Real Time Cost Impact Assessment of Composite and Metallic Design Alternatives

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Abstract

This paper discusses how a process-based parametric cost model, SEER-DFM, is used to facilitate the real time cost impact assessment of composite and metallic design alternatives. The main purpose is to introduce the underlying cost model methodology and demonstrate its flexibility for developing trade studies. Readers are introduced to the model, its premise, and how engineers use it to obtain substantial cost savings through 'real world' examples.

Introduction

Engineers are often called upon to make decisions without fully understanding the manufacturing cost implications of alternatives, and they agree that as much as 70-80% of a product cost is committed during the early stages of product development [1, 2, 3] (see Figure 1). This can have considerable financial consequences; because, product modifications and process alterations are exponentially more expensive the later they occur in the product development cycle [4]. Conversely, the scope for cost reduction reduces.

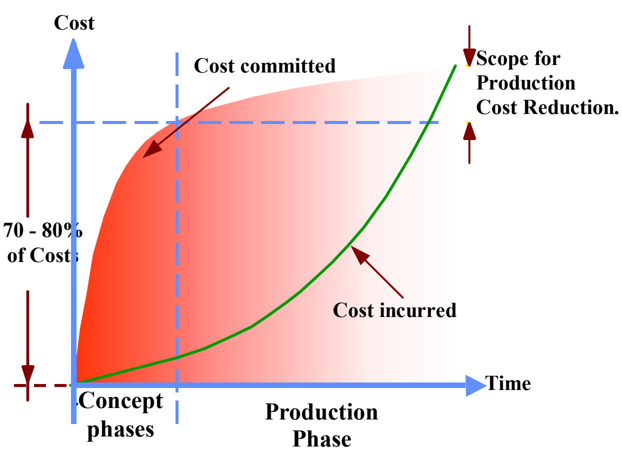


Figure 1: Cost commitment curve [5]

With the cost commitment curve in mind, it is easy to understand why meaningful cost estimates during the early stages of product development are crucial. Recent research demonstrates that companies unable to provide detailed, meaningful cost estimates, at the early development phases, have a significant higher percentage of programs behind schedule with higher development costs, than those that can provide completed cost estimates [6]. It is essential that the cost of a new project development be understood before it actually begins. It could mean the difference between success and failure.

With the increasing use of composite structures across industry, there is a growing need to understand the cost impact of design alternatives alongside more traditional metal working processes. Composite manufacturing poses a new set of issues for engineers. The technology is evolving; it is more complex than traditional metal working processes, and at the same time less familiar to today's engineers.

In response to this, the composites affordability initiative (CAI) was initiated. The CAI is a cooperative government and industry venture. The program was launched in 1996 and is scheduled to run through 2017 [7, 8]. Initial results are embodied within the SEER-DFM parametric cost model methodology. Approximately thirty composite-specific manufacturing processes sit alongside seventy more traditional metalworking processes. This provides design engineers with a comprehensive framework for evaluating the cost of alternative composite materials against more traditional manufacturing processes. Engineers use the cost model to perform and assess trade studies concerning the cost implications of employing different processes or elements of processes. These trade-offs can be evaluated in real time, which result in efficient development of the most affordable designs, based on informed decisions.

The remainder of this article introduces the underlying principles of the cost model methodology and demonstrates how engineers benefit from using it.

The paper is divided into three main sections. The first section highlights the challenges for cost engineers and the underlying principles of parametric cost modeling. The second section discusses the concept of Design For Manufacture (DFM) and the SEER-DFM cost model methodology. The third section provides example trade studies demonstrating how engineers use the cost model to carry out cost analysis of design alternatives in real time.

Background and Related Research

Cost Estimating Challenges

Developing meaningful estimates for design alternatives at the conceptual design phase is not a trivial task [9, 10, 11, 12]. There is a high degree of uncertainty attached to the final estimate, as depicted in Figure 2 [13, 14]. Figure 2 illustrates that during the early stages of development there is a high degree of uncertainty, and consequently a large estimating error. As uncertainty and product detail forms, the expected error range reduces.

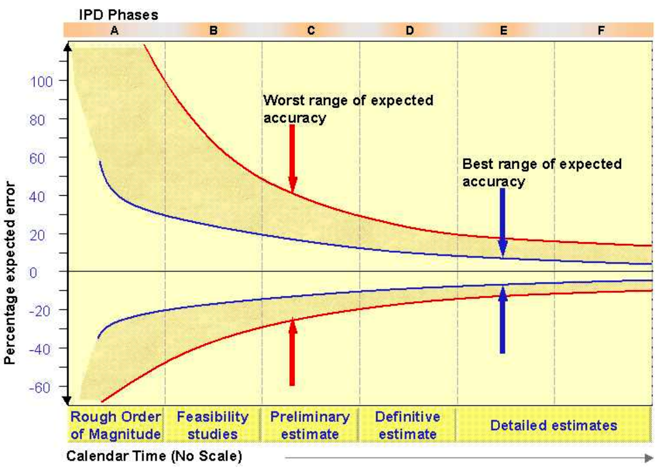


Figure 2: Expected error range of estimates

Uncertainty arises from several major obstacles, which are summarized as:

- Working with a limited amount of available data concerning the new development;
- Accounting for step changes within technology over the life span of product development;
- Requirements to show how cost estimates were derived including the assumptions and risks, and;
- Estimates need to be consistent and reliable.

One widely accepted method of countering these obstacles parametric cost modeling.

Parametric Cost Modeling

The main idea behind parametric costing is to develop a statistical relationship between the attributes and cost of previous products in order to predict the cost of a new product. Parametric cost estimating is typically used during the early stages of development, when there is little product information available. It has been used across industry and government for over fifty years [15]. Many commend its usefulness, such as: Stewart [1], DOD [2], Mileham *et al.* [3], Pugh [9], and NASA [16].

When properly implemented and appropriately used, commercial parametric estimating models can reliably predict future project costs more efficiently than traditional estimating methods [2]. For this to happen, parametric models often need to be calibrated to a specific organization's business environment, culture, and cost history. Furthermore, they need to be flexible enough so that individual companies can model their particular processes and accommodate their own unique methods of working.

To illustrate the concept more clearly the following example will suffice. Typically, for aircraft development, mass relates to the cost of production. That is, as the weight of the aircraft increases, so does the cost of producing it. What's more, this particular relationship is often described as linear, as illustrated in Figure 3 below.

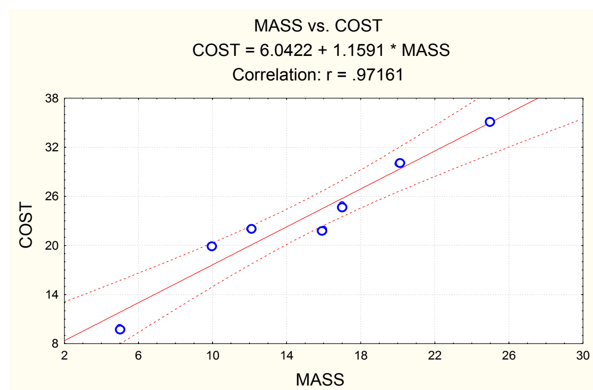


Figure 3: Simple linear equation

In this hypothetical example the points of the graph represent the relationship of cost to mass for different aircraft. The line traversing the points represents a linear relationship i.e. as the mass increases so does the cost. Using relatively simple algebra, it is possible to derive a formula to determine a mathematical relationship for cost to mass. For the above graph, the equation $y = a + bx$ is used to describe the line of best fit between the points. With such relationships defined, it is possible to predict the cost of a product with a relatively limited amount of information in a speedy, systematic fashion.

This is a rather simplistic illustration with respect to parametric estimating; nevertheless, variations of this approach are used widely across industry.

Advanced parametric cost models extend this basic concept such that they can be used to describe and estimate process costs, opposed to specific part or product costs. Using a process-based methodology provides a flexible framework for developing estimates. For example, engineers can assess the cost impact of several options in a fraction of the time compared to more traditional estimating methods. In some cases, parametric models reduce estimating time from two weeks to ten minutes [17]. However, it is more common to see reductions of between 4 to 10 times [18]. Having a rapid evaluation capability provides companies with a powerful methodology to carry out Design For Manufacture (DFM) before committing to a particular design.

Design for Manufacture and the SEER-DFM Cost Model

DFM (Design for Manufacturability) is the practice of designing products with manufacturing in mind. DFA (Design for Assembly) is the practice of designing products with assembly in mind. Until recently manufacturers developed products using a sequential design and manufacturing process with an 'over the wall' mentality. That is, once a design was complete it would be passed 'over the wall' for manufacturers to work with (see Figure 4).

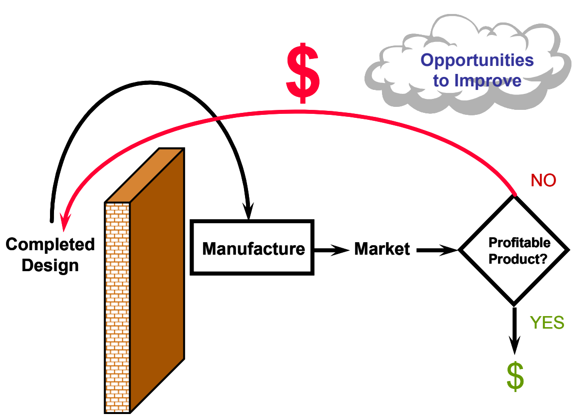


Figure 4: Sequential development process

Manufacturers would attempt to make the product only to discover it was not feasible. This would result in costly, unwanted engineering product changes. Table 1 illustrates that if it cost $\$10^3$ dollars to change a product in the design phase, it will cost $\$10^7$ dollars during the final production phase.

Table 1: Cost of engineering changes during product life cycle [4]

Phases when changed	Cost
Design	$1,000
Design Testing	$10,000
Process Planning	$100,000
Test Production	$1.000,000
Final Production	$10.000,000

Such costs were not acceptable and as a result more emphasis was placed on the integration of designers and manufacturers within Integrated Product Teams (IPTs), (see Figure 5).

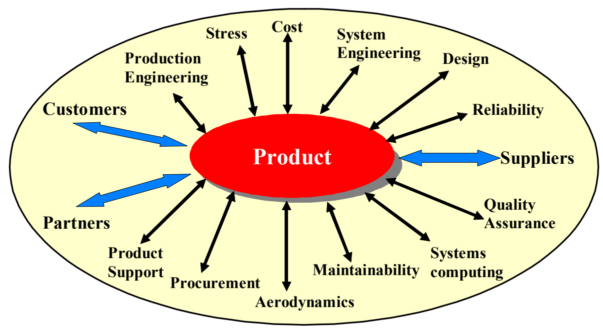


Figure 5: Example IPT environment

Multidisciplinary teams working together reduce the likelihood of product failure. Engineers can make more informed decisions and reduce costs by avoiding costly alterations later in the product life cycle. For example, in a recent survey carried out by out by the Westport Consulting Group [19, 20], all companies using DFM have been able to reduce their costs compared to the original cost projections. 11-20% of respondents saved over 30% (see Figure 6).

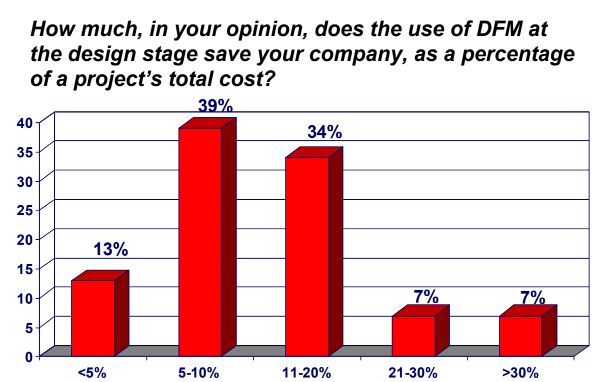


Figure 6: Savings from using DFM

In the same survey, the value of estimation software technology was widely acknowledged even among those engineers without this capability today. Few disputed its general contribution to effective DFM analysis.

Process Based Parametric Model

To develop a parametric cost modeling solution for DFM, specific process parameters that drive cost had to be identified (for a complete list see Table 5 and Table 6 in the appendix). All of these processes were embodied into a customizable software framework, which engineers integrate as part of the design process (see Figure 7).

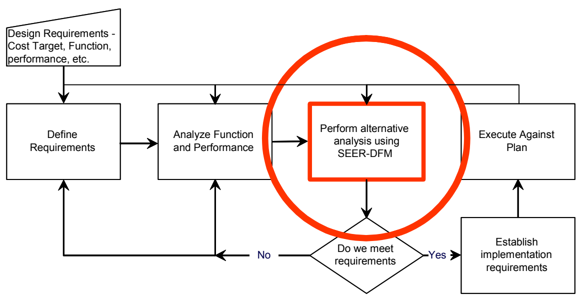


Figure 7: Cost modeling integrated with the design process

Integrating a process-based parametric cost model into the design process allows engineers to effectively include cost as an optimization variable. This is key to fully optimizing the manufacturing and assembly processes during the design phase.

Process-based parametric modeling is successful because it provides greater detail and granularity than other parametric hardware models, which are based mostly on product characteristics such as weight. This increased level of detail offers engineers the advantage for rapid, detailed DFM trade studies. Such insight into cost helps engineers make better decisions with more confidence, they understand risks, reduce failure, and recognize opportunities to improve processes. It also helps managers make critical decisions about trade-offs and alternatives that align innovative product design with optimum manufacturing.

SEER DFM Examples

The following section demonstrates how engineers use the cost model to perform DFM analysis for both metallic and composite design alternatives.

DFM Analysis of Transmission Servo Piston

In this example, a bill of materials and a rough sketch of a transmission servo piston were provided for analysis (see Figure 8) [21]. The objectives were to:

- Ascertain the cost of manufacturing the item as described, and;
- Evaluate tradeoffs, using DFM principles to reduce manufacturing and assembly costs

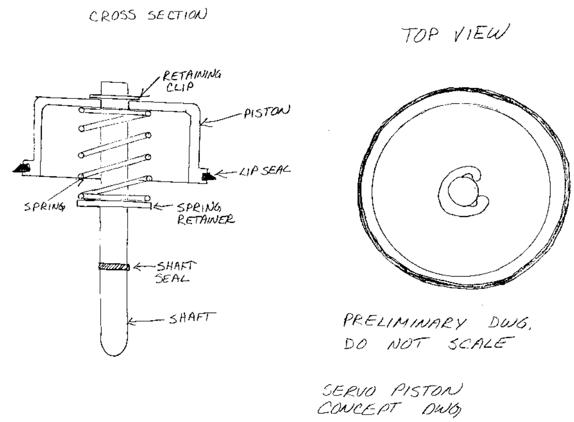


Figure 8: Rough sketch of transmission servo piston

To analyze a manufacturing project, processes are modeled using work elements. The manufacturing of various basic parts might be modeled using a combination of work element types such as: machining, fabrication, or mold/cast/forge. The integration of the resulting parts into an assembly might then be modeled as a mechanical or an electrical assembly operation. Thus, the first stage in the modeling process is to describe the major components of the transmission servo piston, and the assembly of those components. This is achieved through creating a work breakdown structure or 'bill of materials' (see Figure 9).

The next step is to take each line item in the bill of materials and describe it with respect to the people, product, and processes required to manufacture and/or assemble it (see Figure 10).

To reduce the time required for data entry, the model is preloaded with knowledge bases. Knowledge bases are pre-defined repositories of data and information. Users can either select from existing knowledge bases or create their own for later reuse. Knowledge bases are invaluable for creating reusable, systematic cost analysis across design teams within an organization.

Once the parameter inputs for each process type are complete, outputs are analyzed through reports and charts. For the transmission servo piston, the cost allocation chart illustrates that most of the cost is related to labor (see Figure 11). This chart illustrates that the area to focus DFM efforts is the labor cost. The detailed analysis report shows that most of the labor is related to machining the servo shaft (see Figure 12).

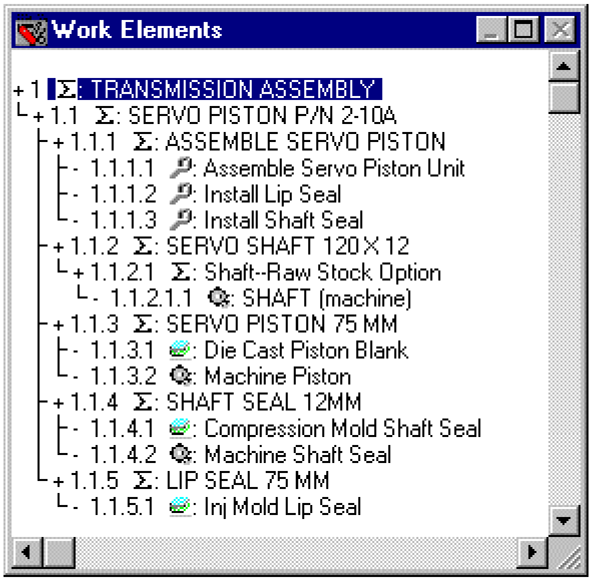


Figure 9: Transmission servo piston 'bill of materials'

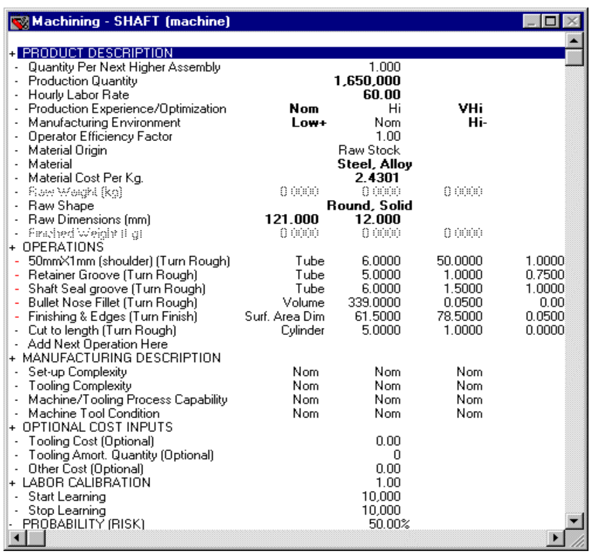


Figure 10: Work element specific people, process, and product attributes

The cost model has an 'alert' functionality that makes two pertinent recommendations:

1. Consider machining the shaft from a casting, rather than machining from raw stock, and;
2. Attempt to reduce parts count by consolidating them.

Engineers can quickly assess both of these options: option 1 by altering the process choices, and option 2 by including the spring retainer as part of the casting, rather than a separate part. This will make the casting more complex, but will reduce final assembly cost.

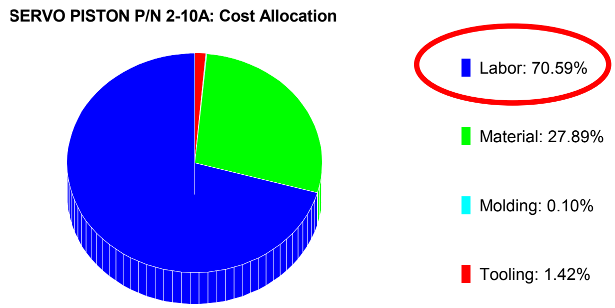


Figure 11: Cost allocation chart illustrates labor is area to focus DFM analysis

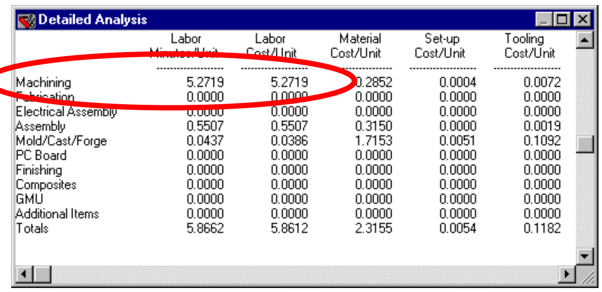


Figure 12: Detailed report illustrates machine labor is area to focus DFM analysis

With just a few adjustments to the work elements and process parameters, engineers analyzed the cost impact of the proposed design changes in real time (see Table 2 and Table 3).

Table 2: Real time cost analysis of options

	Option 1 - Machined Shaft	Option 2 - Die Cast Shaft	Option 3 - Die Cast Shaft / Retainer
Material Cost/Unit	$2.3155	$2.3610	$2.3510
Total Labor Cost/Unit	$4.2944	$3.6463	$3.6316
Tooling Cost/Unit	$0.1161	$0.2843	$0.2925
Total Cost/Unit	**$6.7260**	**$6.2916**	**$6.2751**

Table 3: Impact on bottom Line

Option	Unit Cost	Total Cost (1,650,000 Units)	Savings
1	**$6.7260**	$11,097,900	--
2	**$6.2916**	$10,381,140	($716,760)
3	**$6.2751**	$10,353,915	($743,985)

The transmission servo piston example illustrates how engineers quickly assess the cost of alternative designs by comparing different machining processes and/or assembly techniques. Through this same process companies have significantly reduced their manufacturing costs for both metallic and composite processes [22, 23]. In the next example, a theoretical 'what if' comparison of composites and more traditional manufacturing processes of an SUV Fender is presented.

Composites and Metallic DFM Analysis of an SUV Fender

As before, the manufacturing processes of the SUV Fender are modeled by developing a work breakdown structure (see Figure 13). The model was based on a production run of 180,000, using manufacturing labor rates at US$100 and assembly labor rates at US$75.

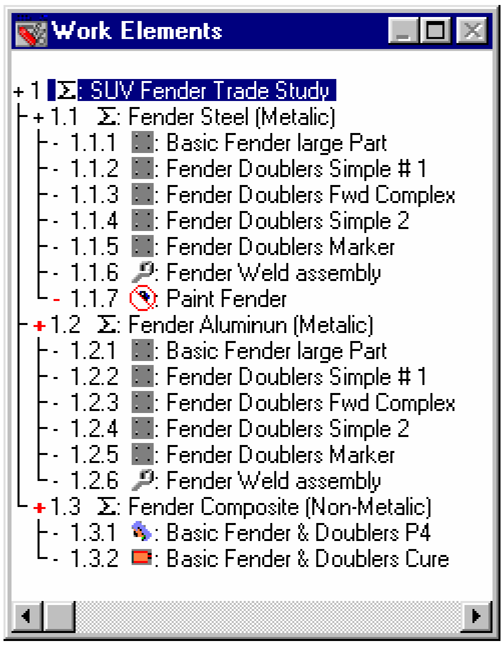


Figure 13: SUV Fender trade study options

The engineer compares three options:

1. Fabrication of a Steel Fender;
2. Fabrication of an Aluminum Fender, and;
3. Composite manufacture using a P4 process and RTM curing process.

Options 1 and 2 use more traditional dedicated tools and dies for the part fabrication, with a welded assembly. Option 3 uses the P4 composite process (Programmable Powdered Preform Process). The P4 or Owens Corning (OC) process was originally developed for use within the automotive industry. General Motors (GM) currently use the P4 process to cost effectively manufacture the Silverado truck cargo boxes (see Figure 14 and Figure 15), which can be manufactured in as little as four minutes [24].

P4 works by pulling multiple tows of carbon fiber through a cutter head and then spraying the cut fibers (using a fiber alignment device) onto perforated screen tools, through which a vacuum is drawn to set the fibers in place. A powdered binder is sprayed onto the preform along with the chopped fibers (see 1 in Figure 16).

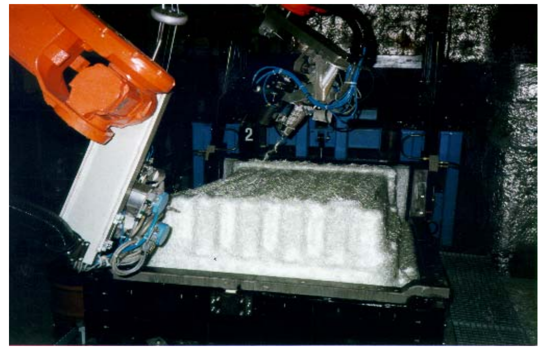


Figure 14: Application of P4 process [25]

Figure 15: Finished composite truck bed [25].

A robot is programmed to move the chopper head around the screen tool to achieve the proper preform lay-up orientation, thickness, and uniform coverage. After the preform is sprayed up, the chopper head moves out of the way and a consolidation screen is lowered onto the preform screen tool. Hot air is then blown through the consolidation tools to melt the powdered binder on the preform (see 2 in Figure 16).

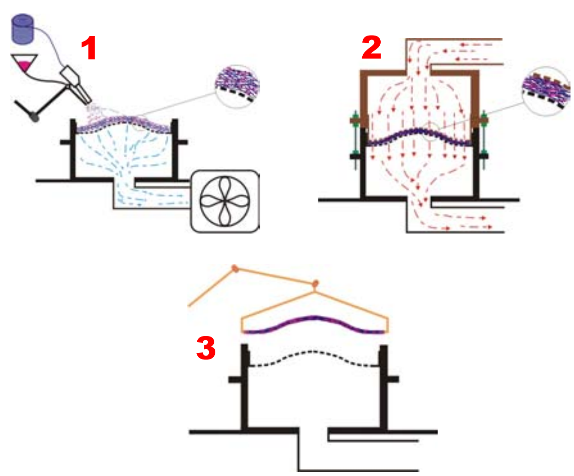


Figure 16: P4 process

Figure 17 and Figure 18 show the specific parameters used to model and cure the P4 process. .

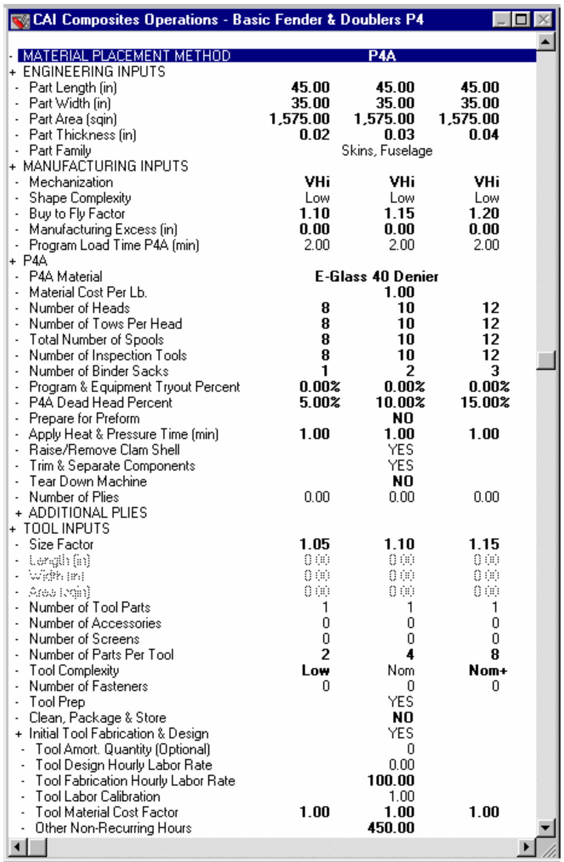


Figure 17: P4 input parameters

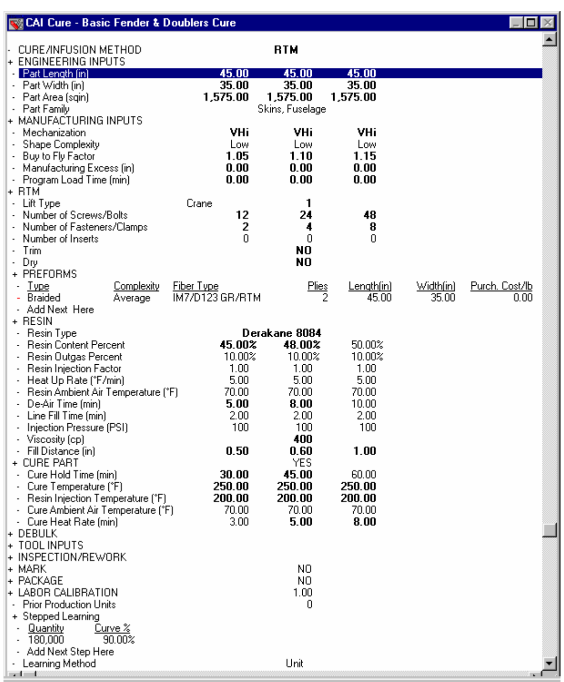


Figure 18: RTM input parameters

Figure 19 provides a 'trade-off' analysis of the three options. The estimate column in Figure 19 represents the manufacturing time and cost for P4 (option 3). The aluminum (option 2) and steel (option 1) are referenced to the right of the P4 estimate. Differences in relation to the P4 estimate are highlighted in the 'Diff.' columns. For example, the P4 total minutes and cost per unit are reduced by 50% and 36% respectively. The P4 material costs are reduced by 45% compared to Aluminum, and 2% compared to Steel

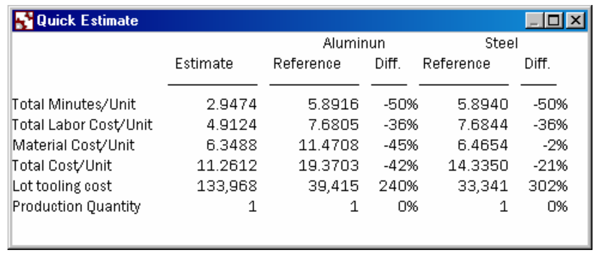


Figure 19: Trade-off analysis

The total cost per unit is reduced by 42% compared to Aluminum and 21% compared to Steel. This is despite the tooling cost increase for P4, which for all options, were amortized over the entire production quantity. In addition, whilst not shown in Figure 19, the P4 SUV Fender provides a lighter solution than either the steel or aluminum options. The effect on bottom line is illustrated in Table 4

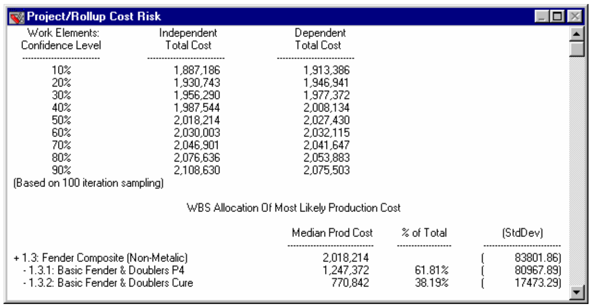
Table 4: Impact on bottom Line

Option	Unit Cost	Total Cost (180,000 Units)	Savings
1	**$14.335**	$2,580,300	--
2	**$19.3703**	$3,486,654	$906,354
3	**$11.2612**	$2,027,016	($553,284)

Along side creating these detailed trade-study analysis, engineers can use the cost model to assess the probability that the estimate for any chosen solution will come true.

Estimate Probability

Every estimate is uncertain (see Cost Estimating Challenges above) and therefore, probabilistic. One key aspect of a design for manufacture cost-model is the ability to predict outcomes. There is no such thing as a single number being an absolute estimate of the future; but rather, there is a range of probable outcomes. Using least, likely, most inputs, provides a range of possibility that is a natural result of uncertainty. Even without precise information, design engineers can use their judgment or best guess. The range inputs are then analyzed to predict a likely range of outcomes. Figure 20 reports the uncertainty associated with the P4 option.



Project/Rollup Cost Risk

Work Elements: Confidence Level	Independent Total Cost	Dependent Total Cost
10%	1,887,186	1,913,386
20%	1,930,743	1,946,941
30%	1,956,290	1,977,372
40%	1,987,544	2,008,134
50%	2,018,214	2,027,430
60%	2,030,003	2,032,115
70%	2,046,901	2,041,647
80%	2,076,636	2,053,883
90%	2,108,630	2,075,503

(Based on 100 iteration sampling)

WBS Allocation Of Most Likely Production Cost

	Median Prod Cost	% of Total	(StdDev)
+ 1.3: Fender Composite (Non-Metalic)	2,018,214		(83801.86)
- 1.3.1: Basic Fender & Doublers P4	1,247,372	61.81%	(80967.89)
- 1.3.2: Basic Fender & Doublers Cure	770,842	38.19%	(17473.29)

Figure 20: Project cost risk analysis

Engineers use the work element confidence level to assess the likelihood of the estimate being true (based on the input ranges). For example, the 10% confidence level represents the probability of the actual outcome lying below the estimate value (indicated in the right hand columns). Thus, reports to management include a range of possibilities, (more akin to reality), from which more informed decisions are made.

Summary and Conclusions

This paper introduces the underlying methodology of a process-based parametric cost model, SEER-DFM, for use in the design phase of product development. Through examples, readers learn how the model is integrated with the design process to effectively and substantially reduce manufacturing costs for both metallic and composite based processes. The cost model provides a framework for considering cost as a design variable, which facilitates effective Design For Manufacture (DFM). SEER-DFM is a unique process-based parametric model that engineers use, in real-time, to substantially reduce the cost of both metallic and composite manufacturing options.

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Appendix

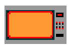
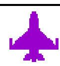
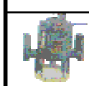
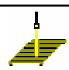
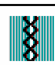
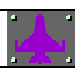
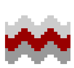
Table 5: Manufacturing Processes Covered by SEER-DFM

Work Element Type	Processes	
Rollup	Covers all activities included in subordinate work elements	
Machining	Radial Mill Rough/Finish End Mill Rough/Finish Chemical Mill Shaping Rough/Finish Turning Rough/Finish Boring Rough/Finish Cylindrical Grinding Centerless Grinding Surface Grinding Rough/Finish High Speed Machining Rough/Finish Screw Machine EDM (Electric Discharge Machine) Drilling: Hand, Spade, Twist, Subland, Countersink	Reaming Tapping Hacksaw Bandsaw Radial Saw Broaching Automated Production Equipment Additional Items Gear Hobbing Deburr Core
Fabrication	Conventional Machines: Nibble, Notch, Shear, Punch, Brake Form CNC Turret Press CNC Laser Beam Cutting: CO2, Nd, Nd-Yag CNC Plasma Arc Cutting CNC Gas Flame Cutting Plate Rolling	Tube Bending Dedicated Tools & Dies Progressive Dies Spin Forming Routing: Profile, Hand, Radial
Electrical Assembly	Cable Fabrication Harness Fabrication	Part Preparation Direct
Assembly	Assembly: Welding: Gas Torch, Arc, Gas Metal Arc, MIG, TIG, Electron Beam, Spot Brazing	Rivet/Stake: standard, w/gasket, lubricated Bonding: Single part, multi-part, thermal
Mold/Cast/Forge/ Powdered Metals	Injection Molding Rotational Molding Thermoforming Sand Casting Die Casting	Investment Casting Forging Powdered Metals Additional Items
PC Board	Blank Board Fabrication PCB Assembly	PCB Test Additional Items

Finish and Heat Treat	Vacuum Metalizing Chromate/Phosphate Air Gun Spraying Electrostatic Coating – Fluid Electrostatic Coating – Solid Thermal Spraying Dip Coating	Brush Painting E-Coat Electroplating Buff/Polish Additional Items Heat Treatment
Composites Basic*	Lay-Up Filament Winding	Pultrusion Composite Spray
Additional Items	User Specified Operation	
Purchased Part	Description Quantity	Installation Difficulty Unit Cost

Table 6: Composite Processes Covered by the CAI Plug-in

Work Element Type	Processes	
Composites – Hand Layup	Roll/Creel Prep Roll/Creel Change Cut Layup	Label Kitting Ply Placement
Composites – Braiding	Twister Wind Set-down	Braid Down Time
Composites – Tow Placement	Roll/Creel Prep Roll/Creel Change Cut Ply Placement Debulk Hot Debulk	Additional Plies Tail Compact Head Rotation Dead Head Time Fuzz Removal Drill, Trim & Remove Part
Composites – P4A	Load Tool Set-up Load Tools Clean P4A Tools Release Agent Clean Heads Locate Heads Modify Heads Thread Tows Load Spools Load Inspection Bins Load Binder	Remove Trial Material Spray Composite Plies Program And Equipment Tryout Clean Head, Remove Fuzz Prep Preform Apply Heat And Pressure Raise/Remove Clamshell Tool Tear Down Machine Remove Preform Trim And Separate Components
Composites – 3D Weave	Set Down Time Set Up Time	Start Up Time Weave Time
Composites – Filament Winding	Roll/Creel Prep Roll/Creel Change Debulk Hot Debulk Additional Plies	Dead Head Time Fuzz Removal Drill, Trim & Remove Part Lay Down Material Cut
Cure - Autoclave	Bag Fab. Cure Prep Set-up Cure Prep Ops. Cure Prep Pleating	Cure Process Debag Remove Part From Tool Deflash
Cure - RTM	Prepare Part For Transfer Position Part To Loading Table Load Mold To Press Transfer Part To Resin Transfer Area Load Preform Locate Preform Install Release Film Pre-Heat Tool Tool Clamp Time	Install Insert Time Trim Time Dry Time Load Resin Cure Part Drain & Flush Open Mold Unload Cure Parts Resin Injection (Witness)
Cure - VARTM	Prepare Part For Transfer Position Part To Loading Table Load Mold To Press	Dry Time Load Resin De-Gas Time

Work Element Type		Processes	
		Transfer Part To Resin Transfer Area Load Preform Locate Preform Install Release Film Pre-Heat Tool Tool Clamp Time Install Insert Time Trim Time	Cure Part Drain & Flush Open Mold Unload Cure Parts Resin Injection (Witness) Debulk Infusion Plies Vacuum Bag
	Cure –E-Beam Fabrication	Shield Apply Adhesive Unshield Obtain Crane To Position Part Load onto E-Beam Station	E-Beam Cure Obtain Crane To Retrieve Part Remove Part From E-Beam Station Remove EBF Part From Tool
	Fitup	Primary Set-up Dimensional Check Load Parts Load - Locate Load - Clamp Unload - Clamp	Unload - Locate Unload Parts Deburr/Clean Drill Holes Hard Shims Clean, Seal & Secondary Bond Unload Assembly
	Drill	Position Tool/Robot Primary Set-up	Drill
	Fasten	Position Tool/Robot Primary Set-up Check Holes Check Torque Apply Sealant	Dry Installs Wet Installs Nutplate Installs Gang Channel Installs Finishes
	Trim	Layout Parts Load Tools & Index Part Equipment Set-up Load Program	Tool Changes Trim Features Unload Parts Deburr
	Paste Bond	Surface Prep Mask Abrade Remove Peel Adhesive Apply Pre-Coat	Spread To Line Apply Beading Cure Cure Tear Down Unmask
	E-Beam Assembly	Move Part To E-Beam Area Cure	Remove Part From E-Beam Area Unload Assembly
	3D Reinforcement	Machine Stitching Install Z-Pins	Clean Z-Pins Down Time
	Sheet Metal	Pre-Form Form	After-Form Finish
	SPF/DB	Clean Diffusion Bond (DB) Leak Check Lubricant Coat Load Sheet/Part/Pack Super Plastic Forming (SPF)	Die Cool Down Unload Sheet/Part/Pack Grit Blast Fitting Mask Test Coupons Final Clean