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DETERMINING THE AFFORDABILITY OF ADVANCED PROPULSION SYSTEMS

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ABSTRACT

The **Integrated High Performance Turbine Engine Technology** (IHPTET) is a joint Air Force, Navy, Army, DARPA, NASA, and industry initiative focused on developing higher performance turbine engines. The goal of IHPTET is to develop and demonstrate propulsion systems that would, by the turn of the century, double propulsion capability (1987 base year). For this reason, IHPTET engines are now test beds for a high number of advanced composites, intermetallics and single crystal alloys. While satisfying the performance requirements, the program has another salient objective of cost **reduction**.

This paper will discuss an approach for cost estimating and modeling of components and sub-components, and demonstrate the benefits of employing simulations. Traditional approaches have relied on comparative techniques utilizing complexity factors or Cost Estimating Relationships (CER's). For advanced materials, these approaches are inadequate, primarily due to non-existence of historic data. A further weakness is their inability to identify **cost drivers** and quantify **cost avoidance potential**. Process-oriented cost estimating, albeit cumbersome during build-up and requiring detailed knowledge of manufacturing and process technology, provides a stable foundation for development of a comprehensive cost modeling system. **Manufacturing Process Flow Simulation** (MPFS) aids in evaluating **evolving** manufacturing processes (in infancy), studying the impact of alternate manufacturing processes and conducting **what-if studies**. MPFS can then be incorporated selectively into a cost modeling architecture capable of evaluating **production** cost for sub-components, components, and complete engines.

1. INTRODUCTION

The goal of IHPTET is to develop and demonstrate propulsion systems that will double the thrust and yet be cost effective. In order to achieve performance requirements, the envelopes of design and materials applications are being pushed to a new frontier. The current design for the IHPTET Phase III engine includes a high number of advanced composites, intermetallics, and new single crystal alloys. These advanced materials are being introduced in novel designs such as fan blisks and frames made from organic matrix composites, turbine rear frame, low pressure turbine blades and vanes from ceramic matrix composites, compressor rotors from metal matrix composites, and single crystal high pressure turbine blades, to name a few. Concurrent with the introduction of these materials, cost reduction objectives have been established as a challenge to the IHPTET community. American Technology & Services Inc. (ATS) is a member of this community working to understand the cost of IHPTET technologies, and to identify ways to reduce future production costs.

The overall cost reduction effort encompasses both the production cost (unit sell price) as well as engine operating and support cost. ATS is focused on the former. The target production costs are expressed in dollars per pound of engine thrust for the turbo-fan/turbo-jet family, while for the tubo-shaft/turbo-prop class it is in dollars per horsepower. The specific cost reduction objectives are -20% for Phase II and -35% for Phase III. For the expendable class the engine production cost goals require -30% for Phase I, -45% for Phase II, and -60% for Phase III.

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Currently, no acceptable, comprehensive predictive methodologies of adequate fidelity exist that will measure hardware affordability early in the design cycle when alternative materials and processes are evaluated and trade studies are to be conducted. This paper will introduce a **predictive methodology** for determining production cost of (manufacturing) processes early in their development cycle.

The prevalent cost-estimating techniques currently used by Department of Defense organizations and contractors fall short in addressing the problem of quantifying advanced hardware costs in absolute terms and forecasting production costs. Various software programs exist to meet the needs of specific users in specific situations; however, there is no generally accepted approach. Current techniques fall into three categories: 1.) Comparative methods, 2.) Parametric cost models, or 3.) Process-oriented cost evaluation techniques.

Comparative methods based on similarities to parts that have been manufactured or procured in the past can be rapidly utilized, and substantiation of the estimate is inherent in the baseline or reference part. These techniques are very adept at evaluating costs of current technology hardware allowing for minor variation, but do not address issues associated with new materials and manufacturing processes.

Parametric cost models include a set of algorithms or mathematical functions describing relationships between selected cost drivers and the corresponding elements of cost, which have been statistically derived from data based on previous experience (1). Only a few details about the process or the parts are needed up front. However, because of its dependence on historic database, they are not readily adaptable to predicting costs for new materials, manufacturing processes, or design changes. Both parametric models and comparative techniques fail to identify individual part cost drivers, quantify the magnitude of proposed cost reductions, and are insensitive to process improvements under development (2).

A process-oriented estimate is useful for understanding the cost of a particular design through analysis of the complete manufacturing process. The resulting cost estimate only represents a snapshot in time and does not account for the cost impact of design variations. As a result, for each design change, a new cost estimate must be generated. Extensive details and knowledge of the proposed process and material is required for each part.

MPFS cost models are constructed from objects or blocks that model the cost of manufacturing operations. The MPFS model can estimate and forecast manufacturing costs and evaluates the cost impact of process changes.

Table 1 summarizes the benefits and limitations of cost estimating techniques in use today (3).

Table 1: Summary of Current Cost Estimating Techniques

Cost Estimating Technique	*Benefits*	*Limitations*
Comparative Method	Quick Based on previous experience	Tied to historical data Depends on part similarity Not adaptable to new processes
Parametric Cost Model	Quick Not much input detail required	Requires substantial quantity of data for equation development
Process-Oriented	Adaptable to new processes Quantifies Cost Drivers Considers Producibility	Slow Requires detailed understanding of mfg. process and part details
Manufacturing Process-Flow Simulation (MPFS)	Extends capability of above methods Easy to modify Quantifies additional cost metrics Multi-level Analysis Tool	Requires detailed knowledge of manufacturing processes to construct robust cost models

2. APPROACH

To address the key issue of affordability for advanced materials and processes, development of new cost-modeling tools is a must. It is imperative that these new tools be capable of predicting, evaluating, and quantifying the costs associated with a new generation of aircraft engines incorporating the latest materials. ATS has developed an approach that builds upon the strengths of existing cost estimating and modeling techniques in conjunction with new developments not adequately addressed by the current cost models. This new modeling technique combines parametric cost algorithms with a process-oriented foundation utilizing machinability standards, accepted time standards for known operations, and Methods-Time Measurement (MTM) for new or unusual operations.

Simulation modeling through object oriented software environments provides an ideal vehicle for implementing this technique. MPFS cost models may be employed in evaluating evolving novel manufacturing processes (metal matrix composite, ceramic matrix composite, organic matrix composite, etc.), permitting the introduction of efficiency / scrap rates and identifying bottlenecks later when production decisions are made. By building and expanding upon process-oriented cost estimating, this simulation approach is unique and well suited to the advanced technology arena where production is far in the future.

The first step in creating a MPFS cost model is to develop a detailed process sequence. Time or costs are applied to each step in the sequence resulting in an initial process-oriented cost estimate. The process-oriented estimate provides significant benefits to both the modeling process and the development of a successful design concept for actual hardware. These include identification of cost drivers, accumulation of process knowledge early in the design cycle, and establishment of cost goals during process development.

In a typical estimating/modeling project, ATS draws from its (200 years of cumulative) manufacturing technology expertise and accumulated knowledge of state-of-the-art processes to develop a viable sequence of manufacturing operations. This process plan establishes the foundation for a detailed estimate of a "mature" production cost for the hardware. Maturity assumes that the process is in control, running production hardware at a rate of 100 units or higher per year, and that major improvement in tooling, fixturing, manufacturing sequence, and the individual operations has been accomplished. For aerospace hardware, this usually occurs at about the 250th unit produced.

The process-oriented estimate utilizes custom parametric algorithms ATS has developed for unique operations along with the *MetCAPP® Knowledge-based Process Planning* and *American Machinist Cost Estimator* (4) software programs to estimate a cost for each manufacturing operation. The *MetCAPP* software is linked to a database of machinability standards and used to estimate the cost of machining operations.

A process-oriented cost estimate provides a foundation for development of a cost model that may be implemented as a process flow simulation model. This simulation is constructed from the process details collected and analyzed during estimating. Statistical techniques are used to model the cost of individual operations, associate probability distribution functions with process uncertainty, and establish confidence intervals for output values. The MPFS model is then implemented in a simulation software environment. To accomplish this, objects from a standard manufacturing library are combined with custom blocks to represent equations. Interconnecting objects to represent the logic completes the model.

The Extend™ Performance Modeling software is one environment for implementing a MPFS cost model (5). By evaluating the steps of any manufacturing process, Extend™ can be used to represent the production economics of a complex system. Benefits derived from MPFS for cost modeling stem from the ability to measure the behavior of a manufacturing system over time. Prediction of the cycle time and capacity of the process is possible, in addition to the estimation of manufacturing cost based on direct labor input and process time or assessed cost. Resource requirements and allocation strategies can begin early in the design cycle and potential manufacturing and producability problems can be identified up-front. Process variation and yield can also be realistically represented by probability distribution functions at the appropriate points in the process. When decisions for production transition are to be made, MPFS can help in optimization studies, justifying new equipment, identifying bottlenecks, and achieving a more efficient distribution of personnel and raw materials in the shop.

3. Example

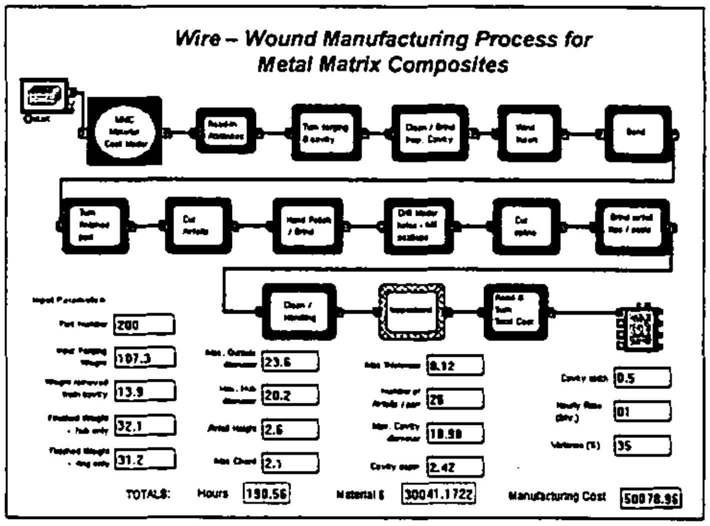

Figure 1: Manufacturing Process Flow Simulation Example

Figure 1 provides an example of a process flow simulation for manufacturing a blisk (disk with integral blades) with a metal matrix composite insert. The manufacturing process utilizes wire-winding to build-up the insert by winding layers of silicon carbide fiber surrounded by matrix materials in the form of wire. The major manufacturing operations or groups of similar operations required to produce this part are represented as blocks (top-level shown in figure 1) in the process-flow simulation.

These blocks are hierarchical in structure, thereby facilitating a multi-level analysis tailored to the knowledge base of the user. For example, a Preliminary Design Engineer may not be concerned with a specific machining operation or the associated speeds and feeds. However, the details are available to the user who is interested in modifying the values or in validating the model calculations. To access the next level of detail, the simulation permits the top-level block to be opened for access to the underlying equations and logic. Table 2 shows the functional content of each level in the hierarchical system structure.

Table 2: Hierarchical Structure of MPFS Model			
Level	Description	Content	Data Used
1-top	*Process*	Top-level manufacturing process sequence; material models, functional blocks, and Operation Models.	Physical parameters that drive cost (e.g. weight, diameter, thickness, num. of holes, etc.).
2	*Feature*	Operation blocks required for a specific feature or Operations grouped by type.	Physical parameters from Level 1 and calculated parameters (e.g. cut length).
3	*Operation*	Algorithms & logic to calculate direct labor input and processing time for each operation.	Level 1 & 2 parameters, process data such as speed, feed, and cut depth for machining.
4	*Algorithm*	Estimating equations for each element of an operation (e.g. load, unload, reposition, cut material)	Level 1, 2, & 3 parameters with coefficients from statistical analysis for each cost element.

Inputs from the example in figure 1 are tailored to the level of detail defined in the Preliminary Design environment to match the knowledge base of the Preliminary or Conceptual Design Engineer. Turning costs are estimated from the weight differential between the input forging and finished weights for the turned part (hub and blade ring). The estimate for milling and finishing the airfoils depends on the number and size as defined by height, mean chord and maximum thickness.

Outputs include the manufacturing cost as shown in terms of direct labor input and material dollars on the example. Additional output values that may be obtained include process cycle time, yield and process capacity over time, and resource requirements to meet the anticipated production schedule.

The inherent properties of MPFS permit a more dynamic analysis of a manufacturing system than any other modeling technique. The structure of the model permits determination of the operations that drive the manufacturing cost of the part as shown in figure 2. This insight can steer process development towards the areas most likely to provide a cost reduction.

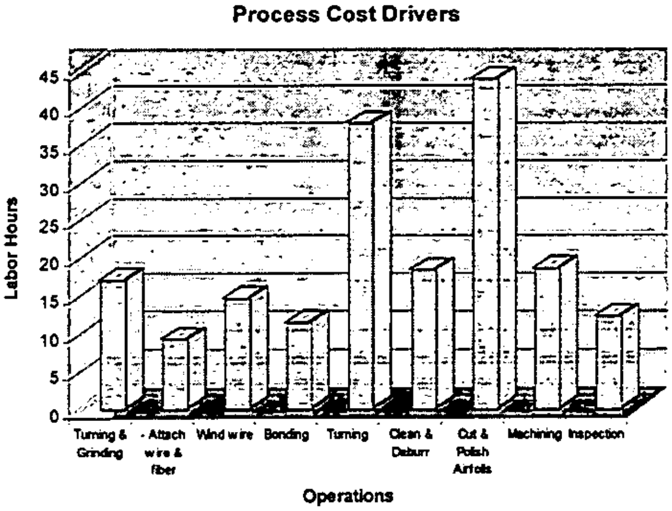

Figure 2: Process Cost Drivers from MPFS Cost Model

The MPFS models can be utilized independently for predicting costs of a new manufacturing process or linked to a larger cost modeling system. This cost modeling system can be customized for specific users such as preliminary design engineers. To accomplish this, the interface is designed with the knowledge base (input parameters) of the user. Figures 3 and 4 provide an example of a user interface for a top-level cost model system.

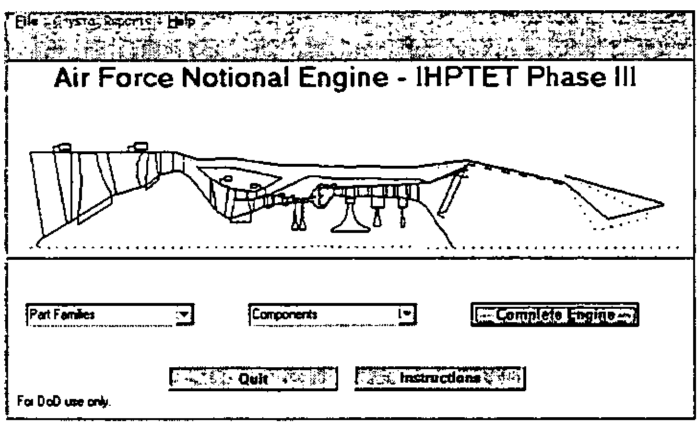

Figure 3: Part Selection screen from ATS *Quick Estimator*

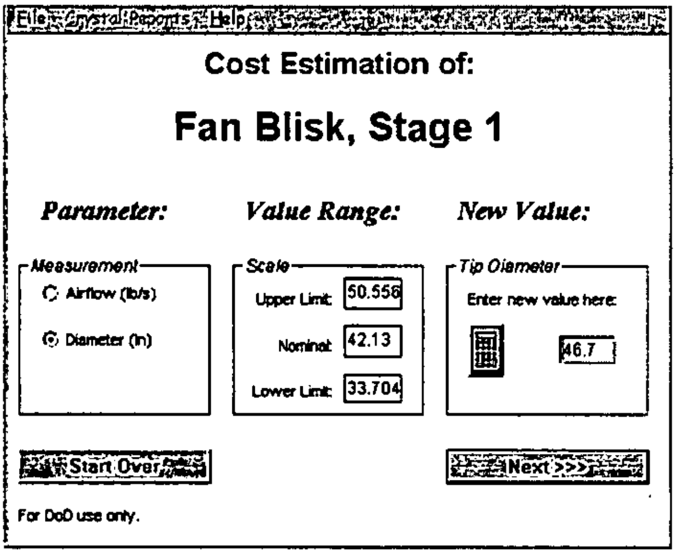

Figure 4: Input Screen for New Part Diameter

5. CONCLUSIONS

Many benefits of this approach stem from capturing the salient details of manufacturing process that impact cost, whether it is in the early phase of development or during production transition. The modular nature of modeling permits quantitative evaluation of alternatives (trade studies) in manufacturing processes or individual operations. MPFS leads to identification and measurement of the process cost drivers and establishment of realistic production cost targets. These features may be viewed as a guidance tool during process development and in directing development effort to programs with highest payoff. By establishing a relationship between part parameters and cost, preliminary designers can get a quick quantitative feedback on the affordability of their designs.

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