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Systems Engineering Methodology for Linking Requirements to Design Complexity and Manufacturing Trade Space Constraints

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Abstract

Aerospace system requirements over the last decade have continued to evolve toward higher levels of performance at lower cost, incurring a major challenge for system developers; how to balance conflicting performance and cost requirements and understand their impact on performance margins as well as the manufacturability characteristics of the design. This paper presents results of a case study performed on an aerospace air turbine starter system in which a top-level systems engineering methodology has been developed to help understand the impact that customer requirements and design decisions have on manufacturing trade space constraints. One of the major findings of this case study is that incremental increases in performance requirements can drive step change increases in manufacturing cost due to discontinuities in the material and process trade space, i.e. using titanium versus aluminum to meet temperature requirements or having to use investment versus sand castings to meet minimum thickness and tolerance requirements. Internally developed quantitative producibility analysis tools are also used to characterize the complexity and Design for Manufacturability (DFM) characteristics of the "similar to" baseline design to identify producibility improvement opportunities for the new design as part of the proposed systems engineering process to mitigate design reuse risks.

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Keywords: Complexity; System Design; Systems Engineering; Trade Space Exploration; Design for Manufacturability; Producibility;

1. Introduction

The development of affordable systems has become a critical issue impacting the aerospace and defense industry as the cost to develop new generations of systems continues to spiral out of control. These same issues are likely to occur on future programs unless something fundamentally different is done in the design and development of these complex systems. The severity of the affordability problem in the defense industry is highlighted by a recent Government Accountability Office (GAO) study which found current defense acquisition programs are experiencing an average 42% growth in research and development costs from original estimates, have an average delay of 22 months in delivering initial capabilities, and 42% of the programs also report a 25% or higher increase in unit acquisition cost [1]. Commercial aerospace system development programs are also experiencing these same affordability problems. For example, the Airbus A380, launched in 2000, and the Airbus A400M military transport plane, launched in 2003, were both years behind schedule and billions of dollars over budget, with Airbus attributing

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these overruns to the inability to price "risk" [2]. Delays also plagued the Boeing 787 Dreamliner launched in 2004 which was expected to revolutionize the way airplanes are manufactured using new advanced materials and a daring global manufacturing network where nearly 80% of the airplane is fabricated by outside suppliers [3], with the first flight taking place nearly two years late [4].

These examples illustrate how significant shifts in the industrial base landscape driven by globalization and the exponential growth in aerospace and defense system complexity over the last two decades has created an environment where the effective application of systems engineering principles and advanced modeling and simulation based design approaches to mitigate manufacturing risks are being recognized as critical needs. In fact, many production issues can be traced to early architecture decisions that place a premium on size, weight, and functionality that resulted in designs which could not be efficiently and economically produced due to overly complex manufacturing processes and/or excessive yield fallout driven scrap and rework levels that were not factored into the original "should cost" estimates. Fig 1 graphically illustrates this point and shows the results of a study that found 70% of the life cycle costs are locked in by the time conceptual design is completed [5].

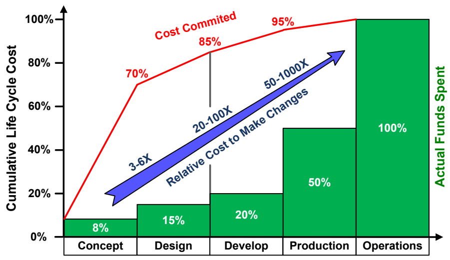

Fig 1. Life Cycle Cost Commitment as a Function of the System Life Cycle

Clearly the largest opportunity to make step change improvements in producibility and affordability is in the front-end of the systems engineering process. However, a universal trend in all aerospace system requirements is the ever increasing demand for higher levels of performance in smaller and lighter systems, higher levels of reliability, availability, maintainability, and safety (RAMS), and lower procurement and life cycle ownership cost than previous systems [6]. These requirements are often conflicting and new design methodologies and analysis tools are needed to help understand trade space constraints and requirement feasibility early in the systems engineering process. One such method is Georgia Institute of Technology's Aerospace System Design Laboratory (ASDL) integrated product and process development (IPPD) methodology which incorporates manufacturing process capability indices early in the design phase to ensure robust design concepts are being developed [7]. This methodology, however, requires that the required manufacturing process capabilities be known a priori, and thus does not capture the interdependencies between requirements and material and manufacturing process trade space constraints that ultimately impact producibility and cost.

It should also be noted that even though producibility is commonly referenced as an important design characteristic to be considered in the systems engineering process, it is usually neglected in the early conceptual and preliminary design activities because it is hard to quantify due to the lack of relevant validated analytical tools. Since producibility and manufacturing considerations are often neglected during these early systems engineering activities, a key customer input has not been included in the requirements definition process - the voice of the producer of the system. The needs of this internal customer are equally as important as the external customer since they will be responsible for the long-term production and profitability of the proposed system, including the design and development of a robust industrial base that must manufacture and sustain the product over life cycles spanning more than 30 years. Producibility has thus been targeted as an "ility" of primary importance where focused research and investments are needed to develop advanced manufacturing M&S-based approaches and systems engineering methodologies that can be used to identify and design-out producibility problems as early design and industrial engineering concepts are being defined and go-forward baselines established.

Unfortunately, current commercially available design for manufacturing (DFM) software analysis packages are largely based on relatively simple approaches where worksheets or automated analyses are used to analyze the impact of reducing part counts, minimizing assembly times, and standardizing parts. However, these simple approaches do not address the fundamental mechanisms driving aerospace and defense producibility issues. For complex aerospace and defense systems, the majority of producibility issues are not being driven by simple part count or assembly time issues, but rather the complexity associated with manufacturing the individual components where maximum functionality has been integrated into the smallest and lightest possible envelopes. Here, producibility problems arise due to intricate internal and external design features, highly complex three-dimensional shapes, the use of exotic and hard to machine/fabricate materials, unique special process requirements, and tightly controlled geometric dimensions and tolerances essential to meet aggressive performance and weight requirements that current commercially available DFM analyses fail to address [7, 9].

As a result, checklists and design rules based on best practices and lessons learned from previous designs are the typical state-of-the-art tool available to aerospace and defense system design teams, with these techniques having limited success in influencing design decisions due to their inability to quantify the impact of potential producibility concerns. If more formal DFM evaluation criteria and analysis tools do exist, they are usually based on checklists that have been loaded into automated computer aided design (CAD) rule checkers used to determine if the designer has adhered to recommended best practices or not. The limitations of these approaches are threefold: first they are only as good as the rules that are captured in the checklists or software, second they are go/no-go and do not quantify the impact of not adhering to the rule, and third they are usually applied when the design is near final and enough information is available to run the CAD-based DFM analysis at which point it is too costly to implement significant design changes as 95% of the cost has already been committed by earlier design decisions, e.g., Fig 1.

The demand for faster time to market and lower development costs and risks has also resulted in a high amount of design re-use in new product development offerings which has created its own set of unique challenges. Presently, nearly all new designs are based off of “similar to” baselines with design and manufacturing assumptions made about what aspects of the design need to be altered to meet the new customer requirements. Unfortunately, many legacy designs were created at a time when customers were willing to pay for the highest levels of performance regardless of the cost, with many of these legacy designs having inadvertently designed-in cost and producibility issues which need to be understood to avoid re-using our “sins of the past”. Hence, identifying the cost and producibility drivers of the legacy “similar to” components and producibility impact of proposed design changes required to meet new customer expectations has become one of the main challenges of modern design.

Presented in this paper is a case study of an aerospace Air Turbine Starter system which uses a previous generation “similar to” design as the baseline that has to meet aggressive performance, weight, reliability, and cost targets. For this product line the output power and reliability have increased 200% and 20% while the size and weight have decreases 30% and 20% respectfully over the last 30 years as summarized in Table 1. These requirement trends have resulted in more complex designs that utilize exotic materials to meet higher temperature and durability requirements and more intricate and complex geometric shapes to meet the size and weight requirements. These design trends have subsequently driven the need for more capable and expensive manufacturing processes and materials, e.g., moving from sand casting to investment casting to meet minimum thickness and tolerance requirements or using titanium instead of aluminum to achieve higher temperatures. Internally developed quantitative producibility analysis tools that overcome the aforementioned limitations of commercially available DFM software are also used to understand the producibility shortfalls associated with the baseline design and identify design improvement opportunities.

Table 1. Inlet comparison

Characteristic	ATS-A	ATS-B	ATS-C	ATS D
Peak Power [HP]	-	+8%	-25%	+27%
Temperature [°F]	-	-46%	-30%	+2%
Airflow [Lb’s/min]	-	0%	-34%	+7%
Length-to-diameter ratio	-	-17%	-40%	-20%
Maximum Weight	-	-3%	-47%	-36%
Power Ratio [HP/Lb]	-	+26%	+21%	+59%
Cost [$/HP]	-	-42%	+5%	-47%
Cost [$/Lb]	-	-25%	+33%	-12%
Introduction Year	1988	1997	2001	2015

2. Air Turbine Starter Case Study Description

Air Turbine Starters (ATS's) are used to start aircraft gas turbine engines by converting potential energy from a high pressure air source, usually a pressurized canister, into rotational energy and shaft horsepower used to drive the main engine gearbox and initiate rotation for main propulsion engine starting. An ATS was selected for this case study for several reasons. First, it represents a moderate complexity turbomachine that features many of the components, materials, and manufacturing processes used in typical aerospace systems. Second, the product features a Bill of Material (BOM) that contains on the order of 150 parts, a handful of which are complex, unlike that of the main propulsion engine where there are several thousand BOM parts, hundreds of which are complex, which would make the case study much more difficult. Third, the ATS product line has a more than a 30 year history of the same increased performance and lower cost demands similar to the main propulsion system it drives, yet is a much more tractable problem to investigate. Fourth, the methodology developed for the ATS case study will also apply to the main propulsion engine and can be used to help guide case studies for more complex systems in which design attributes must be balanced to best meet requirements.

A typical ATS is shown in Fig 2, with the main components consisting of an inlet stator housing assembly, an axial-flow turbine wheel, a primary shaft, a gear train that converts the high-speed low-torque turbine rotation to a low-speed high-torque output, an output drive shaft used to initiate rotation of the main propulsion engine, bearings, an exhaust diffuser housing assembly, and a structural intermediate housing assembly that forms the backbone of the ATS. The turbine wheel typically features complex 2D or 3D airfoils machined from a high-strength aerospace grade aluminum or titanium forging while the inlet, exhaust, and structural intermediate housings are usually sand or investment cast and feature complex thin walled geometries with tight tolerances. The gear train is also complex and consists of a set of ring, planetary, and shaft gears machined from high quality steel, feature tight tolerances, and are heat treated and case hardened to enhance wear resistance. The output shaft also requires the use of high-strength materials and high-demand bearings to support high-loads and fast startups.

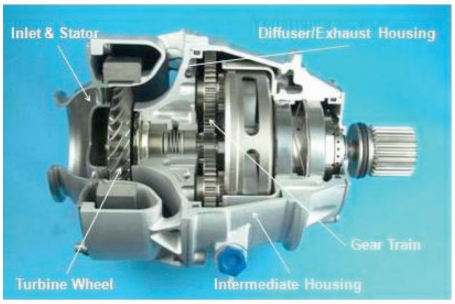

Fig 2. Representative Air Turbine Starter Cross-Section

3. Producibility Analysis Toolkit Description

Customer requirements and overly conservative, and in some cases required, design margins tend to drive complexity into high-reliability aerospace systems which can adversely impact producibility by driving higher costs, longer manufacturing cycle times, and poor yields once the design is transitioned into production. Hence, identifying design-driven manufacturing complexity concerns and thir impact on producibility early in the systems engineering process is required to adequately understand trade space implications so that major competing customer requirements such as performance, weight, reliability, and cost can be balanced and traded-off versus one another. This need was recognized back in 2008 by Honeywell, with a series of quantitative producibility analysis tools for mechanical and electronic components developed to quickly evaluate conceptual design concepts and understand the impact of design attributes on producibility characteristics [10]. These tools consist of complexity characterization models and DFM scorecard analysis tools as shown in Fig 3, with the casting and billet machining complexity and DFM scorecard analysis tools used in the present ATS case study which are briefly described below.

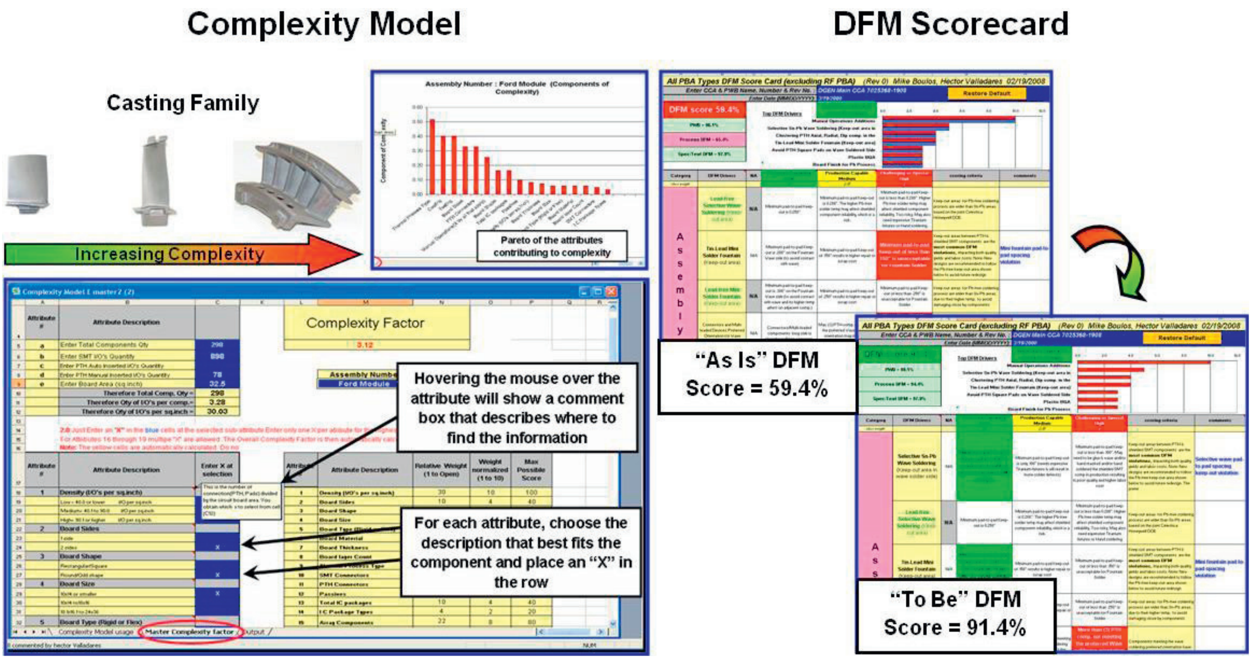

Fig 3. Honeywell Complexity Model and DFM Scorecard Producibility Analysis Tools

The motivation for developing the complexity model was based on the recognition that non-recurring engineering system development cost, schedule, and risk are known to be exponentially correlated to the complexity of the requirements and the systems being designed [11, 12]. From a manufacturing perspective it was recognized that the same correlation should hold true for the recurring engineering costs associated with producing these systems, i.e., the manufacturing cost, cycle time, and yield fallout risk should also be exponentially correlated to the complexity of the manufacturing requirements associated with producing the system. And since any system is a composition of individual components, the individual component recurring manufacturing costs, cycle time, and yield fallout risk should also be exponentially correlated to the complexity of each component that comprises the system. An analytical expression was thus developed to correlate key design attributes/features to component manufacturing complexity, with the exponential correlations for cast and billet machined parts shown in Fig 4. Also displayed are the R^2 values of the regression fits, with weight factors established for each parameter in the correlation to minimize the overall R^2 value against the part cost objective function using an optimization algorithm.

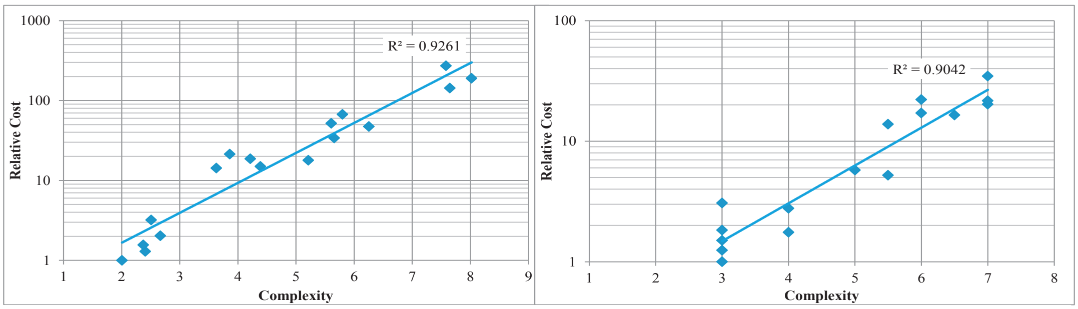

Fig 4. Manufacturing cost and complexity for (left) billet machined, and (right) cast parts

The complexity model shown in Fig 3 was developed based upon these correlations and is a reduced order predictive model that assesses the relative impact of design attributes and features on relative cost driven by complexity. The input to the model is a list of 15-20 key design attribute categories that are known to drive complexity and a range of alternatives within each category. The complexity model, through the use of proprietary weight factors used to establish the correlation, uses these input parameters to calculate a normalized complexity index ranging from 1-10. A score ranging from 1-3 (green) signifies a very simple to manufacture low-cost design, a score of 3-5 (yellow) signifies a moderately complex and medium-cost design, and a score >5 (red) signifies a high-cost highly complex design which will be difficult to manufacture and pose a high yield fallout risk. The model also automatically generates a Pareto plot of the design attributes which are driving the complexity score, allowing the designer to understand which design attributes need to be modified in order to simplify the design if complexity is a concern. Since the correlation is exponential, the uncertainty and scatter in the absolute cost increases as complexity increases, making the model not appropriate for absolute "should cost" predictions, but more appropriate for relative cost assessments of proposed design changes relative to a "similar to" baseline design.

The DFM scorecard analyses looks at more detailed aspects of the design and quantifies the impact of deviating from recommended manufacturing best practices. These best practices include types and grades of materials, tolerances and surface finishes, minimum thicknesses, length-to-thickness aspect ratios, part size, number of dimensions and datum structures, inspection and test requirements, etc. The motivation for developing the DFM scorecard tools was that in many cases DFM best practices are documented in thick handbooks that are difficult to navigate and grade compliance against, are usually go/no-go criteria and, in many cases, it is impossible to satisfy all of the criteria given the requirements and design constraints. Hence, the concept of a DFM scorecard was developed that allows the "DFM goodness" of the design to be quantified using a prioritized set of DFM criteria that have weight factors assigned to them based upon their impact to product cost and quality. In addition, for each DFM criteria three levels of DFM violation severity are defined: green which indicates an easy to meet capability that any qualified supplier can provide, yellow which indicates that the design attribute level is achievable but may require higher capability suppliers, and red which indicates that the design attribute level has exceeded the industry state-of-the-art and that specialized process capabilities will be required, with penalty functions used to quantify this impact.

The inputs to the DFM scorecard model fall within one of three main categories: design, process, and inspection/test, with these inputs designed to capture those attributes which have the largest impact on manufacturability. The output of the model is a score ranging from 0-100%, with an overall score greater than 85% indicating good compliance with the DFM criteria (green), a score between 70-85% indicating the design will challenge some suppliers and pose a moderate producibility risk (yellow), and a score <70% indicating there are numerous DFM violations that have exceeded the current-state-of-the-art capabilities and there is a high producibility risk (red). In addition to the overall green/yellow/red "DFM goodness" score, color-coded scores for each of the three main categories are also calculated and displayed to give insight into which category (design, process, or inspection/test) is driving the low score. All individual red scores are also examined to determine if the DFM violation is being driven by a functionality or performance requirement so that appropriate risk mitigation plans can be developed.

4. Analysis Results

Four ATS systems were selected for this case study, three of which are legacy ATS designs while the fourth is a proposed new ATS system that re-uses several components from these legacy designs as its baseline. ATS A was developed and placed into service in the 1980's and can withstand an inlet air temperature of 830°F, weighs approximately 35 pounds, and is the largest (volumetrically) of the four designs. ATS B was developed and placed into service in the 1990's and can withstand an inlet air temperature of 450°F, weighs approximately 29 pounds, and has a 26% higher horsepower per pound ratio than ATS A as indicated in Table 1. ATS C was developed and placed into service in the 2000's and is the smallest of the four starters while ATS D is currently under development and will eventually replace both ATS A and B. The ATS D design was predominantly based upon ATS C with customer requirements driving it to withstand an 850°F inlet air temperature and weigh no more than 27 pounds, which makes it the smallest and highest performing of the four ATS's. It should be noted that these four designs span nearly 30 years of ATS evolution, approximately one starter per decade, and provide valuable insight into the evolution of how requirements have driven complexity into the components used within each subsequent ATS design concept.

In order to identify the key ATS components which drive the majority of the ATS system cost, a cost build-up for each ATS was constructed. The cost build-up for ATS B is shown in Fig 5 which is representative of the other three cost build-ups, with approximately 20% of the parts driving 80% of the ATS system cost. As indicated in Fig 5, the primary high cost parts identified for further deep dive analysis included forged and machined turbine wheels, cast inlets/housings, and complex gears since they represent the highest cost and most complex components of the ATS. The following discussion will focus on turbine wheels and the inlet/exhaust housings, with gears excluded from the case study since producibility analysis tools have not yet been developed for this family of parts.

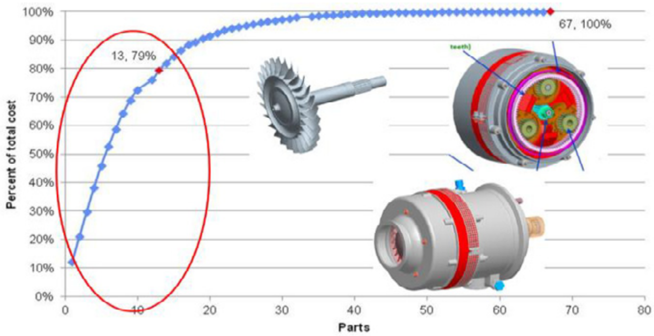

Fig 5. Notional cost build-up depicting Pareto Principle with large cost contributors identified

As Table 2 indicates, the inlet design that redirects and conditions the flow into the turbine wheel has evolved from a two-piece low complexity (3.1) sand cast aluminum plenum and a low complexity (3.7) investment cast aluminum stator assembly in ATS B, to a slightly more complex (4.1) single-piece investment cast steel integrated plenum-stator assembly in ATS D. It is also worth noting that the design change to reduce part counts has reduced the part cost by 33% with only a moderate increase in the complexity of the integrated assembly which is still in the medium (yellow) range. The complexity model also identifies that minimum thickness, material soundness, and profile tolerances as the primary complexity drivers. However, the most pertinent design change was a material shift from aluminum to stainless-steel and a resulting shift from sand castings to investment castings. These trends are depicted in Table 2, along with the relative cost contributions to the ATS system. Interestingly, the stainless steel design was chosen above a titanium alloy in order to reduce cost but results in a substantial weight increase, with the weight requirement now at risk of not being met. It is also worth noting that the analysis demonstrates inlet complexity has increased over time as part counts have been reduced, with the integrated single-piece titanium design having the highest complexity (4.6) which is approaching the high risk regime (>5).

Table 2. Inlet comparison

ATS	Part Description	Complexity	Fabrication Process	Material	Contribution to ATS Cost in 2012
B	Plenum Inlet Stator	3.1 3.7	Sand Casting Investment Casting	Aluminum Aluminum	12.1 %
C	Inlet & Stator (1-piece)	4.1	Investment Casting	Stainless Steel	7.1 %
D	Inlet & Stator (1-piece)	4.1 (4.6)	Investment Casting	Stainless Steel (Titanium)	8.3 %

The forged and milled titanium turbine wheels have primarily evolved from 2-D to 3-D airfoils in order to increase aerodynamic performance as depicted in Table 3, with the cost of these designs steadily increasing. The reason for this trend in cost is that in addition to the geometric changes to increase performance, the material has also evolved toward higher grades of titanium alloy to increase burst and low cycle fatigue margins which have driven additional cost into the design. It is worth noting that the complexity indices are grouped rather tightly between 4.47-4.57 since the current model is not able to adequately differentiate the relative impact of 2-D versus 3-D airfoil designs and the use of the higher grade titanium alloy. Work is underway to determine if additional weight factors and attributes can be added to the model to better differentiate the complexity associated with these attributes, but it is not expected that the complexity scores will change greatly. The reason for this is that the complexity model was developed for all forged and milled rotating wheel assemblies used in Honeywell Aerospace's product portfolios which also includes propulsion engines and auxiliary power units (APU's). The ATS turbine wheels are at the lower end of the complexity spectrum for these turbomachine families, and the scores predicted by the model felt to be in the right ranges compared to the higher complexity turbine wheels used in APU's and propulsion engines.

Table 3. Turbine wheel comparison

ATS	Part Description	Complexity	Fabrication Process	Material	Contribution to ATS Cost in 2012
A	2D Turbine Wheel	4.57	Forging & Milled	Titanium 6-4	6.2 %
B	2D Turbine Wheel	4.57	Forging & Milled	Titanium 6-4	9.8 %
C	3D Turbine Wheel	4.47	Forging & Milled	Titanium 6246	13.2 %
D	3D Turbine Wheel	4.55	Forging & Milled	Titanium 6246	15.4%

Several aluminum, titanium, and steel sand and investment cast housings are used in the ATS system, with these castings listed in Table 4. In contrast to the previous deep dives, numerous housing design trends are occurring simultaneously which are being driven by competing requirements. For example, to reduce part counts and lower cost, the titanium diffuser and aluminum exhaust investment cast housings of ATS A have been combined into an integral single-piece aluminum diffuser-exhaust sand casting in ATS B. This is an instance where two moderately complex high-cost investment castings have been replaced by a single lower complexity and lower cost casting which was only possible by relaxing tolerance and minimum thickness requirements and using aluminum instead of titanium. This design change, however, required the addition of an intermediate support housing to secure the inlet to the diffuser, which for ATS C and D was subsequently eliminated through the use of an integrated single-piece design. For ATS B, C, and D the complexity model predict a steady increase in component complexity over time as part counts have been reduced and casting designs became more integrated, with the latest ATS D entering the complex (red) regime due to design-driven complexity. Here, one might intuitively think the cost of the ATS D housing would be significantly lower than the ATS C housing cost since it is sand cast rather than investment cast, but what this line of thinking ignores are the fundamental design differences between ATS C and D that drive cost.

Table 4. Diffuser and exhaust housing comparison

ATS	Part Description	Complexity	Fabrication Process	Material	Contribution to ATS Cost in 2012
A	Housing Diffuser	4.8	Investment Casting	Titanium	16.3 %
	Housing Exhaust	4.4	Investment Casting	Aluminum	
B	Housing Diffuser +Exhaust (single-piece)	4.2	Sand Casting	Aluminum	12.5 %
	Intermediate Housing Assembly	3.5	Investment Casting	Stainless Steel	
C	Housing Diffuser +Exhaust (single-piece)	3.9	Investment Casting	Aluminum	8.9 %
D	Housing Diffuser +Exhaust (single-piece)	5.3	Sand Casting	Aluminum	10.5 %

As customer requirements continue to evolve toward higher levels of performance and lower-cost designs, properly understanding the impact of requirements on material and process selection alternatives will be crucial. Tables 2-4 show the most common materials used to manufacture the complex ATS components include aluminum, titanium, and high-nickel stainless steel alloys. Fig 6 depicts the trade space for each of these three alloys of interest with respect to their temperature capability and relative cost. Aluminum alloys are the least expensive and lightest material, providing reasonable temperature thresholds. However, with the new demand for more compact designs capable of withstanding higher inlet temperatures and higher stresses, aluminum material properties are no longer adequate. In many cases titanium and nickel based alloys are now required to meet the design requirements since they provide marked temperature improvements over aluminum, but also induce a 6-8X relative cost increase. Similarly, as requirements drive designs to be lighter and more compact, minimum thickness and tolerance requirements will drive the need for many sand castings to be converted to investment castings inducing an additional 2X relative cost increase as shown in Fig 6.

Another important conclusion from Fig 6 is that an incremental increase in temperature, minimum thickness, and/or tolerance requirements could drive step change cost increases due to having to use titanium instead of aluminum or an investment casting versus a sand casting. It is thus imperative that early systems engineering methodologies and producibility analysis tools be available during early requirement feasibility and conceptual design activities to help identify materials and processes utilized in the baseline “similar to” design that may no longer be adequate to satisfy all of the conflicting performance, reliability, weight, and cost requirements. Another observation is that that emerging advanced manufacturing and materials genome technologies offer the potential to bridge gaps in the current trade space if affordability and producibility are treated with the same priority and rigor as weight and performance in science and technology (S&T) portfolios. Currently, new materials and manufacturing processes are usually developed in order to push the performance and weight envelope further and make aerospace systems faster, lighter, and more efficient. What if new materials and processes were being developed that target cost and increased manufacturing capabilities, e.g., a new material with the properties of titanium at the price of aluminum or a new additive manufacturing technology that has the process capability of investment castings at the cost of sand castings?

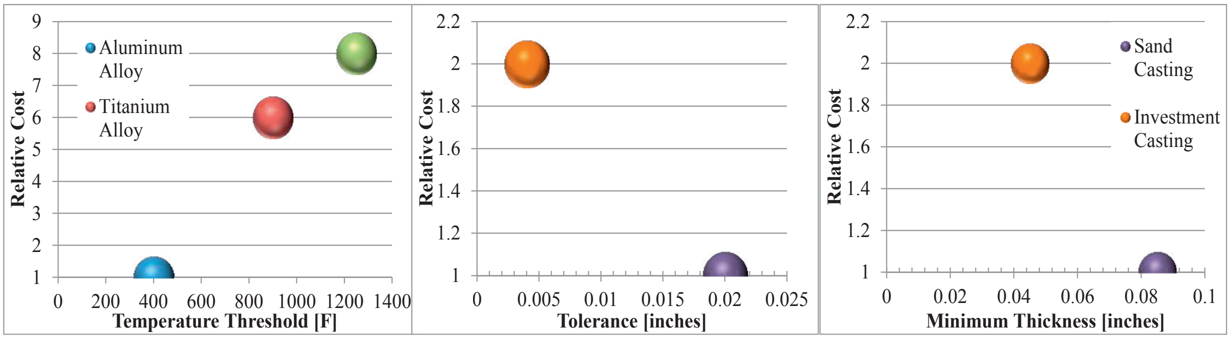

Fig 6. Material and process trade spaces showing (left) relative material cost as a function of temperature capability, (middle) relative material cost as a function of relative weight, and (right) relative cost of costs for sand and investment casting as a function minimum thickness

5. Summary and Conclusions

The ATS case study presented herein demonstrates that properly developed producibility analysis tools have the potential to identify design attributes which negatively impact manufacturability and ultimately drive cost. In addition, by using these tools during early systems engineering trade studies it is possible to identify producibility risks being driven by evolving customer requirements and the reuse of legacy designs that may have inadvertently designed-in producibility and cost issues. These tools also revealed that over time part count reduction strategies have reduced assembly complexity at the expense of increased component complexity, with several of the casting designs approaching the high complexity regime making it important to have tools available to help understand the multiple dimensions of producibility and the associated relative cost impact. The basic methodology presented in this paper is applicable to more complex systems such as propulsion engines to identify producibility risks and design improvement opportunities that can be explored for potential cost savings by enhancing manufacturability. Perhaps the most important item to note is that producibility analyses must be performed as early and frequently as possible in the design process since once the design is locked-down producibility issues are locked-in.

As customer requirements continue to evolve toward higher levels of performance and reliability and lower weight and cost, it is anticipated that inadvertently designed-in producibility problems will become more frequent. Presently, even though producibility is referenced as a key “ility” to include in the systems engineering trade study process, it is often neglected during early design activities due to the lack of validated analytical tools. It is thus imperative that next-generation advanced design methodologies and manufacturing analysis tools be developed to help understand producibility trade space limitations and requirements feasibility early and continuously throughout the systems engineering process. For example, the development of analysis tools that allow the designer to evaluate the impact of design requirements and assumptions on material and process selection alternatives and their impact on system complexity and cost feasibility would be extremely valuable. Since many new system development efforts leverage design re-use to decrease time to market, producibility analyses must be performed starting with the baseline “similar to” design to avoid re-using “sins of the past” that may have inadvertently designed-in problems.

Finally, it was demonstrated that there are large discontinuities in the current material and process trade spaces driven by both cost and material property differences, with an incremental increase in a performance requirement having the potential to drive a step change increase in cost. Methods are thus needed in order to balance the conflicting performance, reliability, weight, and cost requirements customers are demanding and understand if meeting all of these requirements is even feasible before committing to a contract award with a proposed system design concept. In addition, emerging advanced manufacturing and material genome technologies have the potential to help bridge current cost and material property trade space gaps provided that lowering the cost of aerospace systems is given the same S&T priority as developing faster, lighter, and more efficient aerospace systems. This will, however, require a significant culture shift in the aerospace community since manufacturing is currently not viewed as an engineering discipline like it is in other countries such as Germany and the United Kingdom.

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