INTEGRATED AIRCRAFT ENGINE DESIGN - THE IMPLEMENTATION OF THE MASTER MODEL CONCEPT AT GE AIRCRAFT ENGINES

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Keywords: *Aircraft Engine, Design, Master Model*

Abstract

Reducing aircraft engine development time and ensuring robust, high quality products are essential elements in today's competitive global market place. This paper describes the "Intelligent Master Model" initiative at GE Aircraft Engines. There are two key elements of the Master Model concept. The first is the use of a top down CAD design infrastructure that enables the engine to be designed as a complete system. This approach to product design definition parallels the design process in which the overall engine architecture is defined first, followed by the individual components that make up the engine in a hierarchical structure. The second is every design team member throughout the design process has access to a single digital representation of the engine and it's components, the configuration controlled "Master Models". Having a single, accessible representation of the engine ensures the entire team (design, drafting, manufacturing, maintainability, etc.,) makes design decisions with the same and most up to date information.

At GE Aircraft Engines the Master Model concept has been extended through the use of engineering design rules that drive parametric definitions of all the major engine components. For instance, the geometric parameters that define a compressor rotor disk are a function of the weight and radial location of the compressor blade, the rotational speed of the shaft and the material properties of the disc. An engineering rules based approach to engine design allows very rapid scaling of the engine in the early design phases as the aircraft requirements evolve. It also ensures design standardization and the use of best practice design rules. The parametric rules based definition is referred to as the "Intelligent Master Model".

Another advantage of standardizing the CAD representation of the major engine components is that alternative representations can be created automatically from the Master Model. For instance, the stress analyst requires a different representation of the design to that for manufacturing evaluation, tooling design, or maintenance assessment. Different representations of the design are referred to as "context models" and are automatically updated each time the Master Model is updated.

An extension to the Intelligent Master Model process is the use of Knowledge Based Engineering (KBE) techniques that allow rapid changes in the engine configuration and the automation of the definition of complex engine components.

The paper concludes with a look at the future direction of this technology, specifically in the management of analysis data and design in a global heterogeneous environment.

Introduction

Delighting one's customers is critical to success in any business. For GE Aircraft Engines two key elements in achieving this goal are:

- The on time delivery of high quality products.
- Products that are robust to variation in the manufacturing process and the operating environment.

Both of these are addressed as part of the GE Aircraft Engines Six Sigma initiative. GE takes a broad approach to Six Sigma. While Six Sigma originated from the manufacturing arena, concentrating on variability in manufacturing processes, it actually covers any process, and represents the understanding of variability and uncertainty in that process. The new product introduction (NPI) process is simply another process that has variability, which needs to be understood in order to delight one's customers through the on time delivery of new, high quality products.

A complete understanding of the design and development of a new aircraft engine is the first step towards improving this process. At GE Aircraft Engines a significant project has been undertaken over the last four years, called the Thruput Initiative, to rigorously map the aircraft engine development process, gain an understanding of the critical path, determine where data handoffs occur and how information flows. By continually working on the processes that form the critical path, the time required to go from product launch to government (FAA, JAA etc.) certification has been significantly reduced. The goal is to consistently achieve a cycle time of 24 months from product launch to certification.

Another area of Six Sigma is robust design. Our aim is to develop products that are robust to variation in the basic design features, the execution of the design through the manufacturing process and the environment in which the products have to operate. For example, an airplane flying out of Canada sees a very different operating environment than an airplane flying out of the Middle East. The Middle East is a hot, sandy environment, both of which are detrimental to the long-term performance of an engine. If an engine design is optimized for one customer, other customers are not going to be satisfied. Understanding the variability in the design, production and use of our engines is vital if all our customers are to be delighted by our products.

The Master Model

The Master Model provides a single representation of the design configuration that is stored centrally and under configuration control. At GE Aircraft Engines, TeamCenter Engineering (formally known as iMAN) is used to allow everyone access to the one Master Model.

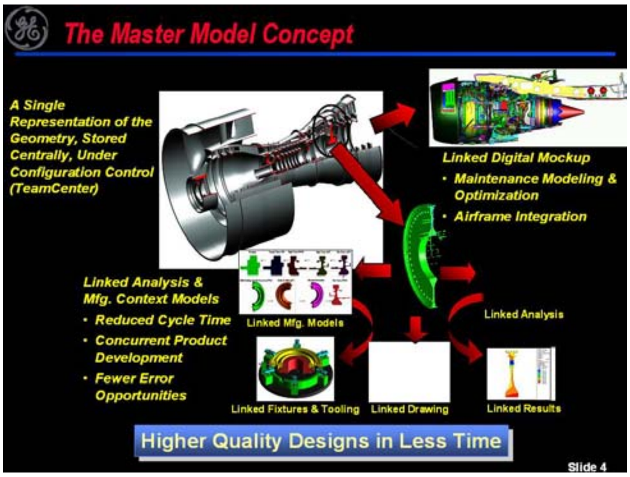

Figure 1 – The Master Model Concept

The Context Model

Different functional specialists typically want to view the Master Model in different ways. Context models are used to facilitate these functional perspectives. From the Master Model, a stress analyst wants to see just the information needed to perform a finite element stress calculation. It is inefficient if they are presented with the product definition required for manufacturing, from which they have to extract the information needed for stress analysis. The same holds true for other specialists interested in aerodynamics, heat transfer, maintainability, drafting, manufacturing etc. This is achieved using Unigraphics WAVE technology to associate and link these specialty specific context models to the Master Model.

In the process developed at GE, each engine component has a defined owner who is the only person who can update the Master Model.

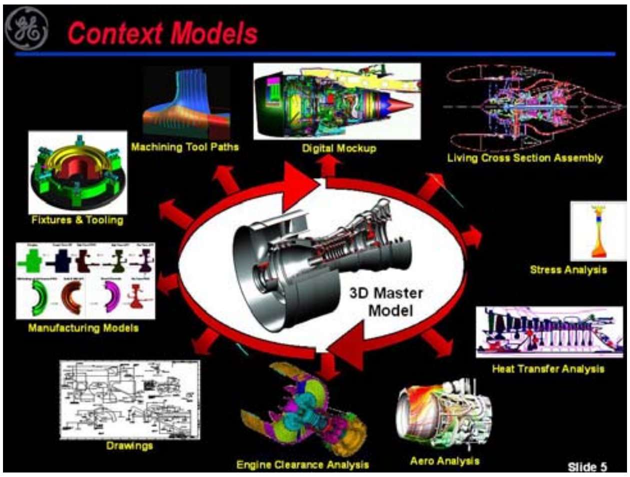

Figure 2– Context Models

As the design evolves, when the component owner makes a change to the Master Model an email message is sent to all the specialists on the design team who own context models informing them that a new version of the Master Model has been issued. Each technical specialist can then review the changes and update their context model. In many cases the entire analysis process has been automated. For example, when the stress analyst updates the stress context model, the appropriate boundary conditions are adjusted; finite element model updated and the analysis can be immediately performed to calculate the effect of the change.

Another context model that has paid huge dividends at GE is called "The Living Cross Section." For an aircraft engine you can see all the major components of the engine by creating a carefully selected cross-section. The Engine Systems organization, which is responsible for the entire engine design, has weekly cross section meetings where the chief designer on that engine program will review a big cross-section to discuss the issues in every module as it is being designed. Preparing that cross section view used to be at least a week's worth of work. The result was that cross-section that was discussed at the weekly meeting was often a week or more out of date. Having the Master Model and an automated process to produce the "Living Cross Section" context model, one can now work to a weekly design rhythm. If the cross-section reviews are on Wednesday afternoon, each engine component owner will update the Master Model Tuesday night. The cross section context model will be cut on Wednesday morning and reviewed on Wednesday afternoon. The design team can work any issues for the following week prior to the next design review. There are huge savings from eliminating wasted time looking at outdated models and a tremendous benefit to the overall efficiency of the design process.

The Master Model has had a major impact on reducing cycle time and has been instrumental in allowing true concurrent design. As soon as the 3-D Master Model is created, each member of the design team can examine the context model specific to their discipline and give their feedback on the design. The result is a more robust design in a shorter time.

Intelligent Master Model

What makes the Master Model intelligent? Rather than using unparameterized solids to define geometry, parametric models are used for all of the major engine components.

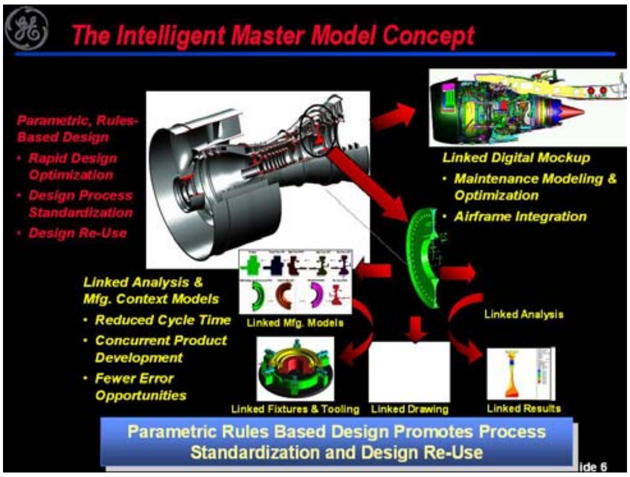

Figure 3 – The Intelligent Master Model Concept

To explain this, consider the example of an engine part called a turbine rear frame, shown in the Figure 4. The center sketch drives the 3-D geometry and is defined parametrically in

Unigraphics. The sketch in turn is driven by a spreadsheet with imbedded basic engineering design rules that control the design. It is not a pure geometric scaling. If one change the flow-through the component, the design will scale appropriately, based on that flow. For rotating turbomachinery components, critical dimensions will scale appropriately with rotation speed based on centrifugal force equations. By having each component defined parametrically, one can very quickly scale the Master Model of the whole engine parametrically and produce context models for each specialist to review and perform the appropriate level of analysis to evaluate the scaled design. This has tremendous potential in the early design stages when the requirements for the engine are still evolving.

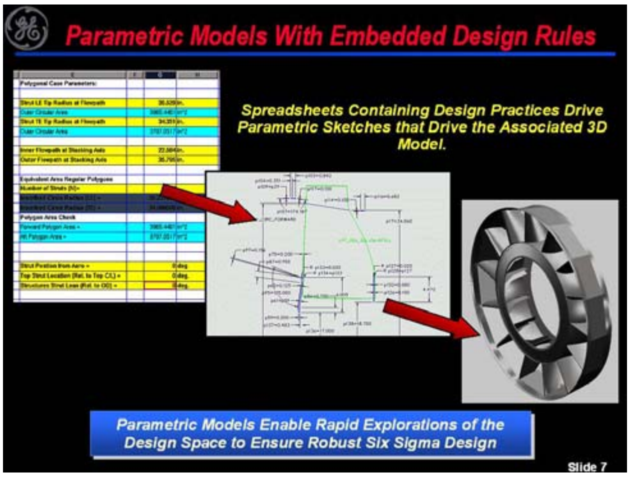

Figure 4 – Parametric Models with Embedded Design Rules

The Intelligent Master Model, context models and the automated analysis processes that have been developed naturally fit into a Six Sigma design for reliability / robust design philosophy. In fact, GE Aircraft Engines has developed a proprietary tool kit of design for Six Sigma and design for reliability tools, including design of experiments tools, optimizers, and robust design tools. Linking the design for Six Sigma toolkit to the parametric Master Models, which are in turn linked to an analysis allows the designer to start looking at parametric design and robust design. Response surfaces can be constructed to investigate the impact on the design if a parameter is changed. One can determine if there is a cliff in the response surface. The optimum design might be right next to a cliff in the response surface, but for robust design one wants to position the design sufficiently away from the cliff to allow for variation.

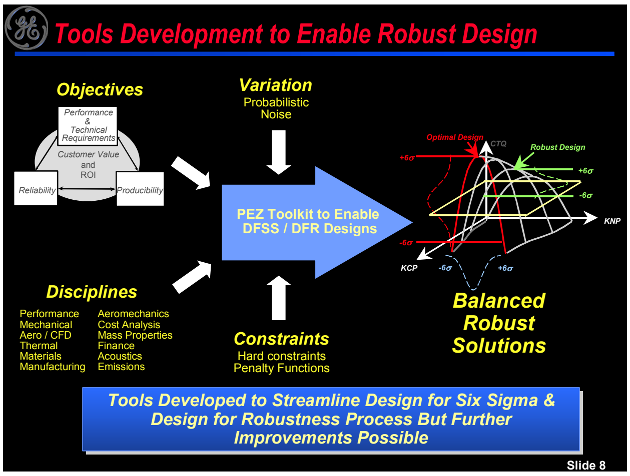

Figure 5 – Robust Design Process

Current Status of the Intelligent Master Model

Today, work is in progress building a library of engine components as Intelligent Master Models. The objective is to have a well-controlled library of Master Models for all engine components and levels of technology that contains the parametric engineering design rules for that component. This will give the design manager the ability to examine different levels of technology for any component and match them with customer requirements early in the preliminary design stage. As new technology components are developed, part of the technology maturation process will be the building of the Master Model with the associated rules and its incorporation into the library of Master Models.

The CF34-10 engine program was the first to use the Intelligent Master Model process. The CF34-10 is the engine for the Embraer 190 and the Chinese ARJ21 regional jet. The version of the engine for the Embraer 190 is currently undergoing flight testing. Prior to the start of detailed design of the CF34-10, Intelligent Master Models had been developed for a CFM56 sized engine. The core of the CF34-10 is an aerodynamic scale of the CFM56 size of engine. Using the Intelligent Master Model, the CFM56 sized core was parametrically scaled to the smaller size of the CF34-10. This allowed the design teams to immediately start detailed design with correctly sized parametric Master Models of the engine components that met the fundamental design rules for the component. They were then able to use these parametric models to perform detailed analysis of the design space. The result was that more analysis was conducted in a shorter time than could be accomplished before, greatly reducing manufacturing costs while still meeting design requirements.

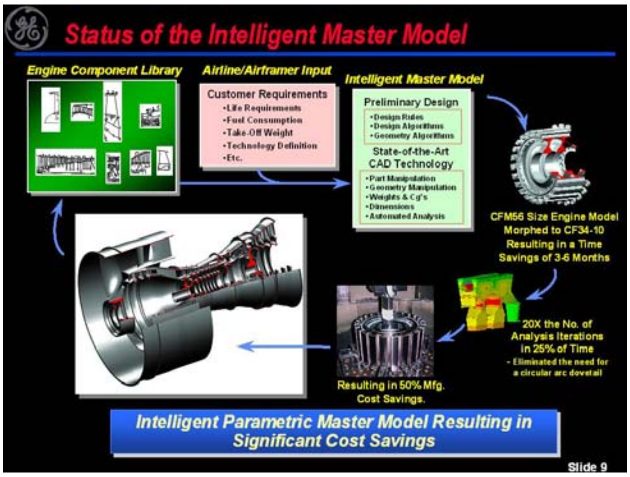

Figure 6 – Example of the Use of the Intelligent Master Model Process

For the CF34-10 engine the Master Model process was introduced at the beginning of detailed design phase of the development program. At this point in the design process the Master Model was scaled and handed over to the detail design teams. The aim had always been to use the Master Model in the preliminary design phases. However limitations in the process were found. The scaling process that was used assumed the topologies of the parent and the child engines were very similar. It was not easy to change the product data structure or topology of the engine. It would take an expert in Unigraphics (UG) about a week to break all the dependencies between parts in the assembly and recreate them for a new topology or product data structure. Members of the Preliminary Design organization typically evaluate hundreds of candidate engine topologies during the early phases of engine design and need the ability to change topology very efficiently. Historically, GE proprietary software has been used to layout two-dimensional engine cross sections for different engine topologies. This software is not linked to the CAD system used by the component detailed design teams and a large amount of time has to be allowed for in the engine development process for building CAD models that match the output of the preliminary design process. Therefore, developing a process that allows the Master Model to be used in the preliminary design process, so that the resulting CAD models can be used directly by the detailed design teams has huge potential productivity savings. Significant effort has been spent figuring out how to allow the preliminary designers to efficiently use the Intelligent Master Models to evaluate different engine topologies during the early design phase.

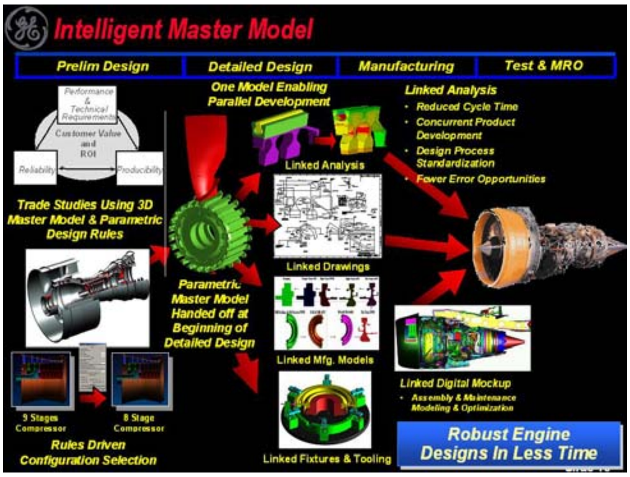

Figure 7 – The Intelligent Master Model Process

Compressor design is a good example of a component topology that is often changed during the preliminary design process. A compressor consists of rows of rotors and stator blades; each pair of rotors and stators is called a stage. An example of a typical design trade study would be to take a nine-stage compressor and determine what would happen to the total cost of engine ownership to an airline if a stage were removed, leaving only eight stages of rotors and stator blades. The advantages of reducing the number of compressor stages include a reduction in part count, manufacturing cost, and weight. The disadvantage is a potential decreased aerodynamic efficiency, causing fuel burn to increase. The challenge was to develop a process to allow members of the preliminary design group to efficiently perform this type of study using the Intelligent Master Model. The solution that has been devised is to link Unigraphics Knowledge Fusion functionality with Unigraphics WAVE functionality, as summarized in Figure 8. An easy to use front-end graphical user interface (GUI) was developed that allows the designer to select basic information about the number of stages, and then Knowledge Fusion drives the product data structure rather than the geometry.

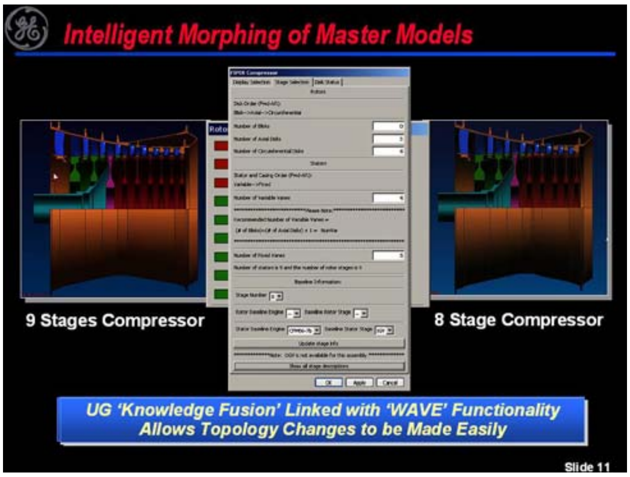

Figure 8 – Intelligent Morphing of the Master Model

The joint GE Aircraft Engines / UGS PLM team has recently demonstrated the capability to go from a nine-stage compressor to an eight-stage compressor by simply changing a number in the GUI, clicking the "Apply" button, and waiting a few minutes for the 3D Master Models to update. Knowledge Fusion can also be used to check the new design for adherence to engineering design rules. The Rotor Disk Status window, shown in Figure 9, indicates that the first three stages do not obey the design rules on how blades are attached to the rotor, and makes adjustment recommendations.

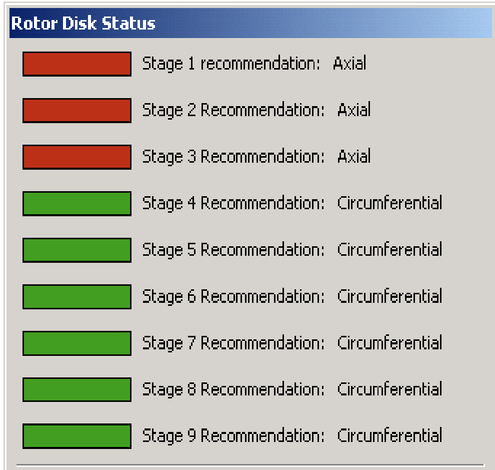

Figure 9 – Output from the Design Rule Checking Process

In the example of the compressor, the next level of the design process has also been automated. A GUI has been developed that allows changing from a circumferential dovetail to an axial dovetail. This is a fairly standard design trade. Using Knowledge Fusion and WAVE functionality, changing the basic topology of the design is possible. This provides an incredibly powerful way to quickly explore different design options that can be used in the preliminary design phase without requiring the designer to be highly proficient in the use of the CAD system.

Figure 10 – Using KBE to Drive Design Topology Changes

Future Direction

An area of great interest for future development is in the management of analysis data. GE Aircraft Engines has seen significant benefits through the implementation of product data management processes for engine component geometry. Consider what happens next. Each engineer conducts analysis for their specific specialty, and a complex web of interconnectivity of analysis data is created. See Figure 11.

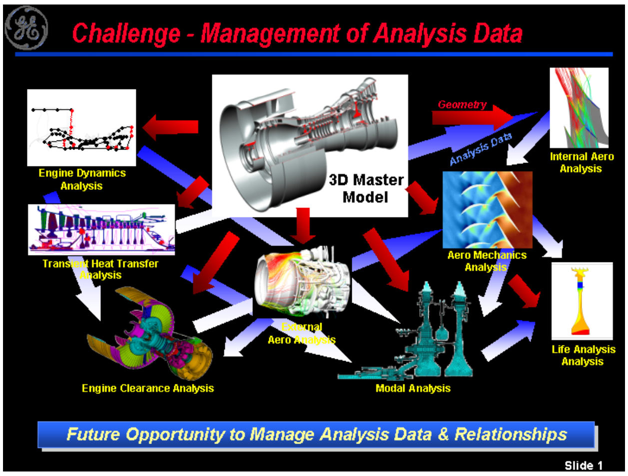

Figure 11 – Analysis Data Interconnectivity

For example, the output from engine thermal analysis is given to the engine clearance specialist. The analysis from the engine clearance specialist is sent to the aerodynamics specialist, who then sends the output of their analysis to the stress analyst. In some cases the data may be passed by email and sometimes 1970's vintage Fortran 4 code may be used to change from the output format of one analysis code to the input format of the next. In other cases engineers write their own spreadsheets to perform these task, or perform them manually and pass the information as handwritten notes that need to be entered into the computer system. All of this is inefficient and prone to errors.

There are huge opportunities for improving productivity and quality by understanding the analysis process and bringing it under configuration control. The vision at GE Aircraft Engines includes configuration control and storage of analysis data, notification of the appropriate engineer when data used as input to the analysis they are responsible for is out of date, and automatically providing them with the updated data in the required format. This is very similar to the Master Model process that has been implemented to control changes to component geometry.

Software vendors are beginning to address analysis data management, but it is not clear that they have a full appreciation for the complexity of the processes involved in the design of a highly engineered product. At GE Aircraft Engines a project is underway to identify our needs in this area and develop a requirements-document. The plan is to use this document to compare our needs with the software vendors' offerings and identify functionality gaps.

Another area of interest is engine design in a global, heterogeneous environment. The GE Aircraft Engines Master Model concept works well if GEAE is responsible for the entire product data structure, since everyone uses Unigraphics and there is a homogeneous computing environment, all the interfaces between components such as the compressor, combustor and turbine and the associated product data structures can be linked. However, it is common business practice to divide the design responsibility among a number of reward and risk sharing partners. The partners may be on the other side of the world, and may not be using Unigraphics to design their components. The Master Model strategy is challenged when design responsibility of a major engine component is given to a partner working in a different CAD, PDM and computing environment.

To address the challenge of global design in a heterogeneous environment, GEAE has been working with NIST, the National Institute of Standards and Technology, and a number of other companies on an R & D project called FIPER, Federated Intelligent Product EnviRonment. The four year long project, that has just been completed, has been an excellent opportunity to understand how to operate in a heterogeneous environment, to try different ideas, and develop software. This software is now being transitioned to Engineous Software (ESI), the FIPER team member responsible from the beginning of the project for commercialization. The FIPER software offers a potential solution to the challenges of global heterogeneous design and will address issues such as business-to-business interfaces in design, including security and crossing computer firewalls.

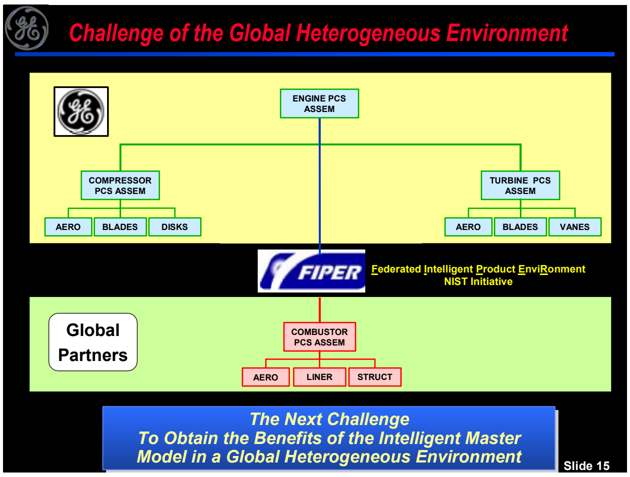

Figure 12 – Design in a Global Heterogeneous Environment

Summary

At GE Aircraft Engines product design and development is an integral part of the Six Sigma initiative. The goal, through the Thruput initiative, is to consistently achieve an engine development time of 24 months, from product launch to engine certification, with a target of achieving eighteen months thruput. Understanding all the sources of variability in the design, manufacturing and operating environment is critical to ensuring that ones products delight ones customers. Design for Six Sigma and Design for Reliability techniques have been developed and incorporated into the design process to allow the designer to determine the confidence, in numerical terms, that the product will meet our customer's requirements.

The introduction of Intelligent Master Model process has been a key to enabling true concurrent design. Linking the Design for Six Sigma tools to the parameters that drive the Intelligent Master Models, which are in turn linked through a context model to analysis process, allows designers to efficiently explore the design space and produce more robust designs in a shorter time.

Future opportunities for increased productivity are anticipated through improved management of analysis data, and the development of software to allow efficient design in a global heterogeneous environment.

Acknowledgements

The authors of this paper represent a small selection of the members of the current Intelligent Master Model development team at GE Aircraft Engines and the GE Global Research Center. The authors would like to acknowledge the contributions of all the current and past members of the team that have been critical to the development of the Intelligent Master Model vision, its implementation and evolution.