ADVANCED COMPOSITE MANUFACTURING COST REDUCTION ACHIEVED THROUGH VALUE ENGINEERING APPLICATION

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In his most recent assignment he has directed the manufacturing process improvement activities for the advanced composite airfoil assembly discussed in this paper.

ABSTRACT

This paper describes how Value Engineering (VE) was applied by United Technologies, Pratt & Whitney, with the assistance of J. J. Kaufman Associates, to reduce costs of their most advanced composite engine components. The VE team used a methodology of brainstorming, functional and paired comparison analysis, and "Fast Modeling" to identify opportunities for design and manufacturing process improvement. These opportunities were packaged into two proposals with near and far term implementation plans. This paper summarizes how those plans were successfully implemented through the breakdown of paradigms and improved communication and cooperation between the design and manufacturing communities.

INTRODUCTION

The advanced composite airfoil assembly illustrated in Figure 1 was selected by the Pratt & Whitney Technical Management Team for analysis in a VE Workshop. Selection was based on the complexity of the advanced design, the temperature and pressure extremes of the material processing, the historically high manufacturing scrap rate, and the unreasonably high cost of production.

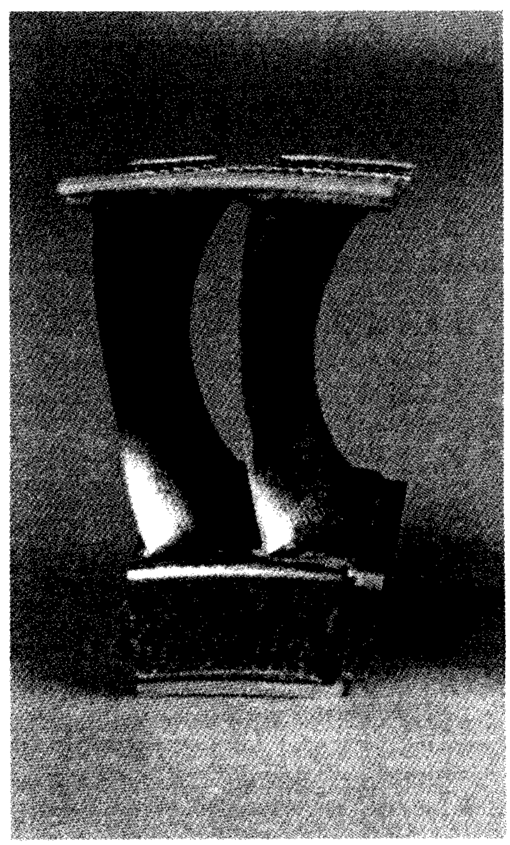

Figure 1. Advanced Composite Airfoil Assembly

This design was heavily influenced by a variety of aerodynamic, weight, efficiency, and performance constraints. These constraints resulted in a design having highly contoured airfoils and tight as-molded tolerances. Weight restrictions, coupled with a severe thermal and high cycle fatigue environment drove the use of an advanced, lightweight, high strength and stiffness composite material system.

To process components from this material system, special capital equipment and other materials were required. This included a 300 ton / 800 F molding press, high quality tool steel molds, high temperature mold release, a wax encapsulation system, and a super abrasive machining center. In addition, highly skilled operators were needed to accurately lay-up and position the 75 uniquely shaped plies of prepreg composite material.

The manufacturing process involved over 30 operations which are summarized as follows;

SUMMARY OF MAJOR OPERATIONS

1. Remove frozen material, thaw, and cut.
2. Organize and stack composite ply shapes.
3. Clean, mold release, and bake mold details.
4. Locate ply stacks on mold details & debulk.
5. Assemble mold details & wedge tool.
6. Press mold at elevated temperature/pressure.
7. Disassemble mold, deflash, and post cure part.
8. Wax encapsulate part, machine, and de-wax.
9. Perform holographic & dimensional inspection.
10. Bond seals, apply erosion protection, & deliver.

Historically, manufacturing yield for the advanced composite airfoil assemblies was only 65%. Nearly 75% of the scrapped parts were attributed to blistering following post cure, at which time 45% of the total cost had been accumulated. The remaining 25% were scrapped following one of the inspection steps for problems arising much earlier in the process. By the time parts reached inspection, they had accumulated nearly 90% of their total cost.

With a high scrap rate, expensive capital equipment, and a large skilled workforce producing a relatively small volume of parts, overhead rates were out of control. Without any additional volume, the only means of reducing overhead related costs were to reduce scrap and improve the efficiency and performance of the workforce. Considering these many issues facing the advanced composite airfoil assembly, it was a logical choice for a VE Workshop.

APPLYING THE VE METHODOLOGY

A diverse and talented VE Team was selected from the fields of design, structural analysis, manufacturing, materials and process technology, project engineering, as well as financial analysis. Each VE team member had some ownership in the design, manufacture, or use of this airfoil assembly. A Steering Committee, consisting of managers from many of these same disciplines, was organized to review the team's proposals, provide the necessary resources to execute their plans, and empower the team to implement the ideas. J. J. Kaufman Associates facilitated the team's activities during the week long workshop.

At the recommendation of the facilitator, the team used this five phase VE methodology.

VE METHODOLOGY

1. Gather information and requirements.
2. Develop creative alternatives.
3. Evaluate these alternatives.
4. Develop firm program proposals.
5. Implement recommended projects & plans.

Phase 1. was accomplished prior to the initiation of the actual VE Workshop. The team met and developed the following mission statement:

MISSION STATEMENT

"Identify advanced composite airfoil design and process improvement opportunities which will reduce cost, increase yield and quality, and enable the team to meet schedule requirements."

From their mission statement the VE Team developed the following objectives:

TEAM OBJECTIVES

- Meet flight test schedule
- Reduce total part cost by 60%
- Increase process yield from 65% to 90%
- Attain 100% dimensional conformance
- Reduce lead time from five to two months

The balance of the team's pre-workshop activities was focused on gathering facts useful in defining the function of the product. These included an estimate of product worth, and various operating constraints such as manufacturing operation sheets, blueprints, specifications, quality documents, and schedules. General information concerning pertinent product technologies was also acquired.

The VE Workshop was kicked off by determination of the key attributes of the advanced composite airfoil assembly. Ideally, these attributes would be provided by the customer or end-user of the product. Unfortunately this was not possible during the workshop, so the team worked with program management to develop the following six attributes.

KEY PRODUCT ATTRIBUTES

- Manufacturing Cost
- Process Yield
- Durability, Maintainability & Repair
- Weight
- Process Through-Put
- Dimensional Conformance

A "Paired Comparison" analysis was then conducted by the team wherein each attribute was compared to the other on a level of importance. This comparison was made qualitative by applying a factor from one to three, three being "of significantly greater importance" to the customer. The numerical results for each attribute were tabulated, and the results normalized on a percent scale. The Paired Comparison results for the advanced composite airfoil assemblies are shown in Figure 2..

The VE Team then performed a Product Functional Analysis. The team had to determine the function of the product as a whole, as well as the function of each detail or feature. These functions were divided into two categories:

- Primary functions - performance features which must be attained
- Secondary functions - features needed due to the method chosen to accomplish primary function or "nice to have features"

After defining these functions, the team was challenged with defining "How & Why" these functions were carried out. For example, the function of turning air was done by creating the airfoil shape to compress the air. Additionally, the function of recirculation prevention was accomplished by sealing air leaks to increase the efficiency.

Building on this "How & Why" functional analysis, a "Fast Model" was created by documenting all the functions, primary and secondary, and the how's and why's on removable paper adhesive strips. The functions, how's and why's, were then organized on a large sheet of paper by "when" they were achieved in the process. A condensed version of the team's "Fast Model" is illustrated in Figure 3.

	B	**C**	**D**	**E**	**F**	**ATTRIBUTES**	**TOTAL**	**Percentage**
A	A2	A2	A1	A2	A1	MFG COST	8	35%
	B	B1	B1	B2	B1	YIELD	5	22%
		C	D2	C1	F2	DM&R	2	9%
			D	D2	F1	WEIGHT	4	17%
				E	F1	THRU-PUT	1	4%
					F	DC	3	13%
						Totals:	23	100%

Abbreviations: DM&R = Durability, Maintainability, and Repair DC = Dimensional Conformance

Weighting Factors: 1) Slightly more important 2) Much more important 3) Significantly more important

Figure 2. Paired Comparison Analysis for the Advanced Composite Airfoil Assembly

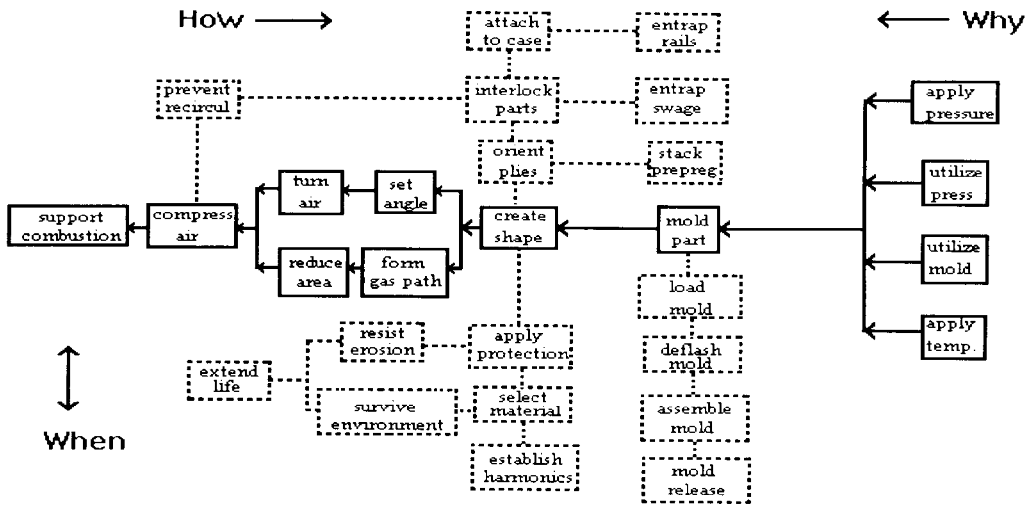

Figure 3. How, Why, & When "Fast Model" Function Analysis of an Advanced Composite Airfoil Assembly

Creation of the Fast Model enabled the team to gain a clear understanding of how and why the product design features drove the material and manufacturing process to satisfy the primary and secondary functional requirements.

2. Develop Creative Alternatives

With a more thorough, function-based under-standing of the design, materials, and manufacturing process the team next conducted a brainstorming exercise. Each function, primary and secondary, was addressed, and ideas were generated and collected on the basis of how each function might be accomplished differently, more efficiently, at a lower cost, or perhaps not at all. The team generated 246 ideas for review.

3. Evaluate Alternatives

The team next analyzed their brainstorming ideas and identified the most promising ones. Team members independently selected ideas which they were willing to champion. Each championed idea was discussed on the basis of the ability to perform the function, ease and cost of implementation, and potential savings associated with that idea. Where logical, common or similar ideas were combined into one. Team members then voted on each championed idea using a numerical scale from a low of 1 to a high of 10, called the GFI, or "Gut Feel Index", in this exercise.

The highest scoring ideas were expanded upon by their champions in the form of one page written summaries. Here, benefits, risks, and implementation costs were detailed, along with a description of the current and proposed approach, and a sketch to clarify the idea. The summaries were reviewed by team members and grouped into three final proposals based on timing of perceived benefits, ease and cost of implementation, and risk.

The brainstorming exercise can be summarized as follows.

Brainstorming Ideas

- Number of ideas 246
- Ideas championed 157
- Consolidated ideas (GFI) 78
- Surviving ideas 58
- Number of proposals 3

The three remaining proposals were then evaluated using the weighted factors from the paired comparison exercise. The results of this analysis are shown in Figure 4.

CRITERIA	M fg Cost	Y ield	D M&R	W eight	Th ru-put	DC		
WEIGHT (Total 100)	**3 5**	**2 2**	**9**	**1 7**	**4**	**13**	**R ATE**	**R ANK**
PROPOSAL								
Current Design & Process		4 4	2 7	8 5	6	13	2 10	4
Component Redesign and One-piece Flow Process	1 40	9 2	3 2	8 5	16	52	4 17	1
Component Redesign without One-piece Flow	1 05	8 8	3 2	8 5	12	52	3 74	2
Process Improvement Package (current design)	1 05	8 8	2 7	8 5	12	39	3 56	3

Abbreviations: DM&R = Durability, Maintainability & Repair DC = Dimensional Conformance

Figure 4. Rank and Rate Results for Advanced Composite Airfoil Assembly Value Engineering Proposals

4. DEVELOP PROGRAM PROPOSALS

Of the three proposals created, the team elected to develop two for presentation to the Steering Committee. The first, entitled "Process Improvement Package", contained the lowest risk, lowest cost to implement, and quickest to market ideas, though ranked third in overall benefits. The second package labeled "Component Redesign with One-piece Flow" required a more extensive capital and manpower investment, and included a complete redesign of the advanced composite airfoil assembly. The risks of this approach were much greater, but so were the benefits.

The Steering Committee warmly accepted both proposals, agreed to provide the necessary financial and human resources, but requested that the implementation schedules be accelerated to achieve objectives sooner. An accelerated schedule was successfully negotiated, and the team was given the authority to implement their ideas. Both the VE Team and the Steering Committee agreed to hold each other accountable for implementation and the provision of resources respectively. A meeting to assess the progress of the team was scheduled for four months later.

5. IMPLEMENT PROJECTS & PLANS

A) PROCESS IMPROVEMENT PACKAGE

Four months after the VE Workshop, the team reassembled to present their progress towards meeting their objectives to the Steering Committee.

The VE Team made progress in every area targeted. They were on schedule for the April delivery of flight test hardware. They achieved major reductions in the cost of the raw material by reaching an agreement with the raw material supplier to couple Pratt & Whitney's orders with that of their co-producer. Because the raw material is batch produced, this provided the supplier with increased volume and enabled them to offer a 50% discount!

Prior to the VE Workshop, the internal quality of the advanced composite airfoil assembly was scrutinized using a holographic laser, non-destructive inspection technique. Though relatively easy to perform, there were a limited number of outside sources capable of performing this inspection, so costs were high and through-put was poor. The team, with the backing of management, acquired its own holographic inspection system and trained two operators, all within a four month period. The investment costs were recoverable after 10 engine sets worth of parts, or about one year. The costs are now accumulated as direct labor and overhead.

Though the need for erosion protection was highly challenged in the VE Functional Analysis, in the end it was deemed critical for meeting durability, maintainability, and repair expectations of the customer. However, during the discussion of championed ideas stemming from the brainstorming event, a potential for reduced cost was identified. Like the processing of the raw material, the application of the erosion resistant coating was batch processed. If coating out-time could be increased, then the batch size could be increased, the amount of wasted coating could be decreased, and an overall cost reduction would be realized. This idea was taken to the laboratory, and three months later incorporated into production at a cost savings exceeding the target by nearly 20%!

Clearly the greatest cost driver in the production of the advanced composite airfoil assemblies was the exceptionally high scrap rate. Discussions with the raw material supplier and co-producer during the VE Workshop led to the incorporation of a series of process improvement activities including three KAIZEN events. Once the root causes of the scrapped parts were identified, manufacturing process development trials could be conducted, and process improvement ideas implemented.

The leading cause of scrap, blistering following post cure, was virtually eliminated. This was achieved by breaking down a series of engineering and manufacturing paradigms regarding ply lay-up, laminate debulking, and the press and post cure cycles. Within five months after the VE Workshop, the process yield following post cure had increased from 70% to 94%! In addition to the overall quality improvements realized, both the press cure and post cure cycle optimization led to reductions in automatic times, providing an increase in process through-put of up to three days!

Despite the reduction in scrap associated with post cure, the team fell far short of achieving its goal of 100% dimensional conformance. At the heart of the problem was the complex, ten-piece press mold tool. Although the team attempted to model the tool detail interactions during high temperature consolidation, they were unable to make any recommendations that would ensure complete mold tool closure. Because of high tool costs, multiple tooling interations were not possible. Further progress was left to the Component Redesign with One-Piece Flow Proposal efforts.

B) COMPONENT REDESIGN WITH ONE-PIECE FLOW PROPOSAL

Nearly a year has passed since the VE Workshop was held in Pratt & Whitney's Composites Product Center, and since then, significant advancements have been made in all aspects of the design and manufacturing process.

The component redesign activity contributed the following improvements to the manufacturing process:

- Reduced part numbers from five to two,
- Modified platform shape for improved dimensional conformance,
- Redesigned ply shapes and sizes,
- Increased leading and trailing edge radii,
- Increased airfoil profile tolerance range,
- Improved standardization with filler ply definition.

Although these design changes led to manufacturing cost reductions and increased through-put, there were compromises in the new design which off-set some of the cost reductions. These included requirements for more durable leading edge erosion protection, and alterations to the design to accommodate a high temperature air seal/leakage prevention system.