This article describes the use of cost models to: evaluate alternative frame designs, trade off applicable manufacturing processes and understand impacts of design features and material selections. This capability goes beyond pure cost values and allows a designer to identify the optimal and most affordable configuration and manufacturing plan during the design phase. Cost models can be tools that engineers rely on to quickly and comprehensively evaluate and compare various options within the design and manufacturing environments. To illustrate this concept, the process of improving the design and manufacturing of an engine front frame using cost and manufacturability models will be presented. Each step of this process will illustrate the use of the cost modeling tools and their respective results. The results of the study illustrate the ability of exercising cost models early on in the design process to yield substantial cost savings.

KEY WORDS: Braided Composites, Composite Structures, Cost/Economics

1. INTRODUCTION

Affordability is the key issue facing design engineers and manufacturers of composite components for current and next-generation aircraft, spacecraft, propulsion systems, and other advanced applications. To realize affordability goals, it is vital for engineering and manufacturing to accurately estimate manufacturing costs and risks at any stage of the program, but especially in the concept and preliminary design stage. Although the concept and preliminary design stages typically consume only 10% or less of program budget, over 80% of product cost is committed in these early stages.

In addition, lead times for design and fabrication of composite components often pace the development cycle. Consequently, a major priority is to reduce design cycle time and still produce the most efficient, lowest-risk component possible. Understanding the impact of critical cost elements on design features is a key step in reducing the overall cost of a component. It is
critically important for the manufacturer to also quantify the cost elements of the manufactured part in order to reduce costs and simplify the manufacturing processes.

2. COMPOSITE COST MODELS

With the progress of technology, many new manufacturing processes and materials have been introduced. With computer automation, cost modeling has become a sophisticated means of understanding the impacts and long term costs and manufacturing issues well before the onset of production. Of course, the success of this effort is dependent on the accuracy and integrity of the model itself. Cost models have expanded beyond simple spreadsheets and algorithms of just cost values, and now include guidance on design and manufacturing issues. Extensive help and built in rules and logic also assist the designer in avoiding undesirable situations and understanding limitations that may exist within a process or due to the selection of incompatible variables. The cost tool utilized in this study is SEER-DFM by Galorath Incorporated.

3. HISTORY

GE Aircraft Engine’s (GEAE) composite cost models were originally defined and developed under the Air Force Design and Manufacture of Low Cost Composites for Engines (DMLCC,E) Mantech program to analyze and estimate the cost of creating composite ducts for jet engines. The models have the capability to calculate the recurring fabrication cost, material cost and various design parameters for three composite manufacturing processes: Braiding, Filament Winding and Hybrid. The Hybrid process reflects a combination of Braiding and Filament Winding. A Hand Layup module was also developed under GEAE funding. While developing and using these models, it became very evident that this type of tool had the capability to assist the designer in the actual design of composites. Using Alerts, Warnings and extensive help text and diagrams, the tool became more than a cost tool by providing direction with respect to manufacturability. This powerful attribute prompted GEAE to further develop this concept for other processes while participating in the Composite Affordability Initiative.

Under the U.S. Air Force-funded Composites Affordability Initiative (CAI), industry members from Boeing, GEAE, Lockheed Martin and Northrop Grumman expanded the commercially available SEER-DFM tool by developing comprehensive cost models for over 20 composite processes. Under this program the CAI team members developed cost modules that plug into the existing SEER-DFM commercial software. This tool also guides the engineer through the selected composite process and, in many cases, identifies changes needed to avoid manufacturing problems or optimize manufacturing conditions. These modules provide a variety of user-friendly features, such as a standard interface and high level reporting functions. The models are easy to use as they contain detailed descriptions for each variable. The descriptions include graphics, pictures and narrated videos as needed. A standard SEER-DFM interface is shown in the figure below:
The top, left corner of the SEER-DFM screen allows the user to create a work breakdown structure (WBS) utilizing all of the work elements, or processes, to represent the configuration being modeled. The composite processes developed under the CAI program include:

CAI Processes in SEER-DFM

- Hand Lay-up
- 3-D Weave
- Paste Bond
- Braiding
- SPFDB
- VARTM
- RTM
- Autoclave
- Trim
- P4A
- Fit-Up
- Fasten
- Chemical Milling
- Tow Placement
- Filament Winding
- Sheet Metal
- E-Beam Assembly
- E-Beam Fabrication
- Core Machining
- 3-D Reinforcement
- High Speed Machining
- E-Beam Curing
- Hand Drill Operations
- Automated Assembly

4. FRAME DESIGN STUDY

In 2001, GE Aircraft Engines (GEAE) embarked on a program to quantify the cost of a composite frame designed to capitalize on the latest advancements in braiding, resin transfer molding (RTM) and towpreg materials. To establish the cost savings over a conventional
composite design, GEAE identified a methodology using a series of cost models to establish both a viable baseline cost, and a realistic end goal cost. The methodology was initiated by building a total of thirty (30) SEER-DFM cost models to represent the TF-34 vane frame designed, fabricated and tested in the 1978-1982 time period. This frame, shown figure 2, represents a design approach that was successfully fabricated and extensively tested.

Virtually all of the frame components were hand layup, press mold or autoclave and paste bonded together. More important, the cost of all component fabrications and assemblies for three (3) frames was captured and documented. This information was utilized to successfully validate the baseline cost models. Once this cost model was complete and validated, all components judged to be candidates for braiding were remodeled in an attempt to establish the cost savings due to automation of the components. It should be noted that this model did not address any improvements due to redesign or assembly. It was then decided to construct a cost model of a front frame designed and fabricated using the same approach, materials and processes as the TF34 frame. This model would serve as the baseline to compare all future design, material and process improvements. Therefore, the next cost model incorporated braiding and RTM in the construction of many components. These last two models identified the potential cost savings achievable through the use of braiding and RTM with no change in TF-34 design methodology. The final cost model represented a front frame completely redesigned with a focus of integrating many components into unified preforms. In addition, all paste bonded joints were replaced with either cocured or bolted joints. The following discussion provides details of the significant results of each of the above-mentioned cost models.

4.1 Model No. 1: TF-34 Baseline Analysis

The original TF-34 design and configuration was modeled in SEER-DFM using Hand Layup of Fabric and Tape, Autoclaving, Press Molding, Paste Bonding, and Modular Assembly. All frame components, as shown in Figure 3, were modeled to represent how the parts were assembled using paste bond technology.
The results were compared and correlated to actual data to construct a baseline and to determine the accuracy of the cost models. As shown in Figure 4, the correlation was excellent. The actual labor for the components was 6.4% higher than predicted. The actual assembly cost was 3.1% lower than predicted.

**Figure 3: Component Assembly Sequence**

**Figure 4: TF-34 Actuals Compared to SEER-DFM Model Predictions**

4.2 Model No. 2: TF-34 Configuration/Automated Once the models were correlated and validated, the study continued by reevaluating the original configuration. Components lending
themselves to newer, automated processes were remodeled to quantify cost impacts. The following processes were evaluated as applicable to each component.

- Automated Braiding
- Resin Transfer Molding

As shown in Figure 5, the results confirmed a significant decrease (61.6%) in the cost of the frame components by implementing automated processes.

![Figure 5: TF-34 Frame Trade Study Results](image)

**Figure 5: TF-34 Frame Trade Study Results**

**Model No. 3: Front Frame Baseline Design** In this analysis a new Front Frame, as shown in Figure 6, was designed using the TF-34 design approach. The frame was evaluated using conventional component manufacturing processes and assembly approaches (e.g. hand layup, press mold, autoclave cure and paste bonding as discussed in Model No.1).

![Figure 6: Front Frame](image)
**Model No. 4: Front Frame Design with Component Automation**  The Front Frame design was re-evaluated using newer, automated processes as conducted on the TF34 frame. For example, many items became braided performs with an RTM cure compared to the original approach of hand layup, press mold or autoclave cure. This approach resulted in a cost savings in excess of 20%.

**Model No. 5: Final Front Frame Design**  The front frame was completely redesigned with a focus of integrating components. Approximately ten separate components were integrated into three braided performs. In addition, all bonded joints were replaced with either cocure or bolted joints. As shown below in Figure 7, the results of this analysis yielded a 46% cost reduction for only the components and assembly. Figure 8 shows the cost savings for the entire front frame including the composite material and all metal components.

![Figure 7: Front Frame Trade Study Results (Labor Comparison Only)](image)
5. SUMMARY

The results of the study described above illustrate the ability of exercising cost models early on in the design process to yield substantial cost savings. Figure 9 summarizes the transition of the critical elements into the final lower cost frame configuration.

Figure 8: Comprehensive Front Frame Trade Study Results

Figure 9: Cost Model Evolution of a Low Cost Frame