for new processes which lack sufficient databases. Additional process and material trade studies will be performed to evaluate cost relationships for different transport fuselage and wing design details. Sensitivity studies will be used to identify the most critical variables to consider during optimization.

The model can be used to estimate the influence of process automation and large material volumes on the cost of composite structures. The capital cost of advanced process and assembly equipment will be traded against costs saved through automation. Finally, the model will be used to compare the projected costs for manufacturing composite structures against those of aluminum for the same time frame. A detailed cost-estimating approach used in the ATCAS program for projecting the costs of transport fuselage structures will be compared to the cost model predictions. This will provide direct comparisons with an industry-accepted approach to cost estimating.

Another form of cost model verification will be possible with proper interpretation of results from ACT fabrication trials. Several contractors have plans to produce composite fuselage and wing subcomponents during the course of the ACT program. Although these subcomponents will not be produced with the automation of a full-scale production hardware program, the cost model should still be general enough to scale for smaller sized panels and reduced production rates.

Progress to Date

Preliminary ATCAS work on a design cost model started during a one-year subcontract with the University of Washington in 1990. Design optimization software (UWCODA) was initially developed with mechanics constraints for minimizing the structural weight of fuselage crown panels (Ref. 10). Following crown global evaluation, it became desirable to enhance UWCODA to include design/cost constraints and an objective function for minimizing cost. Previous sections of this paper described the proposed plans to further generalize the design cost model and its software package. This work will eventually lead to an enhanced version of UWCODA which has been referred to as COSTADE.

Reference 5, which is included in the proceedings for this conference, documents the use of an enhanced version of UWCODA to optimize the fuselage crown panel design. Significant cost and weight savings were projected for design details selected with the help of the design cost model. The cost con-

straint equations for this effort were developed using manufacturing plans and detailed cost-estimating results for a specified factory. Hardware programs are expected to make use of a design cost model in a manner similar to that demonstrated in Reference 5 (i.e., optimize design details for selected manufacturing processes).

Design cost equations developed in Reference 5 treat design details as variables. Constants input to the model are used to characterize manufacturing processes. These variable and coefficient distinctions are consistent with a primary desire to use the model to predict the effects of design details on manufacturing cost. The cost model formulation will also allow analysis of the inverse problem (i.e., effects of process variations on the cost of a given design detail). This can be achieved in parametric studies by trading values of the associated constants for different manufacturing processes.

The geometric design variable found to have the strongest effect on fuselage crown panel cost and weight in Reference 5 was found to be stiffener spacing. The reduced manufacturing cost associated with wider stiffener spacing was traded against the increased weight of a thicker skin gage needed to satisfy loads and design criteria. Initial cost modeling results by Sikorsky Aircraft indicated similar trends for curved stiffened composite panels (Ref. 11).

A detailed evaluation of ATCAS crown panel design/cost relationships indicated that the number of stiffeners affects the cost of numerous fabrication and assembly processing steps. The relatively complex geometry of stiffeners makes them more costly to fabricate than skin; however, this effect was found to be relatively small in comparison to the total costs affected by the number of stiffeners. Stiffener design details increase panel bonding costs due to increased labor during panel sub-assembly, bagging, and inspection. The number of stiffeners also affects the costs associated with the intersections at frame elements (e.g., mouse-hole design details). Fabrication and assembly tooling costs increase with the number of stiffeners. Finally, the cost of circumferential panel joints increases with the number of stiffeners due to a larger number of splice elements and additional assembly labor. The potential for assembly problems (e.g., shimming) also increases with the number of stiffening elements expected to align at major joints.

Sensitivities to design criteria and guidelines were found to have a strong effect on the cost and weight of fuselage crown panel designs. For example, the value of a minimum load level used to constrain skin buckling was found to dominate costs associated with the trade between stiffener spacing and skin gage. Decreased values in the buckling constraint were found to decrease cost and weight until a point at which a new design driver became dominant. Studies such as these suggest that arbitrary guidelines established for composites should be challenged. In many cases, guidelines are used to constrain composite designs within the range of a database. As the database expands, the guidelines should be updated to reflect new insight and avoid adding unnecessary cost and weight.

The design sizing task of blending structural details to satisfy load and design criteria over the full crown panel appeared to influence cost and weight (Ref. 5). This effect was quantified by evaluating the total cost difference between a blended and optimized point design. The blended design appeared more expensive because the total cost of optimized point designs was simply calculated using a sum. In practice, design details will require some blending to avoid affecting automation and adding cost. For example, point-to-point compatibility of the skin laminate lay-up must be maintained to avoid the cost of local ply adds and drops.

One can surmise that the method used for blending designs will have a strong impact on cost and weight. In general, current designs are blended manually with the help of computing tools capable of sizing individual points. As discussed earlier, the development of mathematically based blending functions is proposed to enhance the design cost model. These functions are expected to optimize structural

details for a space containing variable loads and criteria. The blending function should be capable of incorporating advantages of some advanced technologies. For example, automated tow placement will allow greater freedom in ply tailoring (e.g., ply add/drop on the fly and angle changes over a distance).

The material variables considered during ATCAS crown design cost trade studies included graphite fiber type and hybridization. As expected, composite materials having higher modulus fibers were found to have improved performance and some weight savings. However, a material with lower modulus graphite fiber was selected as the most promising candidate for crown applications after comparing cost per unit weight savings (Ref. 5).

Figure 7 schematically illustrates how material cost and weight trade studies are performed using a design cost model. The results of such trades are application specific and depend on interactions with design variables. Therefore, the “best material” will change depending on several factors. Examples of these factors include the structural location, basic design concept, associated design drivers, and the value for an acceptable increased cost per unit weight savings.

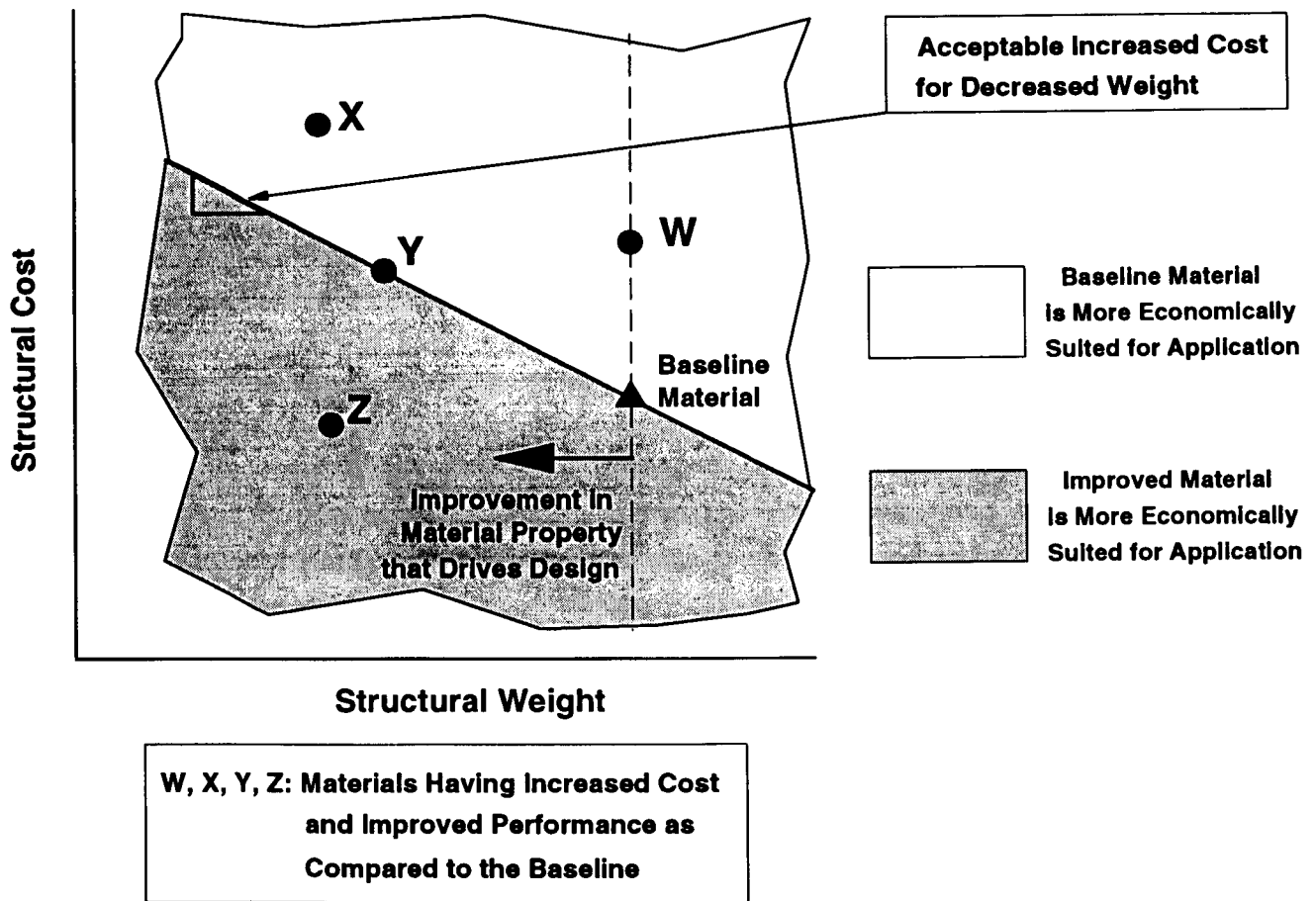


Figure 7: Schematic Diagram of a Trade Between Material Cost and Performance

The example given in Figure 7 compares four materials having both improved performance and increased cost, relative to a baseline material. An isovalue line is drawn in the figure to indicate an acceptable increased cost per unit weight savings. In general, this line will depend on specific hardware program goals. The baseline material would be selected over both materials X and W. Materials Y and Z are shown to have a value equal to and better than that of the baseline material, respectively. The

improved properties of material W are not design drivers, and the design cost increased directly with material cost. Material X is shown to have improved performance for a design driver; however, the weight savings does not warrant increased cost according to specified program goals. Material Z is the obvious choice over all materials shown in Figure 7 since the improved performance yielded both minimum cost and weight.

Cost-versus-performance trades can also be used in a research program to guide material developments for specific applications. This can be done by considering improvements in material properties known to drive design. As discussed in Reference 5, AS4/938 towpreg was selected for ATCAS fuselage crown panel applications. Considering this as the baseline material form, a study was performed for the current paper to determine how changes in the longitudinal ply modulus (E_{11}) affects performance. The acceptable increased material cost per unit weight savings was also determined using the same isovalue design lines applied in the ATCAS crown study.

Figure 8 shows theoretical results for crown panel designs consisting of materials with three different values of E_{11} . For purposes of simplicity, all other properties were assumed to remain the same as that of the baseline material. Material types A and B have the same material cost as the baseline, while C and D have increased costs. The increased E_{11} for materials A and B result in design variations that decrease cost and weight. When the technology required to enhance material performance also increases material cost, it would still be desirable to pursue such developments to the extent that design costs remain below the isovalue line. Material C represents such a case. The material cost for C is approximately twice that of the baseline material, but the value of weight savings possible in crown applications using such a material would be deemed acceptable. The material cost for D is approximately three times that of the baseline material. The crown design cost and weight trade indicate that the baseline material is more economically suited for crown applications than material D.

As discussed at the start of this section, results from References 5 and 11 suggest that cost savings are possible with increased stiffener spacing. Figure 8 showed that improvements in E_{11} allow increased stiffener spacing for a given skin thickness, resulting in lower design weights. As discussed with the help of an isovalue line, the economic value of the design may also be lower, depending on an interaction with material cost.

Another laminated material form which could theoretically allow wider stiffener spacing and reduced costs is one having a constant fiber aerial weight, increased ply thickness, and decreased density. Such a material may also yield a number of structural advantages for fuselage applications because the skin's bending stiffness per unit weight would increase. The material would conceivably have intra-layers consisting of continuous fibers and matrix with volume fractions consistent with current tape prepreg or towpreg. A porous matrix material with discontinuous fiber additives would constitute inter-layers having thicknesses on the order of 1/3 to 1 times that of the intra-layer. The density of the inter-layer would be on the order of high density core materials (e.g., 20 to 30 lb/ft³). Interlaminar shear strength requirements would likely control development of the inter-layers. Future ATCAS studies will consider the cost advantages, manufacturing concerns, and technical issues associated with a low density material having thicker plies.

The trade study shown in Figure 8 was simple in the sense that new materials were conceived to have changes in a single critical property. Cost and weight savings from improving a single material property are limited because a new design driver quickly becomes critical. In general, new materials have unique properties for several different performance issues. In some cases, material characteristics that increase one property can even decrease others. Based on fuselage design studies performed to date, materials having balanced performance attributes are desirable. Advances with new materials should be measured by considering the full range of properties critical to the design and application.

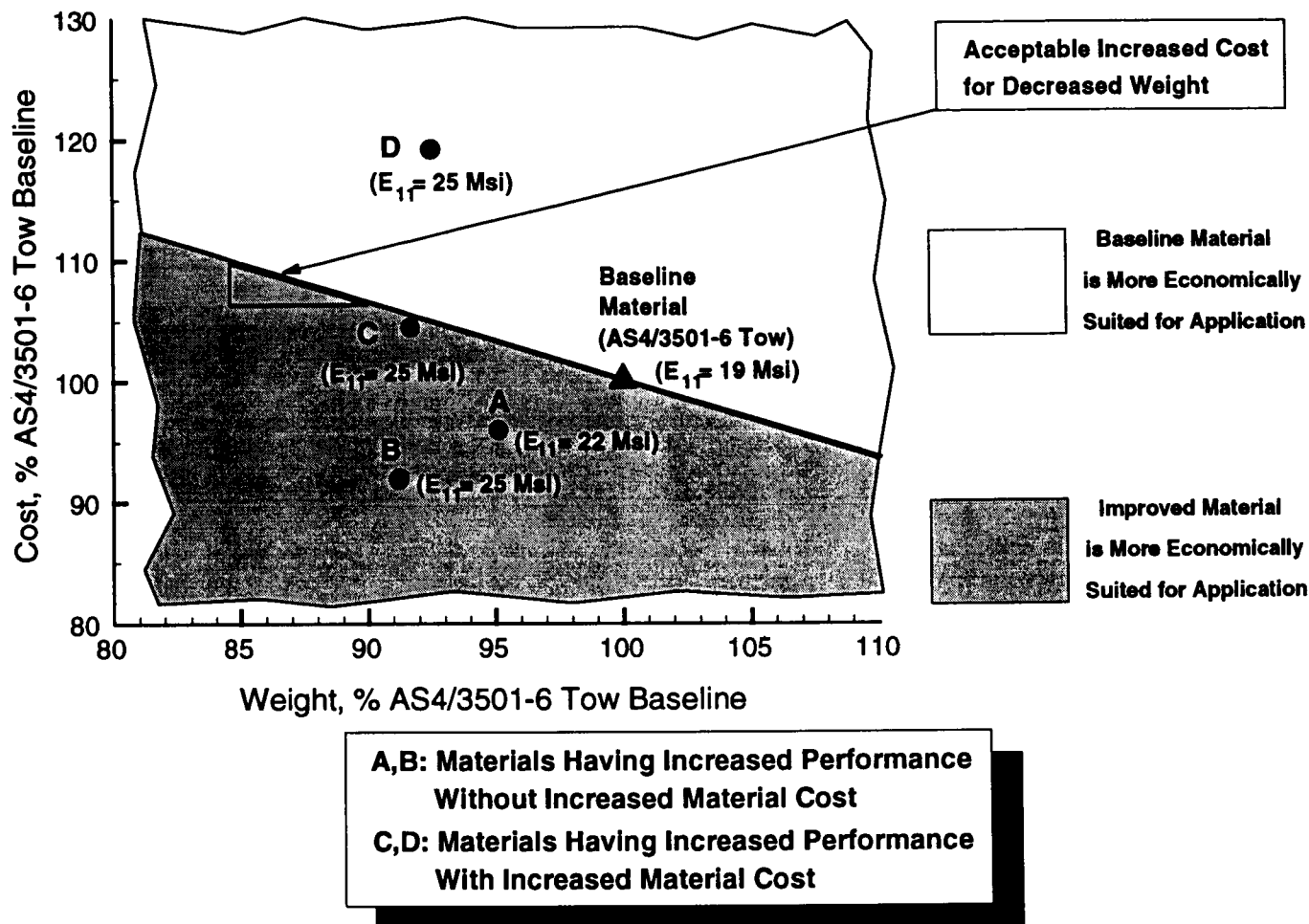


Figure 8: Skin Material Performance Versus Cost Trade for ATCAS Fuselage Crown Applications

Conclusions

The NASA Langley STPO has initiated a program to develop and verify a designer's cost prediction model that will aid engineers in trading the cost and weight of composite transport aircraft structures. Such a model is intended to be used in hardware applications to help design build teams select structural details with projections of their overall effect on manufacturing cost. Research programs may also use the model to guide advanced developments in processes, materials, structural concepts, and design guidelines.

The Boeing Company was selected to develop the designer's cost prediction model. Other industry and university subcontractors will include Sikorsky, Dow-UT, Northrop, MIT, and University of Washington. The Boeing ATCAS design-build-team approach will support model development and verification for fuselage structures. Seven objectives to address major technical issues were identified and a detailed plan was completed to pursue solutions for each of these issues.

Design cost relationships will be developed with the help of existing databases. However, the model's theoretical framework will be general enough to analyze both current and evolving technologies. This requirement is crucial to making the model suitable for predicting the cost of large composite transport fuselage and wing structures assembled in future aircraft factories. The designer's cost prediction

model will be developed to incorporate cost, design, and manufacturing constraints. This tool will be packaged as a computer program entitled Cost Optimization Software for Transport Aircraft Design Evaluation (COSTADE). An optimization algorithm which cost-effectively blends structural details over variations in load and design criteria will be derived as an option for COSTADE. Verification tasks to demonstrate the design cost model are planned throughout the four-year period of study.

Initial design cost model developments have concentrated on fuselage crown panel applications. To date, a software tool was developed for crown panel local optimization and used to perform sensitivity studies on factors critical to the projected cost of a future factory. Results are documented in References 5 and 12, which can be found in these proceedings.

References

- 1.) Freeman, W.T., Vosteen, L.F., and Siddiqi, S., "A Unified Approach for Composite Cost Reporting and Prediction in the ACT Program," First NASA Advanced Composites Technology Conference, NASA CP-3104, Part 1, 1991, pp. 357-369.
- 2.) Ilcewicz, L.B., Walker, T.H., Willden, K.S., Swanson, G.D., Truslove, G., and Pfahl, C.L., "Application of a Design-Build-Team Approach to Low Cost and Weight Composite Fuselage Structure," to be Published as a NASA Contractor's Report, 1991.
- 3.) Ilcewicz, L.B., Smith, P.J., Walker, T.H., and Johnson, R.W., "Advanced Technology Commercial Fuselage Structure," First NASA Advanced Composites Technology Conference, NASA CP-3104, Part 1, 1991, pp. 127-155.
- 4.) Walker, T.H., Smith, P.J., Truslove G., Willden, K.S., Metschan, S.L., and Pfahl, C.L., "Cost Studies for Commercial Fuselage Crown Designs," First NASA Advanced Composites Technology Conference, NASA CP-3104, Part 1, 1991, pp. 339-356.
- 5.) Swanson, G.D., Ilcewicz, L.B., Walker, T.H., Graesser, D., Tuttle, M., and Zabinsky, Z., "Local Design Optimization for Transport Fuselage Crown Panels," presented at the Ninth DoD/NASA/FAA Conf. on Fibrous Composites in Structural Design, Lake Tahoe, NV, November 1991.
- 6.) Krolewski, S., and Gutowski, T., "Effect of the Automation of Advanced Composite Fabrication Processes on Part Cost," SAMPE Quarterly, Vol. 18, No. 1, 1986, pp. 43-51.
- 7.) Foley, M., and Bernardon, E., "Cost Estimation Techniques for the Design of Cost Effective Automated Systems for Manufacturing Thermoplastic Composite Structures," in Proceedings of the SAMPE 35th International Sym., April, 1990, pp. 1321-1335.
- 8.) Gutowski, T., Henderson, R., and Shipp, C., "Manufacturing Costs for Advanced Composites Aerospace Parts," SAMPE Journal, Vol. 27, No. 3, May/June, 1991, pp. 37-43.
- 9.) Shipp, C.T., "Cost Effective Use of Advanced Composite Materials in Commercial Aircraft Manufacture," M.S. Thesis (Mechanical Engineering and Management), M.I.T., May 1990.
- 10.) Zabinsky, Z., Tuttle, M., Graesser, D., Kim, G., Hatcher, D., Swanson, G., and Ilcewicz, L., "Multi-Parameter Optimization Tool for Low-Cost Commercial Fuselage Crown Designs," First NASA Advanced Composites Technology Conference, NASA CP-3104, Part 2, 1991, pp. 737-748.
- 11.) Kassapoglou, C., DiNicola, A.J., Chou, J.C., and Deaton, J.W., "Structural Evaluation of Curved Stiffened Composite Panels Fabricated Using a THERM-XSM Process," First NASA Advanced Composites Technology Conference, NASA CP-3104, Part 1, 1991, pp. 207-232.

- 12.) Willden, K., Metschan, S., Grant, C., and Brown, T., "Composite Fuselage Crown Panel Manufacturing Technology", presented at the Ninth DoD/NASA/FAA Conference on Fibrous Composites in Structural Design, Lake Tahoe, NV, November 1991.