DESIGN TO COST/DESIGN FOR MANUFACTURABILITY

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Abstract

For years Aerospace designers have tended to design for optimum performance. This business model was rewarded through cost plus contracts with cost treated as an output variable. Current cost conscious business models have emerged and now treat cost as an input variable, typically setting aggressive cost targets.
This now requires a Design to Cost (DTC) methodology, which by practical definition means choosing the set of design attributes of lowest cost/complexity that meets performance, weight, reliability and other customer requirements. In other words, cost is now an input variable, not a consequence calculated after a performance driven Bill of Materials (BOM) has been established. System Architectural Trade Study (SATS) methodologies now need to be developed which identify the "sweet spot" or optimum trade space between cost, performance, weight, reliability, etc.

Once this trade space has been defined the major contributor to cost becomes producibility or Designing for Manufacturability (DFM). Producibility is simply a function of design complexity –vs- manufacturing capability. Honeywell has developed producibility tools which have defined manufacturing capability in terms of design attribute limits, i.e. minimum casting thicknesses, shape aspect ratios. When design complexities exceed manufacturing capabilities low fabrication yields increase costs exponentially necessitating less complex redesigns and/or the need to develop more capable "game changer" manufacturing technologies to enhance capability.

This paper will discuss the producibility tools used at Honeywell. They include in-house Complexity, Design for Manufacturability Scorecards, yield models, In-house modified Manufacturing Readiness Level Reviews (MRL) along with recently acquired commercial off the shelf (COTS) should cost and DFM producibility software models. These tools were created to quantify producibility and prioritize those design attributes which impede producibility and increase costs.

Discussion

At the center of this performance versus cost optimization lies design complexity. Hence managing design complexity within the limits of manufacturing capabilities is the key to meeting both performance objectives and low manufacturing cost requirements. A DTC and DFM methodology and culture, implemented early in IPDS phase 1-

3, is required at Honeywell to addresses the effect of design complexity on manufacturability, producibility and resultant cost. This culture and methodology will also identify those manufacturing technologies needed in future roadmaps.

The question most often asked is "How do we make this complex design cheaper?" and the answer, illustrated in figure 1, has usually been globalization, Value Engineering (VE), supplier productivity or new technologies. The question we need to start asking is "Can we simplify the design to make it easier to produce or can we enhance manufacturing capability to make it easier to produce?" Current design methodologies typically estimate a product cost based on similar to component costs and compare the aggregate cost to a cost target perceived to be needed by product marketing to compete in the market place.

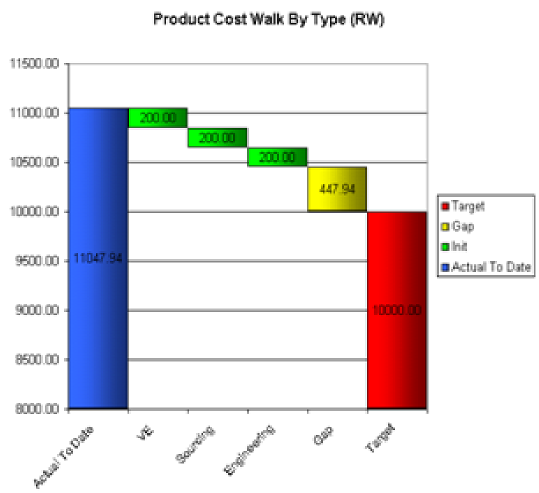

Fig. 1 Traditional product cost walk usually resulting in undefined gap required to meet target cost

This typically results in a flurry of cost reduction activity during IPDS phases 4-6 in the form of value engineering, supplier productivity cost reductions, and transitions to EMR, often resulting in large gaps between actual costs and target costs with no known solution.

It is estimated that 80% of recurring costs occur in the first 20% of design as illustrated in figure 2. Only minor changes to cost can occur without significant disruption once designs are set in IPDS phases 4-6. Hence design complexity needs to be addressed early in IPDS phases 1-3 when designs are being created and can be influenced and changed. Current design strategies typically start with a similar-to configuration, adding and changing design attributes to meet the new customer requirements. The key to cost management is identifying those design attributes which drive cost, those which challenge the manufacturing processes and generate complexity in both the similar to and proposed changes. The challenge stems from the fact that in most cases it is this design complexity which addresses the new customer mandated performance requirements. Industry should cost models are available but are ineffective at predicting the effect of the complexity factor. These industry DFM tools do a good job at calculating the direct material and direct labor required for 100% yield. But numerous other complexity related factors as shown in figure 3 have significant effects on costs. These complexity related factors can significantly increase costs sometimes by factors of 2-3X.

Yields of 50% will double costs. Intangible costs, those which are typically very difficult and inconvenient to quantify, play significant roles. Examples include, higher inventory levels, required learning curves, rework and costs associated with quality and technical troubleshooting of manufacturing quality issues.

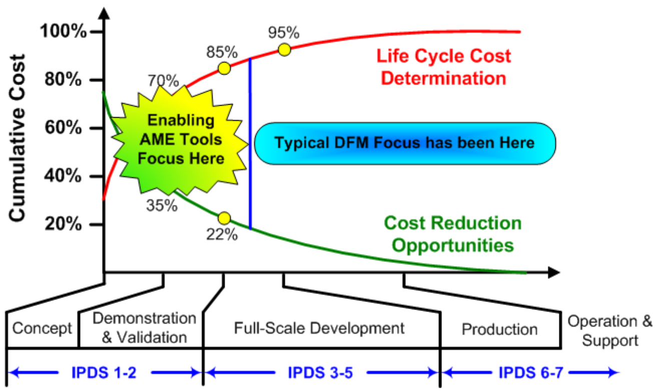

Fig. 2 80% of Cost is determined during IPDS 1-2.

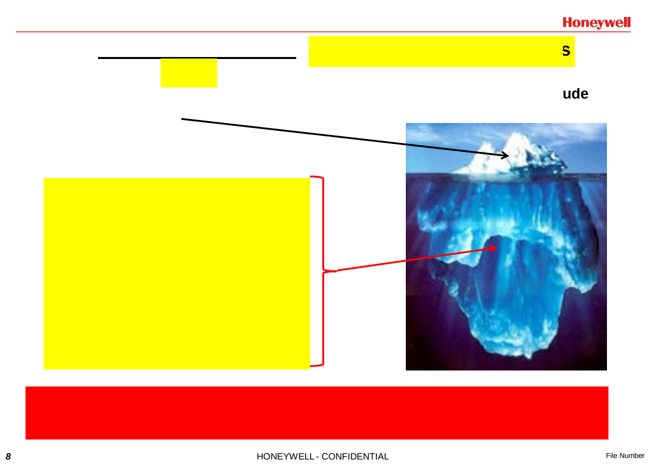

Fig. 3 Large portion of cost occurs due to “Hidden Factory” complexity

Figure 4 illustrates the exponential effect of complexity on relative cost. For those designs whose complexity are on the low side, cost is fairly linear and can be predicted with traditional industry available should cost models, i.e. Boothroyd Dewhurst, MTI, SEERS, Viper, Apriori. But the cost of those designs that include higher levels of complexity can be seen to increase exponentially. Is this complexity required? Sometimes yes, but often no. Since complexity is based on manufacturing capability, the design community has three choices when faced with a complex design, 1) simplify the design to reduce complexity (2) accept the risk assuming high complexity is producing large gains in performance or other life cycle cost (LCC) variables, and/or (3) elevate the manufacturing capability used to make the complex design. Option 1 requires concurrent engineering early in IPDS phase 1-3 development stages between design engineers who are knowledgeable on the effects of complexity on performance and other LCC variables and manufacturing engineers who have expertise relative to manufacturing process limitations and the effect of complexity on producibility. The goal is to identify lower complexity cost driver design attributes which have low sensitivities to performance changes. Option 2 involves identifying a tradeoff between cost and performance, or other LCC variable and recognizing and accepting that the performance or other LCC variable draws significant favor and is worth the risk, extra cost and longer cycle and scheduling times. Taking advantage of option 3 is the best of both cost and performance worlds, but cost effective disruptive manufacturing processes or even current manufacturing processes which have been significantly improved relative to capability are typically longer term solutions. Identifying and developing these improved and/or disruptive manufacturing technologies of tomorrow play an integral part in 5+ year roadmaps.

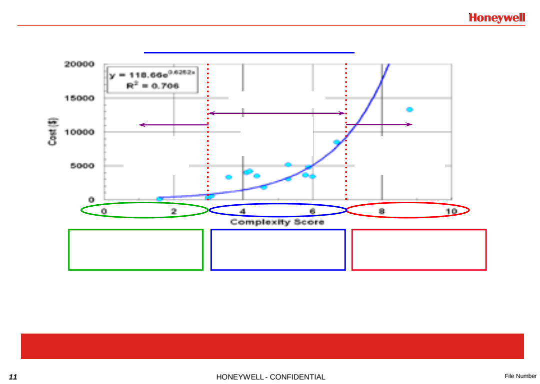

Fig. 4 Exponential effect of Complexity on Cost

Levels of complexity depend on levels of manufacturing capability. Identifying the manufacturing capability requires a large set of manufacturing knowledge, experience and expertise. To facilitate the collection of this manufacturing knowledge base and its effect on design limitations and complexity, a suite of tools are being developed at Honeywell. These tools are designed to 1) identify design attributes which drive complexity and 2) identify simpler, lower cost alternatives. These tools, Complexity, DFX Scorecards and Yield Models are designed around today’s processing capabilities. Knowledge of manufacturing limitations is required to identify when a design attribute is difficult to produce, hence being labeled complex and resulting in decreased yields and increased fabrication costs.

Figure 5 is a snapshot of a complexity model for an investment casting illustrating examples of the types of design attributes deemed significant relative to manufacturability. Per each design attribute a spectrum of complexity levels are offered and ranked 1-10. Weight factors for each design attribute are multiplied by the 1-10 ranking of levels of complexity, totaled and normalized to obtain an overall complexity ranking of 1-10, with 10 being complex. Complexity rankings of 5 or less are typically preferred. Higher rankings contribute exponentially to cost and are difficult to manufacture and produce.

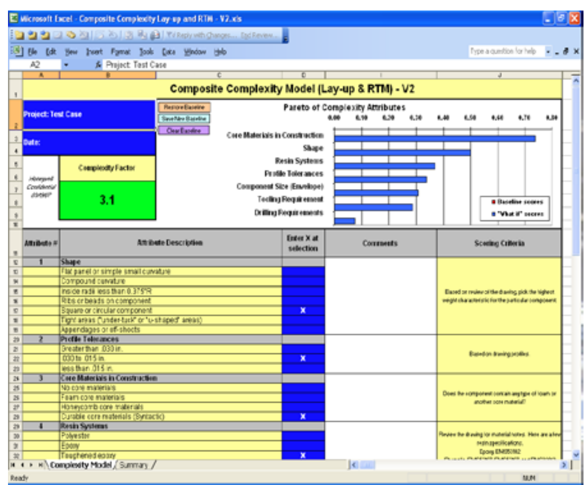

Figure 5 Complexity Model format

Figure 6 illustrates an example of the use of a complexity model to identify and replace complex design attributes which increase cost. A front frame was designed to be cast out of Titanium with a complex shape, a number of long and thin struts and a number of thick to thin transitions, all which increase complexity and cost. The complexity model for large investment cast casings assigned this part a complexity of 7.1 (on a scale from 1- 10 complex). A unique feature of the complexity model is its ability to prioritize the contributions of each design attribute to complexity. The design of a new front frame made several changes which addressed many of these design attributes which influenced complexity. Alloy selection, showing the biggest impact, was changed from Titanium to Aluminum. Changing the material selection to Aluminum, although not captured in the casting complexity model, also allowed other manufacturing processes such as “Hog out” machining to be considered in early trade studies. Other attributes contributing to complexity and increased cost were changed such as increasing minimum thicknesses and decreasing length to thickness ratios. Notice how some design attributes, shape and thick/thin transitions cannot be changed due to their significant

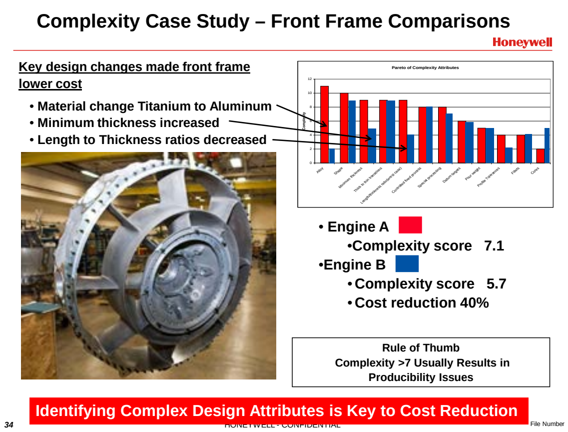

Fig. 6 Results of Cast large frame Complexity model comparing new front frame –vs- old

effect on performance and function. Reducing the complexity of those design attributes which effect minimum compromise to performance and function reduce the overall complexity of the new front frame to 5.7 and reduced the part cost 40%.

The DFX scorecard is another DTC tool being used to assess design attribute complexity relative to manufacturing capability. DFX scorecards are typically more quantitative relative to complexity models and typically used later in the design cycle when a component has been selected and hard configuration lines are being created. Figure 7 illustrates the format and quantification of the scorecard. Figure 8 illustrates the types of design attributes identified and the various levels of complexity within each attribute. The DFX scorecard identifies ease of manufacturability on a scale from 1 to 100, the higher the number the easier to manufacture. It also identifies those design attributes which effect complexity and defines those attribute levels which are within process capability (green), those that challenge (yellow) and those typically outside process capability (red). Those design attributes in red need to be avoided and redesigned with more capable yellow or preferably green levels. Red levels indicate low yields and increased costs.

The yield model is a third tool being used to identify how design attributes effect first pass yield. This model predicts yields probabilistically through the principal that Yield=exp(-OFD*DPMO/10^6). Industry generated Defects per Million Opportunities DPMO) for standard manufacturing processes, such as soldered joints for CCA's (Circuit Card Assemblies) are used in conjunction with opportunities for defects (OFD), i.e. number of solder joints, to generate a probabilistic first pass yield. Effects of inspection processes on final pass yield can also be predicted. Figure 9 illustrates the excel format used to predict first pass yield. In addition to incorporating industry based DPMO data and design/process OFD multipliers, learning curve parameters are inputted which allows the calculated output of early prototype and steady state

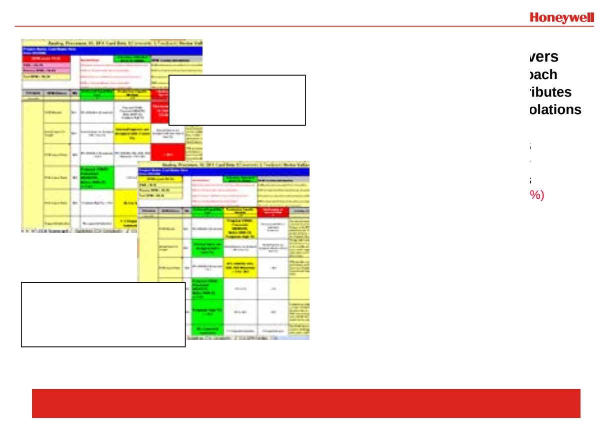

Fig. 7 Overview of DFM scorecard

Category	DFM Drivers	Preferred Capability Low	Production Capable Medium	Challenging or Special High
Core	Alloy	Aluminum, Steel, Nickel	Titanium	Ceramic, plastic, refractory metals
	Fin to tube sheet braze joint contact	Tube to fin contact resulting from fin height .001 in. or higher than spacer bar	Tube to fin contact resulting from fin height .0005 in. or higher than spacer bar	Tube to fin contact resulting from fin height < .0005 in. higher than spacer bar
	Fin sheet metal thickness	.003 to .006 in.	.002 in. to .003 in. or .006 in. to .008 in.	< .002 in., > .008 in.
	Tube sheet metal thickness	Aluminum .012 in. to .020 in. Titanium .008 in. to .020 in. Nickel/Steel .005 in. to .020 in.	Aluminum .010 in. to <.012 in. Titanium .006 in. to <.008 in. Nickel/Steel .003 in. to <.005 in.	Aluminum < .010 in. Titanium < .006 in. Nickel/Steel < .003 in.
	Fin Density (FPI) Fins per Inch	Alum. < 38 FPI SST/Ni201 < 28 FPI Ti < 26 FPI IN 625/718 < 20 FPI	Al, 38-40 FPI SST/Ni201, 28-30 FPI Ti, 24-26 FPI IN 625/718, 20- 22 FPI	Al > 40 FPI SST/Ni201 > 30 FPI Ti > 26 FPI IN 625/718 > 22 FPI
	Fin Height	.050 in. to .500 in.	.030 to .050 in. or .500 to .510 in.	< .030 in. or > .510 in.
	Fin Height profile tolerance	< +/- .0005 in.	+/- .0005 to +/- .001 in.	> +/- .001 in.
	Core aspect ratio (stack height/smallest Lor W)	< 5:1	5:1 to 20:1	> 20:1
	Equivalent thickness of braze coating/foil on sheet material	.0005 in. to .007 in.	> .007 in. or < .009 in	.009 in. or greater, or < .0005 in.
	Fin flow path	Plane rectangular (Straight)	Offset fins (combination of linears) or Wavy fins (Non linear)	Nonplanar 3 Dimensional
	Fin cross sectional shape	Fin draft equal to or > 90 deg. (positive)	Fin draft < 90 deg. (negative)	Negative draft with non linear fin side wall shape
	Geometry	Fin heights, tube sheet metal thickness and bar width constant from layer to layer in plane cross flow configuration	Varying tube sheet thicknesses, hot and cold Fin heights, with a combination of plane, rectangular and off set fin geometry in a cross counterflow configuration.	Various fin heights wihin a passage, High pressure side buffer gap.

Fig. 8 Examples of major design attributes

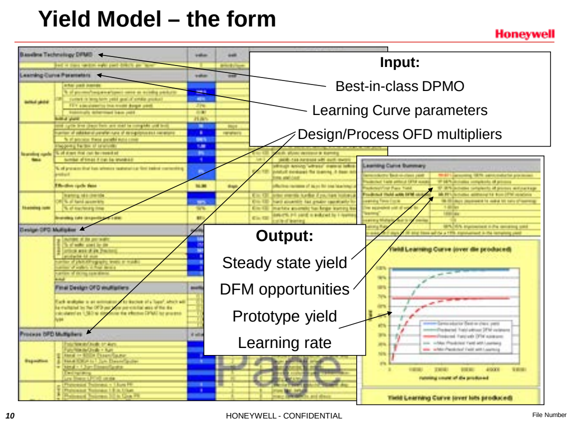

Fig. 9 Example of Yield model format

yields along with a calculated learning rate profile and a prioritized listing of DFM opportunities.

The Manufacturing Readiness Level, MRL, is a tool which compiles a list of questions in 34 subcategories and 5 main categories that highlight those manufacturing issues which need to be addressed throughout the entire IPDS process (fig. 10). This tool is a significantly shortened version of the Department of Energy (DOE) MRL created several years ago. This tool addresses not only design producibility, but materials and manufacturing planning, process capability and control, factory capital and supply chain issues. Pre IPDS 1 concept questions are compiled which will reinforce the consideration of how design attributes and concepts affect cost and producibility.

Of course a quantified measure of DFM and producibility needs to culminate in its effect on cost. Hence Honeywell has taken a commercial off the shelf should cost CAD centric model and is significantly modifying the data base and rules logic to address the many high tech complex products made in aerospace.

Integrating DFM, Producibility, and should cost information into CAD is essential since Model based enterprise (MBE) technologies and cultures are starting to evolve.

Moving forward begs two development needs, quantifying DFM and producibility in terms of dollars and integrating design attribute capability thresholds electronically into the CAD process. Several commercial off the shelf (COTS) should cost models were evaluated. These models tend to address the simple side of complexity, not the complex side, but do offer a template and a starting data base of virtual production labor and burden rates and proposed manufacturing operations. Numerous modifications and additions are required to achieve the aerospace levels of complexity, recently developed manufacturing capabilities and

Thread			Select MRL Sub-Thread to show =>	MRL
Design Producibility	→	1.1	Design Maturity	
		1.2	Key Characteristics	
		1.3	Custom / Critical Components	
	---	1.4	Design for Manufacturability and Assembly	
		1.5	Design for Testability	
		1.6	Design for Globalization	
		1.7	Design for Obsolescence	
		1.8	Design for Environment	
Material & Manufacturing Planning		2.1	Material Maturity	
	---	2.2	Cost Modeling & Analysis	
		2.3	Material Availability	
		2.4	Demand Planning	
	---	2.5	Materials Planning	
	---	2.6	Manufacturing Planning	
		2.7	Special Handling	
Process Capability & Control		3.1	Process Maturity	
		3.2	Special Processes	
		3.3	Assembly Methods	
		3.4	Routing	
		3.5	Test Methods	
	---	3.6	Yields and Rates	
		3.7	Quality Control	
Factory & Capital	---	4.1	Product and Process Modeling & Simulation	
	---	4.2	Manufacturing & Inspection Equipment	
	---	4.3	Special Tooling	
		4.4	Special Test & Inspection Equipment (STE/SIE)	
	---	4.5	Critical Skills	
	---	4.6	Resource Allocation	
		4.7	Quality Assurance Systems	
Supply Chain	---	5.1	Industrial Base Capability	
		5.2	Supply Chain Design	
		5.3	Supply Chain Management	
		5.4	Supplier Quality	
		5.5	Subcontracts	

Fig. 10 Sub-threads of MRL

levels of inspection and surface finish. The elite should cost and DFM models allow the input of a CAD design, offer a proposed series of manufacturing operations and identify and prioritize those design attributes which drive costs or challenge manufacturing operation capabilities.

In summary, increasing design complexity increases cost. This complexity must be addressed early in IPDS design phases 1-3 in the form of system architectural trades studies which incorporate trade sensitivities of functional requirements and cost. As illustrated in figure 11, once high level trade studies are utilized to define design space and sensitivities of major design parameters, use of DFM tools can be employed to further define the lower cost bound of the trade space. Honeywell tools are being developed to quantify relative complexity levels and identify and prioritize those design attributes which challenge manufacturing capability, hence most significant to complexity and cost. Complexity

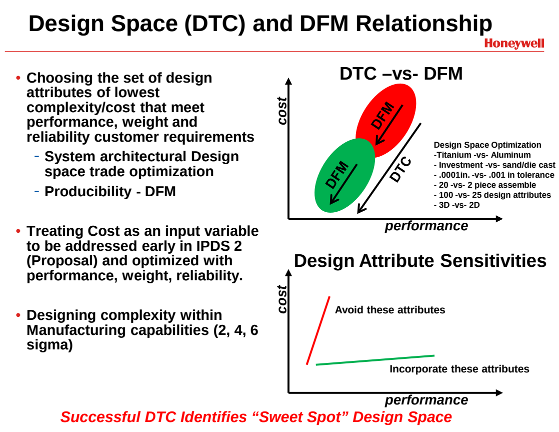

Fig. 11 Relationship of DTC design space to DFM

models, DFM scorecards, Yield Models and MRL's are being developed for various part family/process categories. Current DFM tools available to industry do well with assembly and lower complexity applications but do not incorporate the significant impact design complexity has on part fabrication cost and LCC. Identifying design attributes which drive complexity and cost early in IPDS is essential to successful implementation of an effective DTC culture.