

**DEVELOPMENT OF HYBRID LIFECYCLE COST  
ESTIMATING TOOL (HLCET) FOR MANUFACTURING  
INFLUENCED DESIGN TRADEOFF**

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Apinut Sirirojvisuth

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**DEVELOPMENT OF HYBRID LIFECYCLE COST  
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Approved by:

Professor Daniel P. Schrage, Advisor  
School of Aerospace Engineering  
*Georgia Institute of Technology*

Professor Dimitri Mavris  
School of Aerospace Engineering  
*Georgia Institute of Technology*

Professor Alan W. Wilhite  
School of Aerospace Engineering  
*Georgia Institute of Technology*

Professor David Rosen  
School of Mechanical Engineering  
*Georgia Institute of Technology*

Dr. Michael Richey  
Associate Technical Fellow  
*The Boeing Company*

Date Approved: 17 May 2012

*To my family,*

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## LIST OF SYMBOLS AND ABBREVIATIONS

<b>ABC</b>	Activity-Based Costing.
<b>AbTM</b>	Activity-based Time Measurement.
<b>ACCEM</b>	Advanced Composite Cost Estimating Manual.
<b>ALCCA</b>	Aircraft Life Cycle Cost Analysis.
<b>CA</b>	Contributing Analysis.
<b>CAD</b>	Computer Aided Design.
<b>CATIA</b>	Computer Aided Three Dimensional Interactive Application.
<b>CERs</b>	Cost Estimate Relationships.
<b>CFD</b>	Computational Fluid Dynamics.
<b>CLIPS</b>	C Language Integrated Production System.
<b>CSD</b>	Computational Structural Dynamic.
<b>CTR</b>	Cycle Time Reduction.
<b>FEA</b>	Finite Element Analysis.
<b>FLOPS</b>	Flight Optimization System.
<b>GAC</b>	Grumman Aerospace Corporation.
<b>HLCET</b>	Hybrid Lifecycle Cost Estimating Tool.
<b>IPLE</b>	Integrated Product Lifecycle Engineering.
<b>IPPD</b>	Integrated Product and Process Development.
<b>MADM</b>	Multi Attribute Decision Making.
<b>MDAO</b>	Multidisciplinary Design Analysis and Optimization.
<b>MI</b>	Mission Capability Index.
<b>MOST</b>	Maynard Operation Sequence Technique.
<b>MRL</b>	Manufacturing Readiness Level.
<b>OEC</b>	Overall Evaluation Criteria.
<b>OI</b>	Total Ownership Cost Index.

<b>PbRM</b>	Process-based Recurring Manufacturing.
<b>QFD</b>	Quality Function Deployment.
<b>RDS</b>	Robust Design Simulation.
<b>RSE</b>	Response Surface Equation.
<b>SI</b>	Structural Performance Index.
<b>SME</b>	Subject Matter Expert.
<b>TCM</b>	Tailored Cost Model.
<b>TOPSIS</b>	Technique for Order Preference by Similarity to Ideal Solution.
<b>VDD</b>	Value Driven Design.
<b>WbPL</b>	Weight-based Parametric Lifecycle Cost.

## SUMMARY

In complex aerospace system design, making an effective design decision requires multidisciplinary knowledge from both product and process perspectives.

Integrating manufacturing considerations into the design process is most valuable during the early design stages since designers have more freedom to integrate new ideas when changes are relatively inexpensive in terms of time and effort. Several metrics related to manufacturability are cost, time, and manufacturing readiness level (MRL). Yet, there is a lack of structured methodology that quantifies how changes in the design decisions impact these metrics. As a result, a new set of integrated cost analysis tools are proposed in this study to quantify the impacts. Equally important is the capability to integrate this new cost tool into the existing design methodologies without sacrificing agility and flexibility required during the early design phases.

To demonstrate the applicability of this concept, a ModelCenter environment is used to develop software architecture that represents Integrated Product and Process Development (IPPD) methodology used in several aerospace systems designs. The environment seamlessly integrates product and process analysis tools and makes effective transition from one design phase to the other while retaining knowledge gained a priori. Then, an advanced cost estimating tool called Hybrid Lifecycle Cost Estimating Tool (HLCET), a hybrid combination of weight-, process-, and activity-based estimating techniques, is integrated with the design framework.

A new weight-based lifecycle cost model is created based on Tailored Cost Model (TCM) equations [3]. This lifecycle cost tool estimates the program cost based on vehicle component weights and programmatic assumptions. Additional high fidelity



cost tools like process-based and activity-based cost analysis methods can be used to modify the baseline TCM result as more knowledge is accumulated over design iterations. Therefore, with this concept, the additional manufacturing knowledge can be used to identify a more accurate lifecycle cost and facilitate higher fidelity tradeoffs during conceptual and preliminary design.

Advanced Composite Cost Estimating Model (ACCEM) is employed as a process-based cost component to replace the original TCM result of the composite part production cost. The reason for the replacement is that TCM estimates production costs from part weights as a result of subtractive manufacturing of metallic origin such as casting, forging, and machining processes. A complexity factor can sometimes be adjusted to reflect different types of metal and machine settings. The TCM assumption, however, gives erroneous results when applied to additive processes like those of composite manufacturing.

Another innovative aspect of this research is the introduction of a work measurement technique called Maynard Operation Sequence Technique (MOST) to be used, similarly to Activity-Based Costing (ABC) approach, to estimate manufacturing time of a part by virtue of breaking down the operations occurred during its production. ABC allows a realistic determination of cost incurred in each activity, as opposed to using a traditional method of time estimation by analogy or using response surface equations from historical process data. The MOST concept provides a tailored study of an individual process typically required for a new, innovative design.

Nevertheless, the MOST idea has some challenges, one of which is its requirement to build a new process from ground up. The process development requires a Subject Matter Expertise (SME) in manufacturing method of the particular design. The SME must have also a comprehensive understanding of the MOST system so that the correct parameters are chosen. In practice, these knowledge requirements may demand people from outside of the design discipline and a priori training of MOST.

To relieve the constraint, this study includes an entirely new sub-system architecture that comprises 1) a knowledge-based system to provide the required knowledge during the process selection; and 2) a new user-interface to guide the parameter selection when building the process using MOST.

Also included in this study is the demonstration of how the HLCET and its constituents can be integrated with a Georgia Tech' Integrated Product and Process Development (IPPD) methodology. The applicability of this work will be shown through a complex aerospace design example to gain insights into how manufacturing knowledge helps make better design decisions during the early stages. The setup process is explained with an example of its utility demonstrated in a hypothetical fighter aircraft wing redesign. The evaluation of the system effectiveness against existing methodologies is illustrated to conclude the thesis.

# CHAPTER I

## INTRODUCTION

### *1.1 Problem Definition*

The product design process in general is essentially a serialization of activities where customer requirements are translated into product attributes. These attributes are then used to synthesize a new or derivative product. For complex aerospace systems, this process is time intensive and requires effective communication and knowledge transfer among various subject matter experts. It also requires a very delicate balance among conflicting requirements imposed by difference disciplines. To achieve an optimal design for the given requirements, Multidisciplinary Design Analysis and Optimization (MDAO) is typically utilized where multidisciplinary analyses are brought to a consistent stage and simultaneously optimized with respect to one or more goals. Furthermore, there are multiple stages in the design process, most commonly classified as conceptual, preliminary, and detailed design phases. Each level requires a diversity of analysis fidelities and varying degrees of interactions among the disciplines. Organizations need to decide, at the onset of the project, how much information is needed at each design stage and the major milestones that constitute the design handoffs from one level to the next.

Traditional system design and analysis methodologies tend to overlook some aspects of the product in the area of material and manufacturing alternatives, especially in the early stages where design freedom is great and changes incur relatively low cost.

In conceptual design phase, “a notional set of disciplines in an aircraft design

trade study might include aerodynamics, propulsion, weights, thermodynamics, performance, stability and control, and cost.” [9]. The inclusion of aforementioned disciplines is effective as long as the design is based largely on previous similar products. The problem, however, arises when a dramatic change occurs in the way aircrafts are designed and produced today. Many advancements in material sciences and manufacturing processes helped push aircraft performance beyond limits not achievable in the past. One example is the advent of composite materials that are much stronger and lighter than Aluminum. Composite part designs for primary and secondary structural components can also be combined and tailored to specific loading conditions, thus reducing the need for many post-fabrication processes (e.g. finishing, and assembly). The high stiffness, high strength-to-weight composite material helps increase many performance and aerodynamic characteristics of the aircraft. However, composite incorporations usually come with high penalty in terms of cost and producibility. Many recent failures in aircraft design occur when metallic components are replaced with composite counterparts without significant effort put into the design such that full advantage of the material is realized. Instead, part designs are maintained because of the notion that they are already optimized on previous design with metallic parts. This design practice is synonymous with *black aluminum* design. As a result, more disciplines need to be included in the decision making process as early as possible to understand the true impact of these advancements and take full advantage of them.

There is no more the era of “*performance at any cost*” as described by Charles Saff, a Technical fellow at Boeing, Phantom Works [49]. Hence, new design approaches need to account for customer demands, address a balanced view of performance, cost, producibility, and risk, and support robust design and optimization.

In preliminary design stage, lack of back-and-forth communication between the product and process sides gives the notion of *over-the-wall* practice. A manufacturing

process has to be engineered to comply with the product definitions that are preliminary defined. In most cases, the incompatibility between product and process result in a very expensive rework and project delay. It is no more a matter of finding the design that gives the best performance at the lowest cost, but rather a compromise between difference designs and manufacturing alternatives to find a solution that best serves the interest of customers.

Another possible improvement in the product development process is the lifecycle cost prediction. Lifecycle cost analysis in the conceptual stage is one of the most problematic areas in today's product development. Current costing techniques vary across the aerospace industry and include the use of both proprietary and nonproprietary methods. Most companies retain a traditional cost estimating department that uses experienced professionals who infer new estimates from a large proprietary database. The requirement of rapid assessment of design options in the early stages makes it difficult to move away from weight- and complexity-based estimating techniques, which rely heavily on engineering judgment of experienced individuals. Weight-based cost estimating techniques are insensitive to material variation and manufacturing complexity of equally weighted parts. It is nearly impossible to see the impacts of new technology infusion or advanced manufacturing techniques implementation on a product unless the right complexity factors are used. Another serious deficiency of weight as a primary cost driver is that, in most systems or products, weight is already part of key figure of merit on which the design is assessed. When cost is predicted by weight, the effect is as if weights are counted twice and costs are ignored. [11]

Although the drawbacks can be remedied by introducing higher fidelity analysis tools, caution should be exercised to find the right balance between shortening the design cycle time and optimizing the design solution. This finding also coincides with the recent study by NASA with industrial collaboration on the Cycle Time Reduction (CTR) initiative [53].

## ***1.2 Motivation***

There is a critical need for a new system design framework that provides solution to the aforementioned problems. This thesis is proposing a way to include manufacturing considerations and high fidelity lifecycle cost analysis in a design framework used throughout the design process from conceptual to detailed design. The implementation of the concept is done through Georgia Tech's Integrated Product and Process Development (IPPD) methodology developed within Integrated Product Lifecycle Engineering (IPLE) laboratory.

The IPPD implementation helps eliminate the traditional over-the-wall practice during design handoffs and pave the way to realizing concurrent engineering. Moreover, Robust Design Simulation (RDS) methodology can also be incorporated to facilitate design and simulation to yield an optimal design — a design which directly corresponds to customer desires and disinclines to performance degradations due to noise and uncertainties.

The new design architecture will be created, enabling rapid design tradeoffs and improving confidence in making design decisions. The analysis fidelity can be incrementally increased due to the modularity of the architecture. At the same time, this new methodology should neither reduce the flexibility in making design changes, nor impede the ability to quickly reassess design changes. Finally, this system will also enhance the connectivity between product and process development.

## ***1.3 Objectives and Goals***

The following section lists four research objectives that correspond to the motivation mentioned.

- 1. Create a design framework that revolves around and is driven by customers needs*

First, the customer requirements always constitute the need for a superior product at the lowest possible price, which depends on various economic factors like number of competitors, demand, and cost to the manufacturer. The requirements themselves are sometime vaguely stated. Translating requirements into engineering characteristics requires effective communications and inputs from all disciplinary experts. Structuring the design process around customer needs should reduce the uncertainty in the design direction.

*2. Create a modular and scalable modeling and simulation environment—  
an analysis-oriented environment built from ground up*

Integrating high fidelity analysis tools into existing multidisciplinary design framework is difficult because the developments of these tools took place in a stand-alone basis and did not take into account the compatibility issues when they are interfaced. Information loss during the translation between analyses presents many challenges. Also the amount of architectural changes and time required to establish the proper interactions may be prohibitive. As a result, building a new framework from ground up potentially leads to a better integrated analysis framework and encourages future additions.

*3. Bring in manufacturing-influenced decision support and high fidelity lifecycle cost analysis early in the product development cycle*

When the product characteristics are laid out by the designers, the downstream disciplinary experts then start to analyze the system characteristics against the customer requirements and other constraints. Manufacturing engineers working in the integrated design environment can

proactively participate in the product design iteration by sending feedbacks to influence the design early on. High fidelity lifecycle cost analysis fills in many gaps in decision making process traditionally left open by using only weight-based estimates.

#### ***1.4 Success Criteria***

Successful implementation of this dissertation comprises the following:

- Formulation of an integrated, modular design synthesis and analysis framework that assists design activities throughout product development process
- Implementation of a methodology to create a digital product definition that enhances the data reuse in downstream design activities
- Implementation of a new Hybrid Lifecycle Cost Estimating Tool (HLCET) to facilitate an incremental fidelity improvement from knowledge acquisition throughout product design process
- Comparison of published cost data and those from Hybrid Lifecycle Cost Estimating Tool (HLCET) as a proof of concept
- Solution for a sample design problem using the fully integrated design framework proposed in this thesis
- Comparison of development time, efficiency, and other merits and demerits from existing design methodologies and those of this study



## CHAPTER II

### LITERATURE REVIEW

#### *2.1 Aerospace Design Environment*

Multidisciplinary Design Analysis and Optimization (MDAO) is an essential part in aircraft design due to the complexity and magnitude of disciplinary knowledge involved. Traditional MDAO, as described in [9], and [56] focuses on various aspects of vehicle performance including but not limited to aerodynamics, propulsion, weights, thermodynamics, performance, stability and control, and cost.

Tight integration among analysis tools makes it possible to perform simultaneous optimization of many design aspects against one objective function, e.g., lowest weight while meeting mission or performance requirements.

Recently, there has been an increased emphasis on MDAO that incorporates manufacturing aspects [49], as well as requirement for a better lifecycle cost prediction method to reduce future cost of products, processes, organization, and associated business risks [21].

Chae et al [10] uses LCC from Bell PC-based model and part-level manufacturing cost/time as an objective function in the optimization process. Bao et al [2] includes material, manufacturing process, and assembly process as part of an objective function for the optimization. Bao has shown how this incorporation in the early conceptual design phase can help differentiate various wing material and structural concepts that would have been difficult with just weight and weight-based cost considerations alone.

Will Marx [38] introduces the concept of integrating design and manufacturing optimization during the early design process by creating a framework that enables

the transfer of manufacturing knowledge to the designers. Will Marx's research incorporates many useful tools for preliminary design of aerospace systems. However, there are several pitfalls and more room for improvement opportunities, one of which is the reduction of data structure complexity. Several tools are tied together to enable automation and automatic knowledge transfer, but this adds complexity to the framework, which prevent typical users to configure the underlining assumptions for their specific problem. Another improvement area is to increase the flexibility of the knowledge database part of the framework which uses CLIPS as knowledge repository and inference engine. The coding syntax is primitive and not very intuitive which makes it hard to identify the right part of the knowledge and add new knowledge or modify the existing one in the correct format. Marx incorporated top-down lifecycle cost tool (ALCCA) [40] and bottom-up, knowledge-based expert system manufacturing cost estimate (CLIPS) [48] in his design framework. This approach to LCC estimate is very promising, but there are several problems. CLIPS algorithm is primitive, and all the knowledge pertaining to manufacturing process has to be reconstructed in a specific format. Finally, the framework is not flexible enough to move away from weight-based cost analysis — and progress toward process-based as time goes and more knowledge accumulated. This work however has laid out foundation for this dissertation.

Marx's thesis focuses on the paradigm shift from the aluminum age to composite age that drove companies to create their own techniques to design, develop, and manufacture composite parts. As a result, the need to protect their intellectual properties has been a common place in order to gain competitive advantage. Adding insult to the injury, the highly protective nature of the business means that there is no one tool that can accurately predict the cost of composite manufacturing since most are developed and built from vastly difference origins. This is evidenced by an example

of the two studies, first by Northrop Corporation Aircraft Division in 1976 who created a composite fabrication cost estimating tool called Advanced Composite Cost Estimating Manual (ACCEM) [34]. Later in 1979, Grumman Aerospace Corporation (GAC) [46] applied ACCEM to estimate their current composite parts which proved to be inaccurate. Even though, this problem becomes less prominent in the today ever more automated and standardized manufacturing processes that stems from decades of trial-and-errors and industrial standard improvements. Even so, there is still a need for a tool that can tailor to company specific scenarios and be used to realistically estimate the lifecycle cost of a new product.

## ***2.2 Cost and Economic Analysis***

### **2.2.1 Classification**

Cost analysis plays a key role in any system design. It is a study to quantify one or more aspects of cost of a future system. Malstron [37] lists many purposes of cost estimating throughout product lifecycle including, quotations check from suppliers, aid the make-or-buy decision, evaluate product design alternatives, assist long-term financial planning, help control manufacturing cost, and provide standard for production efficiency. The area where cost analysis can most add values is probably during the early design of a product where 70% of its cost is determined [20].

There are many kinds of cost analysis methodologies, varying from a rough estimation of a future system based on similar existing systems to very detailed analysis aimed to determine the actual cost incurred within a project.

Makepeace [36] classifies cost models in several ways; the level of sophistication (simple to complex), function served (budgetary use to long-term planning), likelihood of repetitive use (one time or general use), and context of the subject matter intended to represent (part- to system-level representation)

In the design and engineering community, cost estimating techniques are usually

categorized as: intuitive, analogical, parametric, and analytical methods. The simplest form of cost analysis is intuition where the analyst estimates the cost based on his or her intuition and past experience. Analogical method utilizes cost comparison with similar products with known costs. An example of cost estimating technique that combines intuition and analogy based approach is the Delphi method as described by Isom [28], which systematically gathers expert opinions using questionnaires, then rates and compares the results to quantify the effect of composite usage on the system cost. Parametric methods estimate the cost of a product from parameters that are used by designers, usually represented by simple equations. Parametric models typically rely on empirical data to construct Cost Estimate Relationships (CERs) between dependent variables (cost, or time) and one or more independent variables (weight, speed, range, part dimension, etc.). Finally, analytical methods, like Activity-Based Costing (ABC) decompose the work required into elementary tasks, and then assign cost/time to each activity. The ABC methods provide more accurate and traceable cost estimation because they trace the cost via activities performed. Properly use, this method can aid in production streamlining and elimination of non-value-added activities throughout the enterprise. It can also be used to estimate the cost of design and development activities, a practice commonly used in accounting [4] and [22].

The key difference between parametric and analytical method is the type of input parameters required. Parametric method usually requires parameters from the designers, whereas analytical model uses the parameters most relevant to the particular activity in question. The benefit of the parametric method is that analysis depends on few design parameters, such as weight and speed, and the changes can be made quickly when new design iteration is performed, a quality most suitable for conceptual design environment. On the other hand, analytical approach, while giving more accurate result, requires comprehensive knowledge of the activity or product in question. Any changes requires tedious rework.

The following paragraphs describe available tools and methodologies in these two areas.

### **2.2.2 Parametric Cost Estimating Techniques in Product Development Environment**

Effective Lifecycle Cost (LCC) estimates must be able to accurately predict non-recurring and recurring product costs plus the operation and support costs [38], since they comprise the majority of the LCC

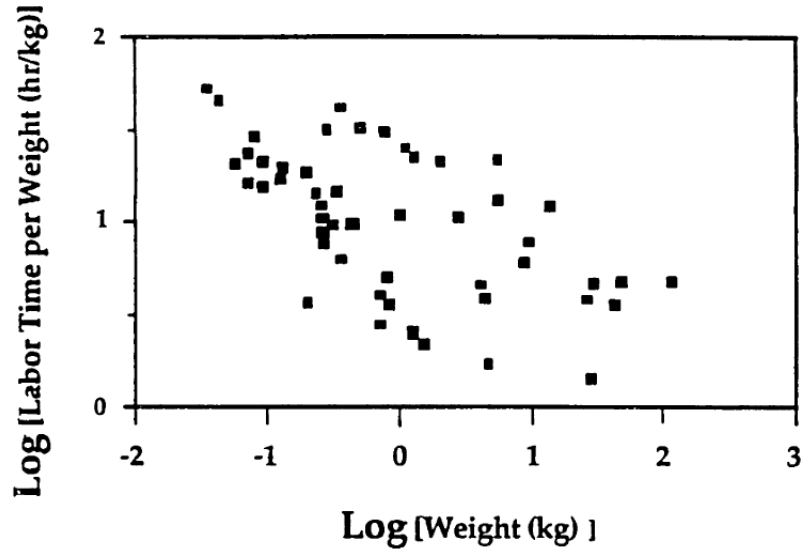
In the aircraft design environment, weight-based parametric cost estimating techniques are typically used because of its consistency and direct correlation to product design parameters. This techniques conveniently estimate cost from readily available design parameters and utilize historical data of previous similar aircrafts to generate relationship between basic product parameter, i.e. weight, and cost.

The simplest form of CER is the linear regression of a design parameter and resulting cost. Power law relationship is also used when the relationship is non-linear. A more complicated CER depends on the multiply regression analysis called Response Surface Equation (RSE) [2].

One example of the weight-based parametric cost estimating models is Bell PC-based cost model [5]. It uses a top-down cost allocation approach to estimate rotorcraft LCC cost. The analysis process starts by taking vehicle gross weight and then allocating component weights based the type of vehicle application and operational environment. The component costs are then calculated using Cost Estimating Relationships (CERs).

ALCCA and its variations, MALCCA and TRLCCA [40] are another examples of weight-based models. They are similar to Bell PC-based model in their functionalities, but applicable for commercial fixed-wing, military, and tilt-rotor aircraft respectively.

Tailored Cost Model (TCM) [3] is another comprehensive LCC model developed by NASA. The model breaks down cost elements into corresponding lifecycle phases



**Figure 1:** Relationship between Labor Hours/kg and Part Weight for Composite Aerospace Parts

namely Research, Development, Testing and Evaluation (RDT&E), Production, Support Investment, and Operation and Support. Then each vehicle component is assigned costs based on the lifecycle phases they incurred. The equations are of simplest form with one independent parameter per cost category.

The accuracy of parametric methods however heavily depend on how closely the underlining assumption and historical database these equations are drawn upon [44]. Parametric models are very process and company specific as reported by Gutowski et al [23]. The report shows the reducing trend in labor hours as part weight increases for the hand lay-up process. Figure 1 shows the entire data set from three manufacturing companies that produce aerospace composite parts using hand layup. A low coefficient of determination was observed for the linear fit of combined data point. On the other hand, a much better fit can be observed when separating the data points by their corresponding company of origins. This evidence shows that parametric models are highly dependent on the database in which the CERs are created, and should not be used without thorough understanding of the model.

There are various publicly available sources of aircraft and its component CERs.

Resetar et al [47] provides comprehensive CERs for fixed-wing aircrafts including MV-22 Osprey. Large et al [33] provides database of jet fighter aircraft component costs based on vehicle weights and speeds.

### **2.2.3 Analytical Model and Process Driven Cost Estimates**

Another domain of cost estimation is determining cost to manufacture parts. Currently there are two types of estimating techniques — Parametric and Detailed cost estimations [44].

In the 1980s, Kaplan and Cooper of Harvard Business School [15] developed Activity-Based Costing as an alternative to traditional accounting techniques. It has become popularized in both business and manufacturing applications [14, 13, 8].

Spedding et al [52] applied discrete event simulation software called WITNESS to model manufacturing sequence of a semiautomated Printed Circuit Board (PCB) process. The processing time and resources consumed were assigned to each activity by observation of the actual assembly line. The cost incurred from each activity was then calculated by multiplying the processing time with “Cost Rate” appropriated for each activity, plus the cost of resources consumed. The model further incorporated Monte Carlo simulation based on the observed distribution of processing time to strategically place quality control stations to minimize cost of rework.

Northrop Corporation Aircraft Division developed a software tool that estimates cost of composite part manufacturing called Advanced Composite Cost Estimating Manual (ACCEM) [34, 35]. The same model was later implemented by Grumman Aerospace Corporation (GAC). The report laid out several merits and demerits of the method, and suggested some improvement areas.

#### *2.2.3.1 First-Order Models*

The first-order analytical cost estimating model was proposed in 1994 [24]. The estimation mimics the response behavior of the first-order dynamic systems to step

velocity input. It has been observed that many manual and automated manufacturing processes follow the same behavior as that of the first-order response.

Boa [2] applied this concept to the optimization of a generic wing design. The incorporation of manufacturing specific parameters like material, manufacturing and assembly process as part of the objective function produces a more optimal design point than just the weight and weight-based cost alone. It allows designers to take into account manufacturing parameters in the design process, hence increases design flexibility.

### *2.2.3.2 Information-Based Models*

Collopy et al [11] applied Shannon's theory of information to cost estimation of machined part. He and his colleagues created an information-based cost estimating model that calculates manufacturing costs based on the amount of information stored within CAD drawing. As a result, the designers instantly see the cost implication of the design changes by altering CAD model.

Muter [44] in his thesis suggested a way to measure part information by counting all the bits required to describe the part in the drawing. The relationship between manufacturing time and information content can be constructed using simple linear regression. One limitation of this method is that it requires detailed part design in order to estimate cost/time. It renders ineffective for early design phases where product information does not contain complete fabrication and assembly related information.

### *2.2.3.3 Other Advanced Analytical Models*

One of the more advanced, hence more application specific, types of cost model can be described as a generative cost model which is based on a feature-based analysis of the part design. They require detailed information in order to produce a process plan which determines cost.



Kiritsis et al [32] developed Petri Net model that represents the sequence of manufacturing process of mechanical work piece with moderate complexity. The associated cost incurred on each state and transition in the model can be assigned to get the total cost. Given feature-based description and associated alternative manufacturing operations for each feature together with required resources, he also developed a new PP-net model (Process Planning net) to enhance original Petri Net. It extends the existing concept by virtue of defining the states and transitions properties that allow the calculation of costs.

Object-oriented approach to estimate manufacturing cost has also been applied to some manufacturing environments [58, 55, 54].

#### **2.2.4 Summary of Literature Review**

All LCC models in the early design stages are limited to weight-based approaches since information about the product and process is very limited. As a result, the cost data in these stages provide little or no connection to specific material or manufacturing process being used. On the other hand, most ABCs are geared toward process improvement and quality initiative, not for conceptual work.

There is an opportunity to combine the advantages of the simple yet rapid development of top-level cost modeling with flexibility and accuracy from complex estimating tools like Process-based and Activity-based cost models. A successful integration can yield a quick, simple cost modeling tool that can be expanded and tailored to include more meaningful information as it becomes available along the product development process, while simultaneously limit the complexity and time-consuming works required by detailed analyses. The result is a better and more accurate top-level LCC model that can be sustainably advanced along the product design maturity cycles.

From the literature search, there is very little evidence of the ABC application in

aerospace engineering community, even less so in early design stages. The Process-based cost models are regarded as a natural extension to existing weight-based approach, but none of the studies actually combined both methodologies in a single framework.

Evidently, there is a need for a hybrid cost estimating tool that takes advantage of the simplicity of weight-based approach and has the ability to increase analysis fidelity by incorporating the process-based and activity-based approaches as design matures.

## CHAPTER III

### HYPOTHESES AND RESEARCH QUESTIONS

#### *3.1 Research Questions*

There are needs for a better, more coherent product and process development framework to help engineering organizations focus resources on developing and determining the best design alternatives and optimal course of actions throughout the product development process. The framework is created to facilitate ad-hoc integration of various fidelity analysis tools that are suitable for a particular design stage. Two decision support analyses to be emphasized in every design phase are lifecycle cost estimation and manufacturing consideration since affordability, manufacturability, and profitability are becoming more critical to the business success in the globally competitive market.

Based on the above needs, a series of research questions identified below should be addressed:

1. How much does lifecycle cost analysis influence design decision?
2. What are the limitations in today's cost analysis methodology as applicable to early design activity?
3. How can these limitations be eliminated or reduced?
4. How can a cost analysis framework be developed that aid designers in high fidelity cost analysis?
5. How can producibility considerations and manufacturing knowledge be captured and used in the early design process?

6. How does high fidelity lifecycle cost estimation increase chances of arriving at an optimal design?

### **3.2 Hypotheses**

The following hypotheses answer the aforementioned research questions and provide a framework for systematic aerospace system design.

*Hypothesis 1:* If process characteristics of composite design are considered in lifecycle cost estimation, then certain design characteristics that yield cost and time benefits over traditional metallic design can be found – a task that cannot be easily achieved with weight- and complexity-based parametric approaches.

*Hypothesis 2:* If the effects of material and process variations on product lifecycle cost are to be captured, the weight-based cost analysis approaches cannot be used since they do not provide enough sensitivity required. To achieve the added sensitivity, process- and activity-based cost estimating approaches must be used to be able to capture product and process-related impacts.

## CHAPTER IV

### METHODOLOGY

This chapter discusses the advanced system design and analysis methodology and how it can answer the research questions posed in the previous chapter. The methodology is divided in two parts — the Hybrid Lifecycle Cost Estimating Tool (HLCET) developed in this dissertation as a new approach to cost engineering, and an Integrated Product and Process Development (IPPD) approach to complex aerospace system design that will be used as a framework to provide necessary flow of information required for the costing activities throughout the product development process. These developments will demonstrate how the hypotheses can be addressed.

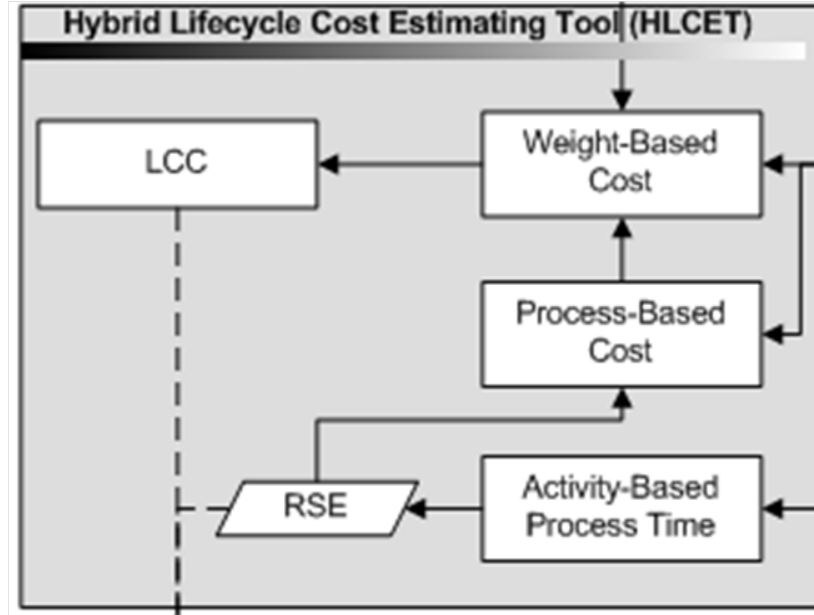
#### *4.1 Hybrid Lifecycle Cost Estimating Tool (HLCET)*

The cost models that exist in the conceptual and preliminary design such as parametric models are too simplistic and do not have enough fidelity required for design trade studies that go beyond traditional designs that were used to generate the CERs. On the other hand, detailed engineering bottom-up models are too complex and required detailed product and process characteristics that is prohibitively time-intensive to be useful on their own. The major deficiency of this type of top level cost analysis, as mentioned in literature review, is that their CERs are typically generated from database of previous metallic parts or components. To estimate cost of product with new materials and processes, engineers typically resort to some established complexity factors that can be found from literature. An example of a comprehensive cost factor information can be found in RAND study on various fighter aircrafts that has composite applications in the design [47]. This type of workaround for composite part cost prediction only accounts for general factors related to higher raw material

and support material, more labor intensive processes, higher capital investment and etc. It does not; however, provide sensitivity with respect to design complexity, and assembly consideration resulting from the use of composite. As a result, design tailorness, consolidation of parts into module, and the reduction of assembly requirements that potentially add value to the design cannot be properly accounted for with this technique.

An integrated architecture for cost engineering called Hybrid Lifecycle Cost Estimating Tool (HLCET) developed in this thesis is an approach to integrate high fidelity estimating techniques like process-based and activity-based into a hierarchical lifecycle cost model to increase the sensitivities of the top-down LCC model to changes or alternatives evaluated at the part or component level where tradeoff is required. Instead of applying arbitrary complexity factor to existing CERs to account for difference material or process selection, high fidelity tool can be used to related product and process parameters specific to the design to generate new result that can then be used to update top-level cost result. This new addition introduce sensitivity to material selection and manufacturing processes that come from actual design parameters as oppose to the traditional technique than depend on some fixed factors to quantify the deifferences, but the sensitivity of the result still come from weight alone. The resulting integration allows detailed product and process parameters primarily used only during detailed design to be brought earlier into the design process. Figure 2 provides conceptual view of the HLCET framework.

The use of cost models concurrently with product and process design brings about many challenges, including the issues of data fidelity, analysis time and mapping of product and process design variables. The following paragraphs discuss the tools used and integration methodology.



**Figure 2:** Hybrid Lifecycle Cost Estimating Tool Framework

#### 4.1.1 Weight-based Parametric Lifecycle Cost Model (WbPL)

A newly developed costing methodology starts off with weight-based parametric model. The approach to analyze overall lifecycle cost of the system is adopted from the parametric model called Tailored Cost Model (TCM) developed by Mr. Greg Bell at McDonnell Douglas [3]. Cost Estimate Relationships (CERs) for the parametrically driven cost elements are developed from large historical databases or selected from the public domain models [30], [6], [19], and [7]. The Tailored Cost Model (TCM) provide mechanism for creating independent cost estimates that can be used to provide “should cost” target for functional organization and to support conceptual design studies. The cost elements are integrated into a MIL-STD-881 [25] type Work Breakdown Structure (WBS)

The model provides detailed breakdown of total ownership cost elements by the product lifecycle phases namely RDT&E, Production, Support Investment, and Operation and Support costs. The RDT&E and Production costs are determined based on SAWE-RP8 group weight statement [50] and others programmatic assumptions as

the independent variables. The CERs are exponential function of the form:

$$CostElementDV = A * (IVTC)^B$$

where:

$DV$  = Dependent Variable

$A$  = Intercept Value (Log-Log)

$IVTC$  = Independent Variable Technical Characteristic

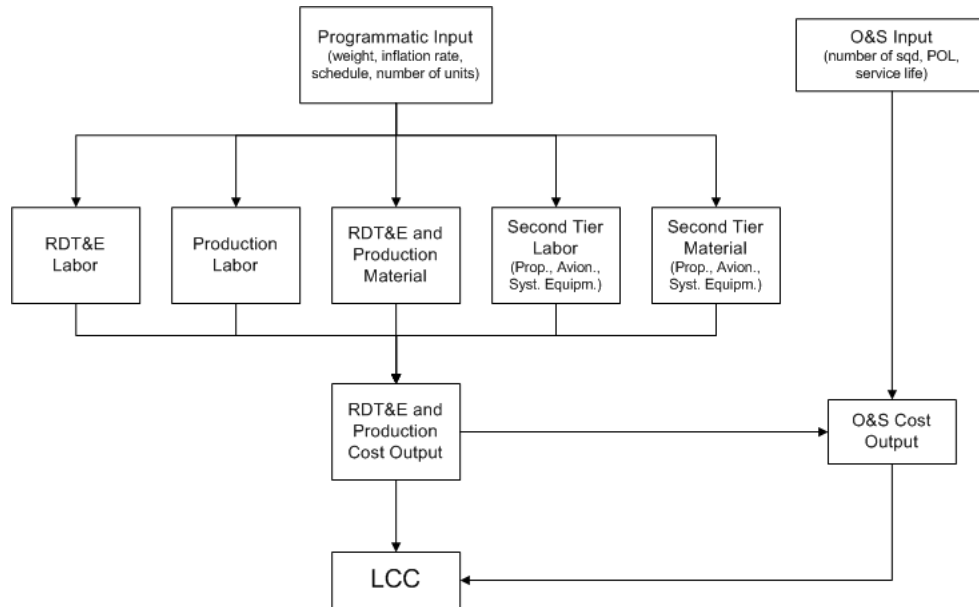
$b$  = *Slope(Log – Log)*

Operational Flight Software (OFS) associated with the avionic architecture is estimated by breaking the total system into component functional modules (Navigation, Communication, Flight Control, Display Processing, Fault Management and Reconfiguration, Map Processing, and etc.) Each functional module was sized in thousands of lines of deliverable source instructions (KDSI) by analogy. Key assumptions for RDT&E calculation are technology factor, test requirements, year of introduction, and complexity factors. Major assumptions for production cost calculation, in addition to those of RDT&E are learning curve slopes, complexity and technology factors, production schedule, and lot size. Operation and support cost structure are modeled using Cost Oriented Resource Estimation (CORE) model published in AFR-173-13 [ref]. Programmatic inputs such as fleet size, force structure, aircraft per squadron, service life and flight hours are required in addition to group weight statement. Figure 3 depicts the Tailored Cost Model structure.

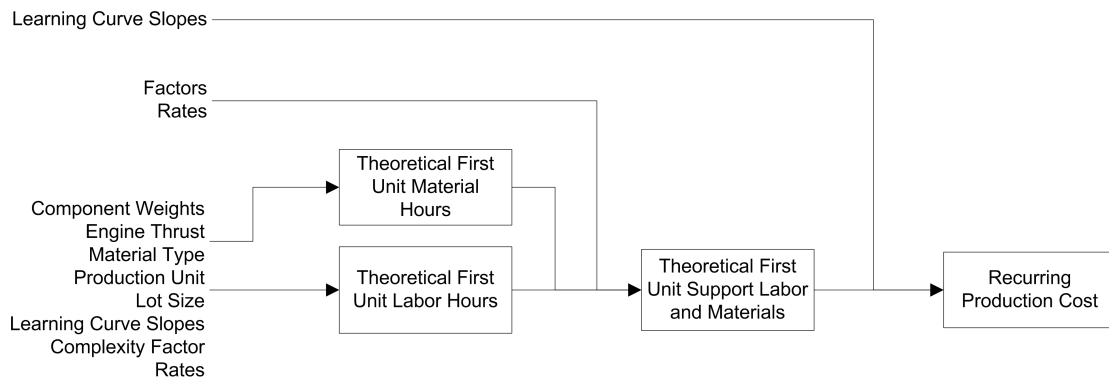
#### 4.1.1.1 *Recurring Production Model*

Basic factory labor (also called touch labor) includes manufacturing efforts and processes required to fabricate parts and assemble them to form an airframe. Also included are efforts to integrate, assemble, and checkout supplier. TCM uses a series of weight dependent CERs to estimate factory manhours for an idealized first unit





**Figure 3:** Tailored Cost Model Structure

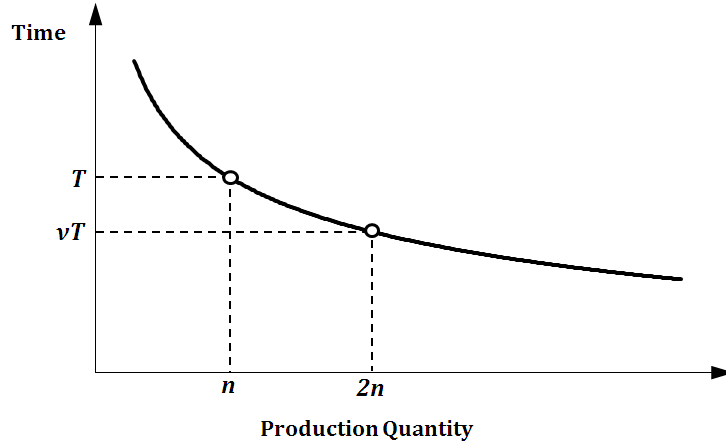


**Figure 4:** Tailored Cost Model Production Cost Model

(called  $T1$ ). Factory effort to produce subsequent units is estimated by applying learning curves slopes. Figure 4 shows the manufacturing cost module available at the system level.

#### 4.1.1.2 Learning Curve Slopes

*Learning curve*, as referred to its utility in manufacturing, is a representation of the concept that the more units of a product that are manufactured, the less time it takes to make an individual unit. This improvement in efficiency can be quantified by observing the constant percentage reduction in time required over successively



**Figure 5:** Relationship Between Production Time and Quantity

doubled quantities of units produced, called *the rate of learning or learning curve slope*. The effect of learning improvement can be attributed to increase in worker's skill levels, improved production methods, and/or better production planning.

Learning curve analysis is used to predict the cost of making the  $n$ th unit given the time and cost of making the first unit. In many instances the first unit cost or time is calculated based on a parametric equation, the result of which is referred to as theoretical first unit (TFU). Figure 5 demonstrate how the learning slope  $\nu$  is calculated. When the production unit doubled from  $n$  to  $2n$ , the labor hours required reduces from  $T$  to  $\nu T$ .

Wright's learning curve model [57] was introduced in 1936 to calculate the cost to product the  $n$ th unit given the cost of first unit and the learning curve slope. The learning curve unit function is defined as follows:

$$y_n = T_1 n^\beta$$

where:

$y_n$  = the time (or cost) per unit to produce the  $n$ th unit

$n$  = the number of units produced

$T_1$  = theoretical first unit time (or cost)

$$\beta = \text{Log}_2(\text{Slope})$$

Reduction in learning performance beyond the two-hundredth unit is often observed in industry [3]. This effect can be accounted for through the use of more shallow slopes. The production learning curves are applied to labor hours to produce the aircraft. The material learning curves are applied for material costs including raw materials, casting/forgings, and purchased parts required to fabricate and assemble airframe structures.

It is also useful to calculate a cumulative total hour of a production lot. The cumulative manufacturing hours for a given number of units is can be estimated using the following approximation:

$$T_n \approx T_1 n^{\beta+1} / \beta + 1$$

where  $T_n$  = the cumulative time (or cost) to produce  $n$ th unit

To estimate cumulative production hours for a specific lot with first unit number  $f$  and last unit number  $n$ , the above equation can be modified as follow:

$$T_{f,n} \approx \frac{T_1 n^{\beta+1}}{\beta+1} - \frac{T_1 (f-1)^{\beta+1}}{\beta+1}$$

Up to this point, TCM is streamlined and restructured for user-friendliness; however, the underlining assumptions are that of *more weight equals more cost*. The reader is reminded that this relationship only applies to traditional metallic parts. The same cost trend for composite part may not be valid; most likely the relationship is not proportional to weight alone. Composite application takes advantages from its additive nature - the ability to tailored ply thickness and orientation are examples of these benefits that also invalidate the traditional weight dependent nature of metallic part. As a result, a more detailed, weight independent, manufacturing cost analysis may be required. Advanced Composite Cost Estimating Model (ACCEM) is one of

the process-oriented cost models designed to estimate composite manufacturing cost using part information, i.e. length, area, fiber direction, etc. This tool is used to replace TCM result on specific parts or components that required more accuracy.

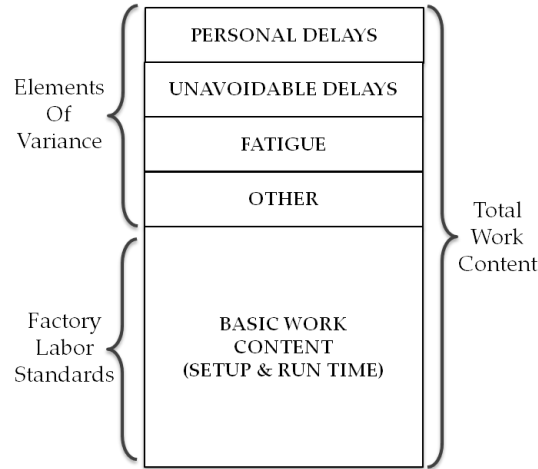
It is important to realize that a majority of LCC comes from recurring manufacturing costs. These costs are directly related to product design and can be controlled by the designer. The process-based cost model may be more relevant especially when the underlining assumption for cost analysis is not met, i.e. when composite material is used.

#### **4.1.2 Process-based Recurring Manufacturing Model (PbRM)**

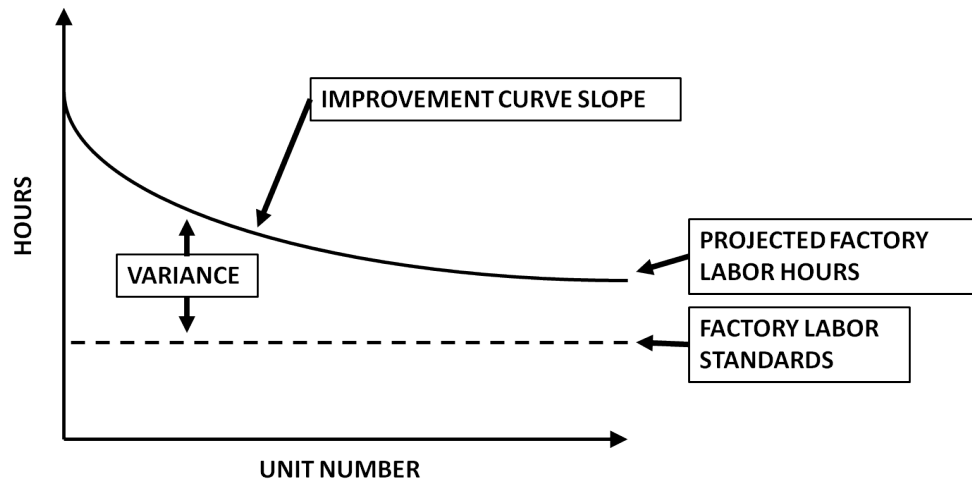
In 1976, Northrop Corporation, Aircraft Division developed a computerized methodology for estimating the recurring costs associated with fabrication of advanced composite parts called Advanced Composite Cost Estimating Manual (ACCEM). It was one of the first of its kind. The emerging new and advanced technologies in composite manufacturing resulted in the need for a reliable historical cost database for use within the government and industry for cost estimating, tradeoff analysis, allocation of research and production funds, and pricing.

The ACCEM utilizes Industrial Engineering Standards equations to calculate the pure labor standard hours associated with the detail fabrication operations. The Standard Hours are defined as the “number of hours a skilled worker would take in completing a given job under normal conditions. Standard hours are computed by using time and motion studies, and are used as a measurement in standard costing” [43]. It then applies another estimating technique to account for elements of variance, such as, fatigue, waiting time for tools and materials, attention to personal needs, etc. Figure 6 depicts the total work content of factory labor.

The factory labor hours at specified units of production can be estimated by the application of appropriate variance factors and improvement curve slopes to the



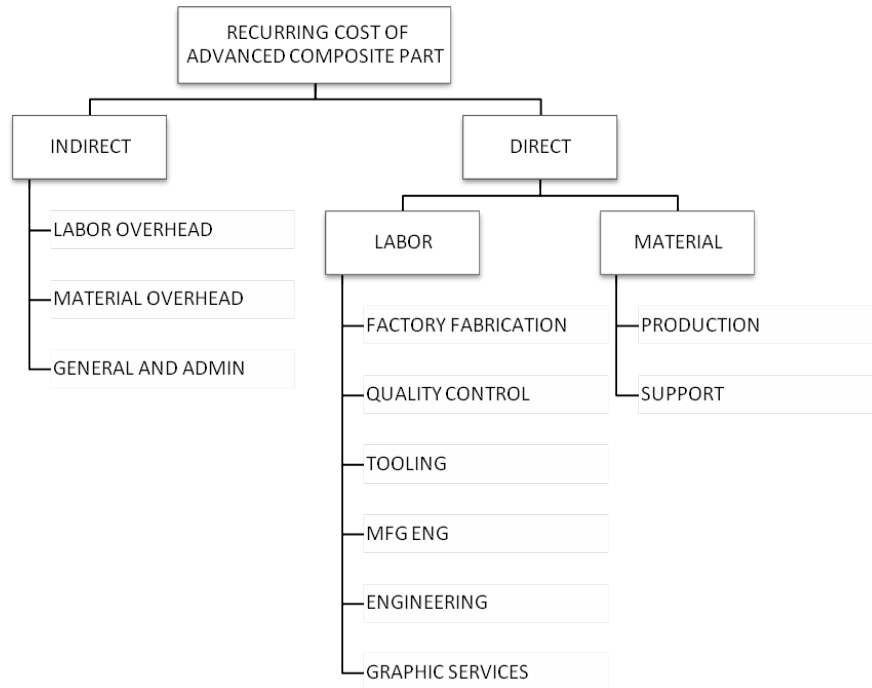
**Figure 6:** Total Work Content of Factory Labor



**Figure 7:** Estimating Factory Labor Hours

standard hours. The procedure for applying these variances is illustrated in Figure 7.

The scope of the estimation only covers the recurring costs associated with fabrication of composite parts. These costs are highly sensitive to design and manufacturing processes and provide a responsive criteria for evaluating the cost effectiveness of these parameters. Recurring costs include Factory Fabrication Labor, Support Labor Functions for Engineering, Quality Control, Tooling, Manufacturing Engineering, and Graphic Services. Production and Support Material indirect charges include Labor and Material Overhead and General and Administrative costs. These elements are

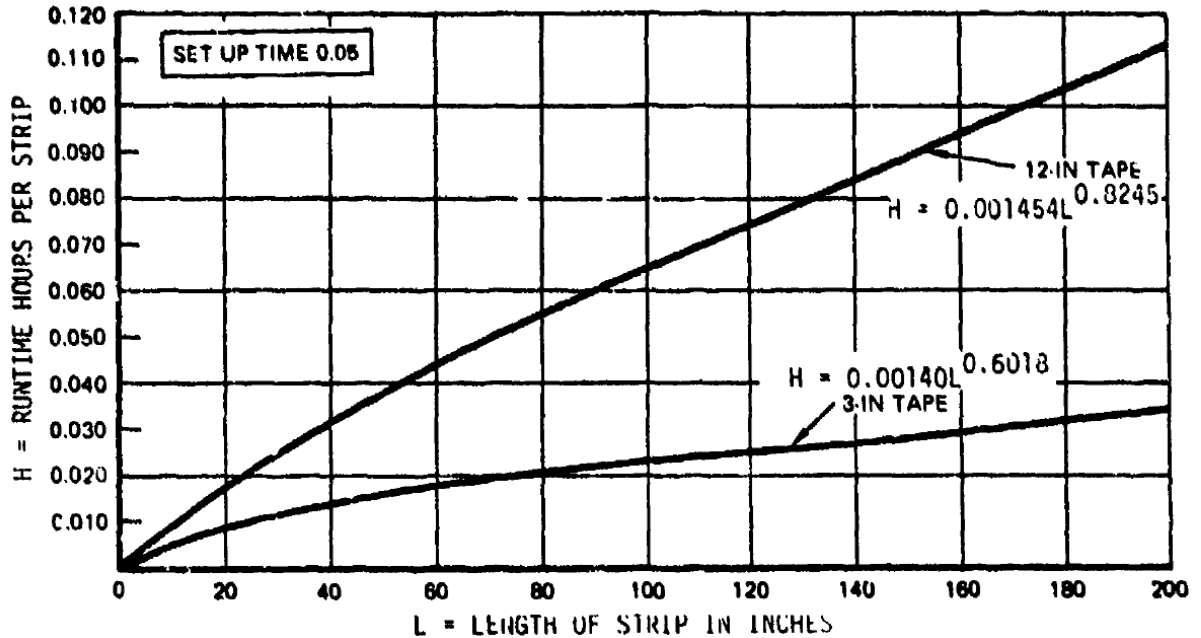


**Figure 8:** Recurring Cost of Advanced Composite Part

illustrated in Figure 8.

The factory fabrication processes covered in this methodology are grouped into four major categories: Layup, Honeycomb Core Operation, Part Consolidation, and Finishing.

Detailed definitions of part, such as geometry and material composition, are used as inputs to estimate the standard hours for activities performed during layup, core operations, part consolidation, and finishing. The inputs are then fed into standard hours estimating routine to solve the appropriate detail Industrial Engineering Standards equations. The labor hours required to complete a process is directly a function of part geometry. Figure 9 demonstrates the relationship between standard hours for manual composite layup as a function of part length and tape width. This fact that labor hours are estimated from process-dependent parameters makes it possible to include part complexity, and process alternative considerations in the lifecycle cost analysis.



**Figure 9:** Standard Equations for Manual Layup of 3" and 12" Unidirectional Tape

Figure 10 is an example of standard equations for various techniques for composite layup including manual layup, machine assisted hand layup, and automated layup processes.

The estimates of direct factory labor hours are developed through the application of appropriate variances to the standard hours at specific production units.

Finally, the Support Functions estimating routine calculates additional recurring support functions associated with the fabrication of an advanced composite part. These estimating relationships cover labor functions as well as support material cost including Engineering, Tooling, Manufacturing Engineering, Quality Control, Graphic Services, Support Materials, and Manufacturing Allowances.

The next activity of interest is to integrate the calculated manufacturing labor hours from process-based model to existing lifecycle cost calculation. The fact that the top level weight-based model calculates component costs based on theoretical first unit labor hours makes it possible to directly supplement the detailed manufacturing labor hours to the component manufacturing TFU. The only discrepancy between

2.1.1.7 SUMMARY OF LAYUP STANDARDS

BASIC DEPOSITION

<u>DETAIL ELEMENTS</u>	<u>SETUP</u>	<u>RUNTIME</u>	
CLEAN LAYUP TOOL SURFACE		0.000006A	(L1)
APPLY RELEASE AGENT TO LAYUP TOOL SURFACE		0.000009A	(L2)
POSITION TEMPLATE (MYLAR) ON TABLE AND TAPE DOWN		0.000107A <sup>0.77006</sup>	(L3)
PLY DEPOSITION			
MANUAL - 3" TAPE	0.05	0.00140L <sup>0.6018</sup>	(L4)
- 12" TAPE	0.05	0.001454L <sup>0.8245</sup>	(L5)
- WOVEN MATERIAL	0.05	0.000751A <sup>0.6295</sup>	(L6)
HAND-ASSIST - 3" TAPE	0.10	0.000368L <sup>0.8446</sup>	(L7)
- 12" TAPE	0.10	0.001585L <sup>0.5580</sup>	(L8)
CONRAC AUTO. (720 IPM)	0.15	0.00063L <sup>0.4942</sup>	(L9)
(360 IPM)	0.15	0.00058L <sup>0.5716</sup>	(L10)
TRANSFER PLY FROM TEMPLATE TO STACK OR LAYUP TOOL		0.000145A <sup>0.6711</sup>	(L11)
TRANSFER STACK TO LAYUP TOOL		0.000145A <sup>0.6711</sup>	(L12)
CLEAN CURING TOOL SURFACE		0.000006A	(L13)
APPLY RELEASE AGENT TO CURING TOOL SURFACE		0.000009A	(L14)
TRANSFER LAYUP TO CURING TOOL		0.000145A <sup>0.6711</sup>	(L15)

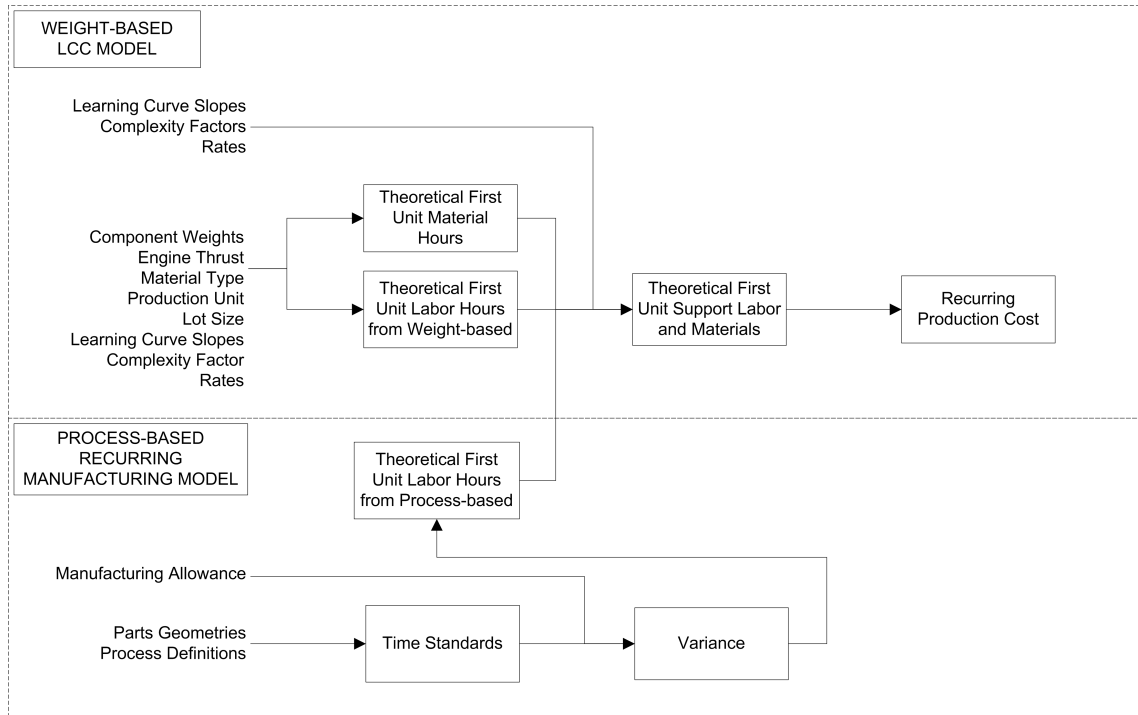
WHERE:

A = Area of ply, or greatest ply area of stack or layup, in square inches

L = Length of ply strip, in inches

Figure 10: Manual Composite Layup Process Standard Hour Calculation Routine





**Figure 11: ACCEM Analysis Diagram**

the two models is that top-level model estimate group costs from group weights, also called component weight (e.g. wing group). On the other hand, process-based manufacturing model works on the part level (e.g. wing skin panel). As a result, an intermediate step to subtract part weight from the component weight is necessary in order not to double the calculation. The Composite Feasibility Analysis (CFA) module is created and designed to manage part-level manufacturing labor calculation by constructing the Manufacturing Bill of Material (MBOM) that includes parts subjected to process-based calculation, and at the same time, keep track of total weights being built up. The total weight is then used to subtract from the component weight at the top level. Figure 11 illustrates the linkage between weight-based lifecycle cost model and process-based manufacturing labor model.

CFA module also provides the user with a set of prescribed composite manufacturing process models as well as materials type compatible with the process being selected. The built-in Knowledge Based System (KBS) gives the user the feasibility

of the selection (a combination of material type, process model, and production rates) through a score to determine the level of confidence. Selection within the range of existing processes and material types will generate a high confidence level, which in turn, give a better estimate result. On the other hand, selections that are not within the range of existing model in KBS produce a low level of confidence. More accurate model may be required, or large contingency in the results may be included.

The nature of process-based estimates is that it requires more detail inputs that are specific to part geometry and manufacturing process, rather than just part weight as in weight-based cost analysis. To acquire the detailed information about the part, Computer Aided Design (CAD) tool may be used to acquire information necessary.

#### **4.1.3 Activity-based Time Measurement Model (AbTM)**

The Time Measurement system being used in this research is Maynard Operation Sequence Technique, MOST. It is a method by which a chain of activities is constructed from elementary tasks (building blocks). Then, the total time required to complete the process is calculated once all the parameters required are identified. There are four systems within MOST; BasicMOST, MiniMOST, MaxiMOST, and AdminMOST. The applicability of each system depends on the application. In this work, MaxiMOST is the most suitable system to be used for estimating highly complex, long cycle time, and non-repetitive processes such as the ones typically found in the aerospace manufacturing and complex system of systems manufacturing communities, such as manual composite constructions.

The MaxiMOST sequence models provide the analysis of movement of objects. It has been determined that three sequence models are needed for the analysis of long-cycle, manual activity namely, part handling model, tool use model, and machine handling model. A full understanding of individual parameter definitions is required to properly index each parameter. The correct index value is assigned as a subscript

to the appropriate parameter. When the entire sequence model (operation) has been indexed, the time in Time Measurement Unit (TMU) is calculated by adding the index values for each sequence model, applying a frequency if appropriate, and multiplying the total by 100. The conversion from TMU to actual time is done through the following simple relationship;

$$1\text{hour} = 100,000\text{TMU}$$

MaxiMOST can be used to construct new manufacturing step by filling out the form that will allow for the calculation of total processing time. It is possible to construct a process that require multiple workmanships, as well as process step that repeated more than once. Excel-based macro spreadsheets are created to replace manual form-filling operations and calculations. The list of all operation in an assembly or fabrication sequence can be populated in a single sheet. Then, MaxiMOST index values are assigned next to each operation sequence which will then be used to determine its actual standard time. The sum of all the standard time represents total standard time of the particular manufacturing sequence. Figure 12 illustrates the linkage between process-based manufacturing model and activity-based standard time calculation.

To make sure that all the step are included, virtual manufacturing software, like DELMIA could be used to simulate the sequence of operation to visualize the sequential operations that must occur in order to complete the sequence of operation. It can also help determine the possible range of parameter variations due to product variability, plant layout, and other variations pertaining to shop floor activities.

It is possible to create Response Surface Equations (RSEs) that represent approximate behaviors of the manufacturing enterprise. Many complex and time-consuming analyses can be simplified. In this case, the procedure of predicting the manufacturing time based on activities required to produce the part can be simplified with RSE.

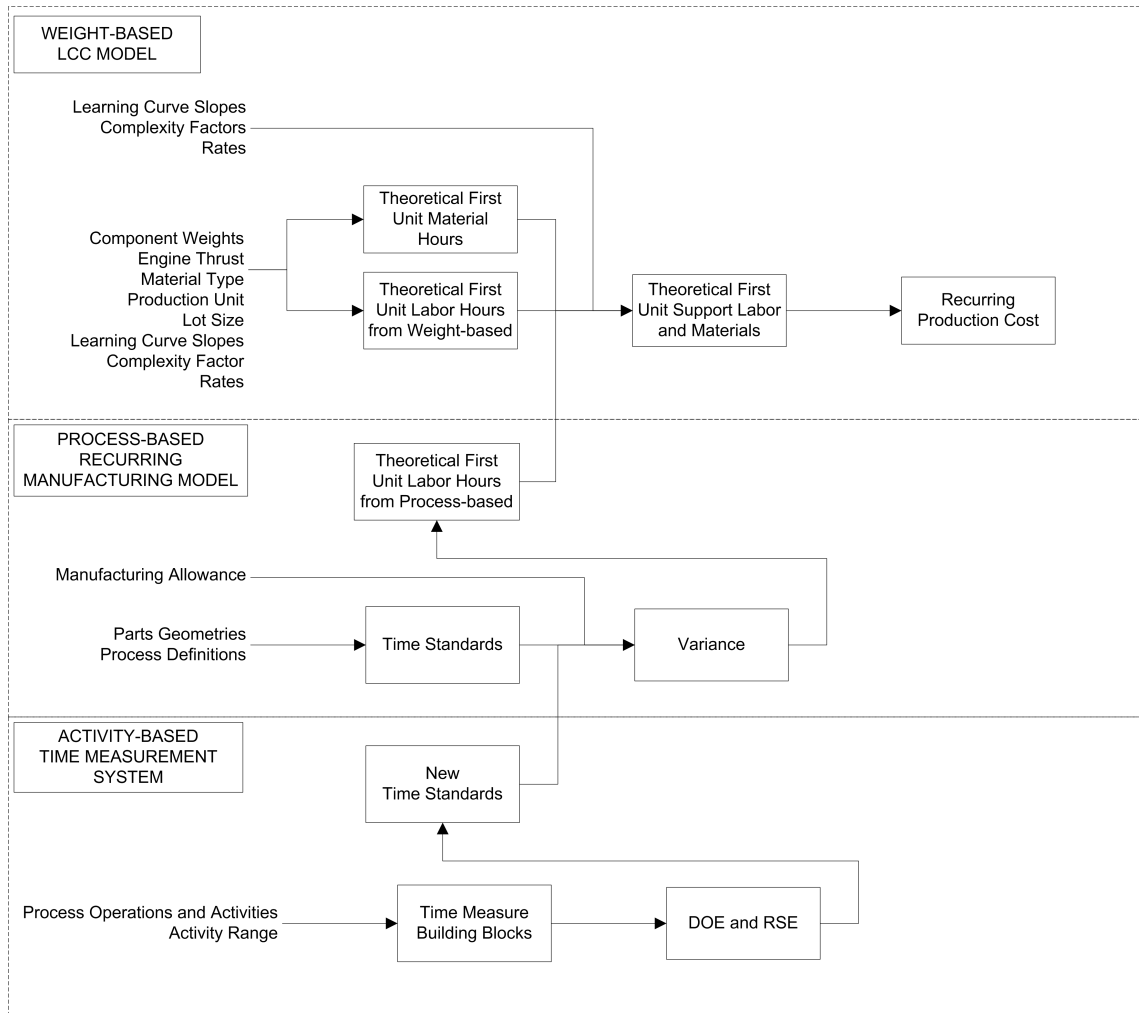


Figure 12: MaxiMOST Analysis Diagram

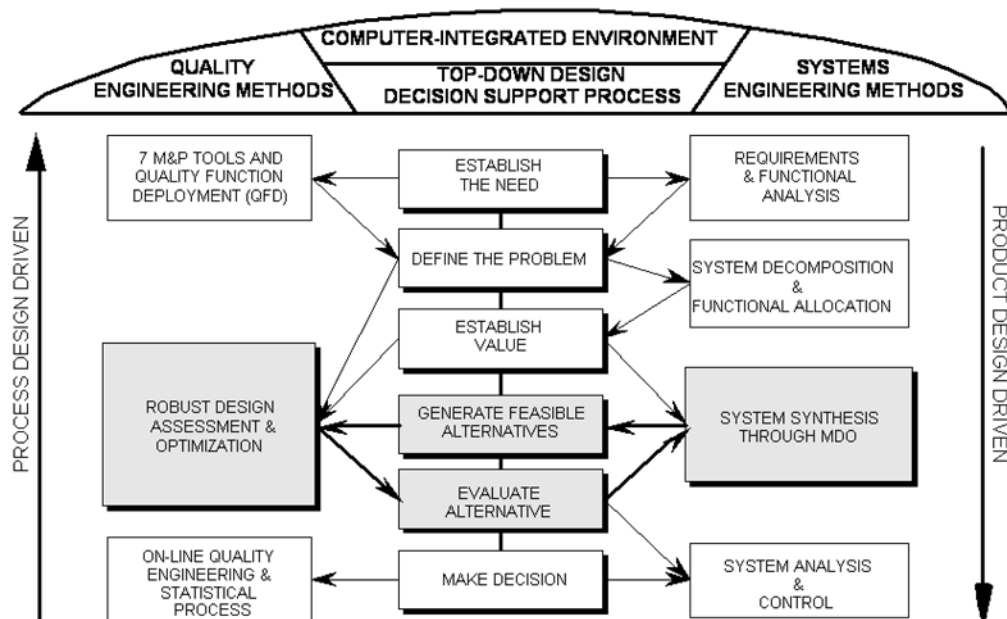
#### 4.1.4 Design of Experiment and Response Surface Equation

At any point in the product development process, from conceptual to detailed design, the need to quickly assess the new cost estimate often emerges whenever there is any change to the design. This is very common in the early design stage but also true even at point far along the development cycle. It may be very difficult and time consuming to have to go through the entire analysis over and over. Sometimes the changes may seem insignificant, and only partially affected the analysis, the updating cycle is still necessary as part of the tradeoffs and product optimization.

In order to rapidly integrate this new design changes into the IPPD framework, Response Surface Equations (RSEs) are used to represent the approximation of the results. However, not all parameters may be required since 80% of the variations are driven by 20% of the parameters according to Pareto's principle. This analysis step is done by converting a set data into RSEs that approximate actual response. It may also require that the engineer and designer work together to relate a set manufacturing parameters to a set design parameters. For example, the time it takes to tighten 5/4" screw is dependent on the number of screws, and type of screw. This parameter cannot be used directly in the design process since it is not part of the design parameters (product variables). Part length may be used as an independent variable relating the space between each screw to the total number of screws needed for that part. This conversion process is necessary each time new case is studied. Design of Experiment is used to determine the optimal experiment cases needed for this conversion. Finally, Response Surface Equation (RSE) is created through regression analysis.

#### 4.2 IPPD Approach

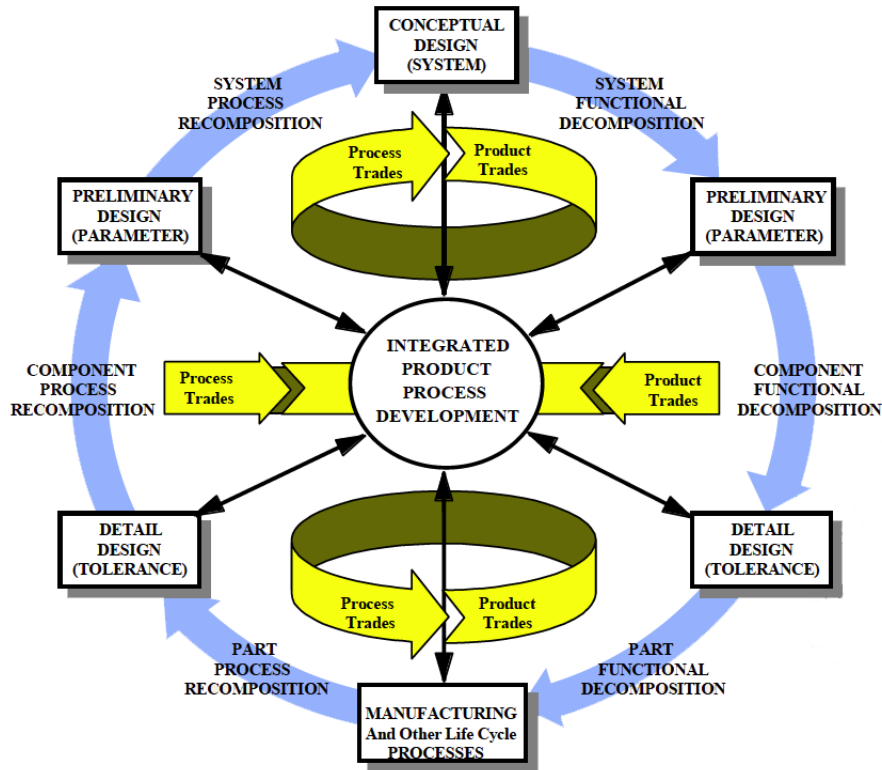
The design framework suitable for complex aerospace system design and analysis is based on the Integrated Product and Process Development methodology developed in the school of Aerospace engineering at the Georgia Institute of Technology, as



**Figure 13:** Georgia Tech Generic Complex System Product-Process Tradeoff Environment

shown in Figure 13. This methodology has been successfully used as a guideline for the design process and knowledge transfer protocol in the Georgia Tech graduate program in Aerospace Systems Design.

The simultaneous consideration of product and process characteristic is facilitated by the IPPD methodology. Figure 14 illustrates the decomposition activities from conceptual to detailed design level on the right half. Continuing to the left is the re-composition activities from part-level design back to system level design at the top. By re-composition of the part and component design considerations, the product and process tradeoff at the system level can be materialized. Similarly, the middle loop represents the tradeoff between component functional decomposition and process consideration. Finally, the part level tradeoff can be done through the consideration of part level design parameters and their corresponding process characteristics. The ability to have parallel product and process design trades at the system, component, and part levels allow more manufacturing knowledge to be brought in early and

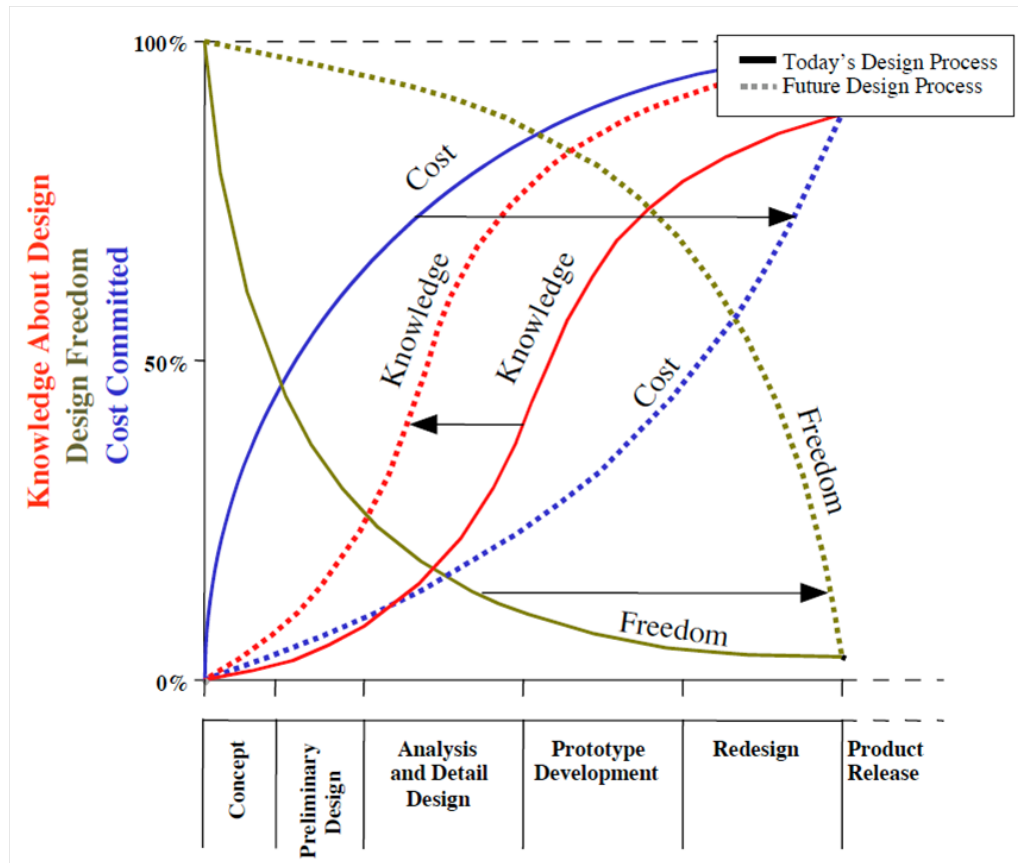


**Figure 14:** Georgia Tech Integrated Product and Process Development

reduce design cycle time by virtue of reduction in incompatibilities between design requirements and process capabilities as can be visualized in Figure 15.

The following sections explain how the design progresses in time and an appropriate analysis tool for each of the steps. Once again, the purpose of this framework development is not to integrate all available tools and construct a complete design framework, but rather to demonstrate how Hybrid Lifecycle Cost Estimating Tool (HLCET) can be utilized in the IPPD context. Many analysis tools are needed to provide necessary linkages for successful trade studies.

Typical aerospace system design process can be divided into three phases by the progression of development time, analysis fidelity and knowledge about the design, namely conceptual design, preliminary design, and detailed design phase.



**Figure 15:** Relationship between Knowledge About Design, Design Freedom, and Cost Committed Along Design Process Timeline



## 4.2.1 Conceptual Design Phase

The conceptual design phase starts at the inception of the project where the customer expresses his or her needs for a new system or derivative of an existing system. These requirements can be initially vaguely stated, unrelated to the characteristics of the system, and can be described as incomplete at best.

### *4.2.1.1 Established Need and Problem Definition*

One of the first tasks the designers and engineers need to complete is to convert the customer requirements, through brainstorming activities, into some engineering characteristics that can be understood by the engineers, analysts and other designers. A very well known method that is used throughout the engineering community is called Quality Function Deployment (QFD), or commonly referred to as House of Quality. It can be viewed as a central communication tool among designers. House of Quality is a tool that facilitates the capturing of customer's requirements (voice of the customer/WHATs), systematically relates them to engineering characteristics (HOWs), and helps define the targets with which the new system is to be met. These relationships are then weighed against engineering judgments and experience from the experts to derive the relative importances of accomplishing the targets as influenced by the requirements. The results of this analysis, if done properly, can provide problem definition and help narrow down the best course of actions that lead to the final design that is compatible with the requirements. The reader is referred to the work by Hauser and Clausing [26] for an extensive explanations on the subject and how to complete a house of quality. Figure 16 [49] show a generic setup of the House of Quality.

There exist multiple levels of Quality Function Deployment as suggested by its name. The system-level QFD is the first level in the series that relates customer requirements to the system level characteristics. The deployment of the system-level

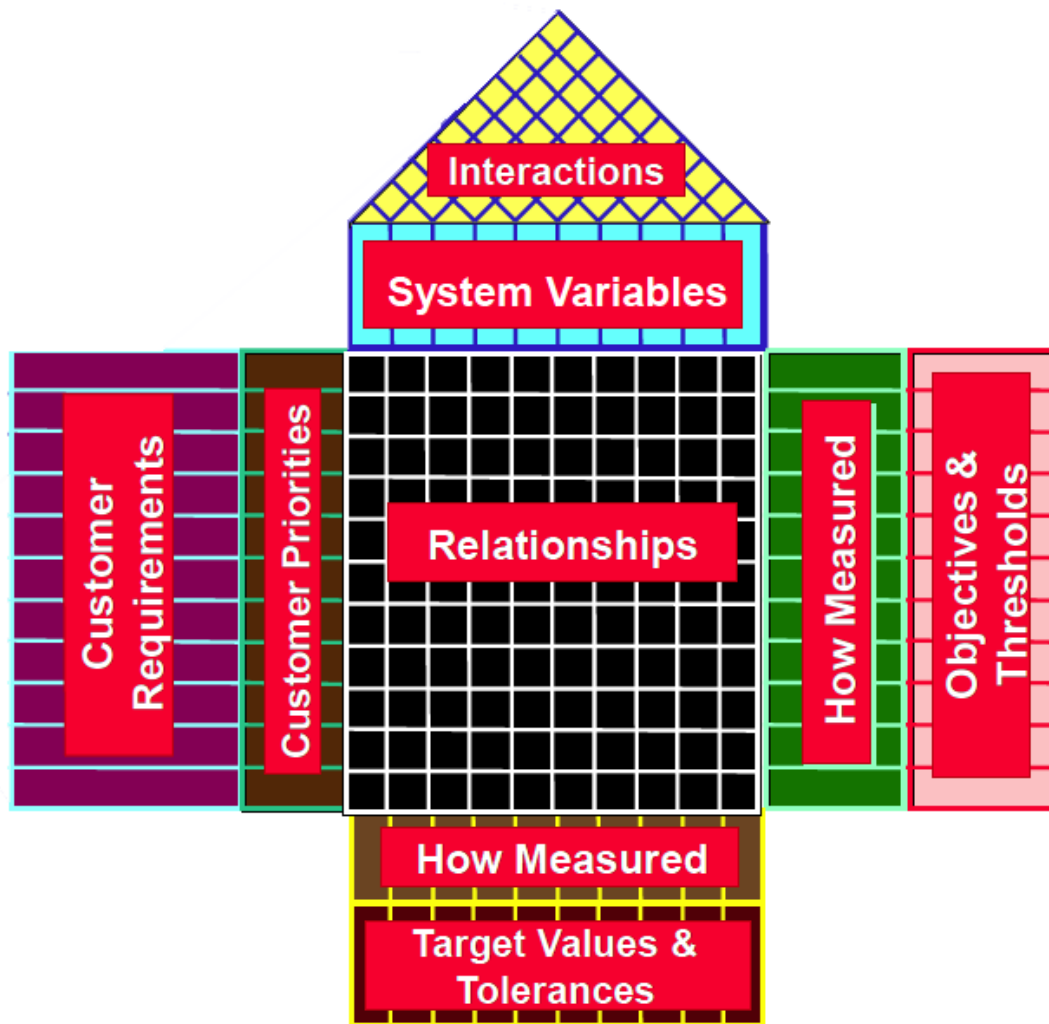


Figure 16: House of Quality

to the next level down is done through the decomposition of the system to sub-system level, i.e. engine, airframe, flight control system, and etc. The procedure for creating sub-system level House of Quality is essentially the same as described in the system level; only now the customer requirements are derived from system-level characteristics (system-level HOWs) developed earlier. The deployment continues until House of Quality of individual part is analyzed, and the part-level characteristics are defined. Each of the House of Quality plays different role in the product development lifecycle; i.e. only system-level and/or sub-system level QFDs may be used during conceptual design, whereas the part-level may be necessary during the detailed design phase. The importance of Quality Function Deployment cannot be emphasized more as this activity dictates how the product is to be designed.

#### *4.2.1.2 Established Value*

Once design requirements have been defined, the next step is to create an Overall Evaluation Criterion (OEC) to help identify design value against a baseline.

The OEC is a function designed to illustrate the correlation between system effectiveness and cost. The ratio between benefit to cost is typically used to represent a value function. As such, the OEC forms a basis for the objective comparison of design alternatives.

The criteria used in the analysis are directly derived from the customer's requirements (system-level WHATs) and the engineering characteristics (system-level HOWs). A baseline value is then assigned on each criterion; hence the OEC value of the baseline is always unity. The value higher than one means the particular design is better than the baseline.

Typical OEC calculation disaggregates the system effectiveness and cost into several groupings for increased traceability as illustrated below.

$$OEC = \frac{Benefit}{Cost} = \frac{\alpha(Capability) + \beta(Availability) + \gamma(Dependability)}{\delta(RDT\&E) + \epsilon(Production) + \zeta(Operation\&Support)} \quad (1)$$

Where;  $\alpha$ ,  $\beta$ , and  $\gamma$  are normalized weighting factors corresponding to the relative importances of benefit metrics as defined by the customer. Similarly  $\delta$ ,  $\epsilon$  and  $\zeta$  are normalized factors based on relative importance from cost metrics.

In order to assign numbers to metrics in OEC, one can use his or her experience and engineering intuition as a starting point. However, the evaluation of the baseline and target metric values usually requires more sophisticated synthesis and sizing tool, or modeling and simulation environment. An example of simple vehicle sizing method is called  $R_f$  method where the vehicle available propulsion are matched with the specific mission that the vehicle required to perform in terms of fuel available and fuel required respectively. Typical  $R_f$  method for rotorcraft conceptual design is shown in figure 17.

#### 4.2.1.3 Feasible Alternatives

Another brainstorming activity is now required to develop possible design alternatives. This step is typically done at the sub-system or component-level, and will set the stage for the preliminary design activities that follow. Morphological matrix is commonly used to list all possible alternatives of the design, categorized by its engineering characteristics. For instance, at the subsystem-level (wing-level), these characteristics may include material compositions, structural concepts, airfoil types, and fabrication and assembly methods. Different combinations of alternatives can be constructed which are referred to as “design options.” Figure 18 [41] shows an illustrative example of the design options of a pen in the form of Morphological matrix.

Once all the feasible design options are established, the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS), a Multi-Attribute Decision Making

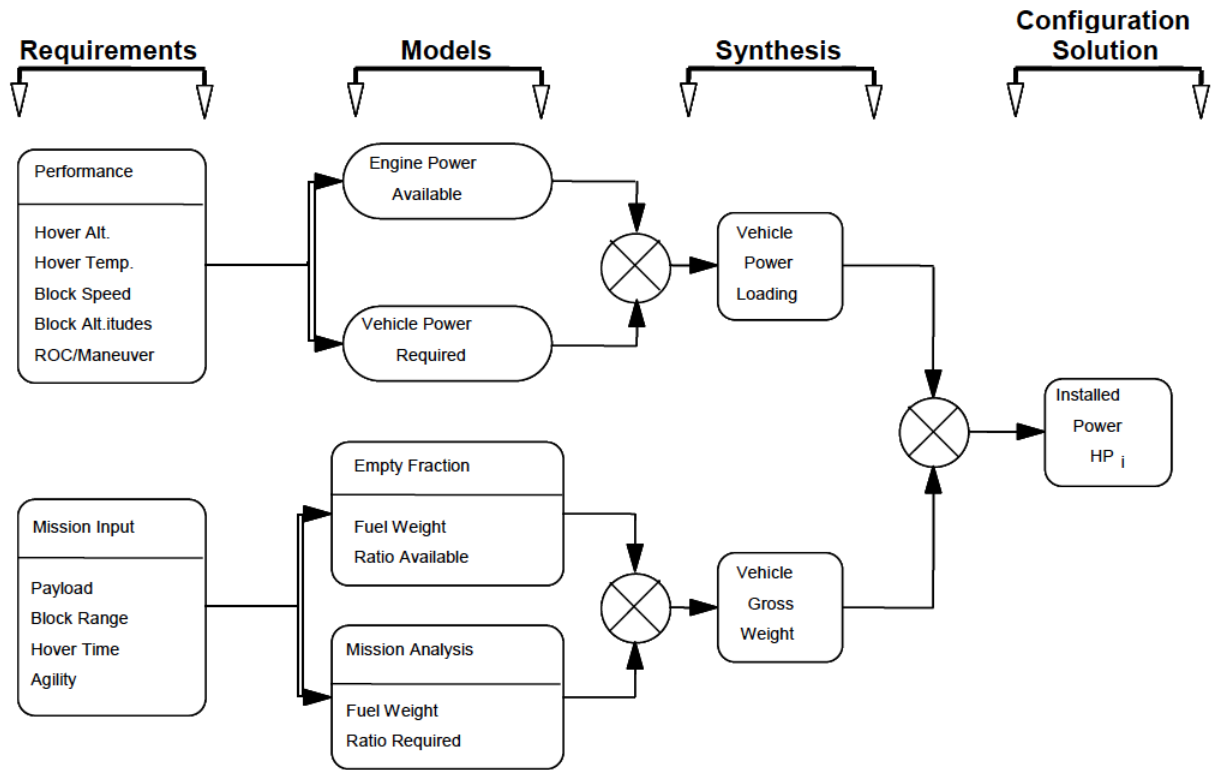


Figure 17: Flowchart of Extended  $R_f$  Method

		Alternatives		
		1	2	3
Characteristics	Casing	Plastic	Metal	Hybrid
	Writing Tip	Felt	Ball	
	Color	Black	Red	Blue
	Line Width	Fine	Medium	Heavy

Figure 18: Example Morphological Matrix

(MADM) assessment, is typically used for concept selection. In the TOPSIS method, scores are assigned on a scale from 1 to 10. Next, the distance from the most ideal and negative solution is measured for each criteria, and then weightings are applied. Finally, a ratio of positive ideal to negative ideal is calculated, and the best alternative is the one with highest score.

#### 4.2.2 Preliminary Design Phase

In the previous steps, the voices of the customers are captured and converted into some product and process attributes through QFD deployments. The ratio between baseline and target value for each characteristic is generated and combined in the form of value function, which can be used to gauge design goodness. High fidelity disciplinary analysis tools are now required to confirm those characteristics values.

A modeling and simulation environment utilizing physic-based analytical models is required to gain better insight into design specific knowledge. In some instances, mathematical approximations (metamodels) representing approximation to physic-based analysis results are used to reduce the analysis time, thus replacing a given discipline deficiency [17]. This step marks the beginning of preliminary design phase dictated by the IPPD methodology. In the beginning of this design phase, the product definitions can be very simple and generic.

The primary goal in this design phase is the design synthesis. It is defined as “the process of recomposing a system, previously decomposed for individual contributing analysis, based on a number of possibly coupled disciplines to form an integrated product” [16]. It is necessary now, more than ever, that system lifecycle cost prediction plays a major role in determining the success of the project. Typically, a system-level weight- and complexity-based cost analysis is used to predict lifecycle cost of the system at this stage. However, higher fidelity estimations like process-based and activity-based tools should be incorporated especially for non-traditional

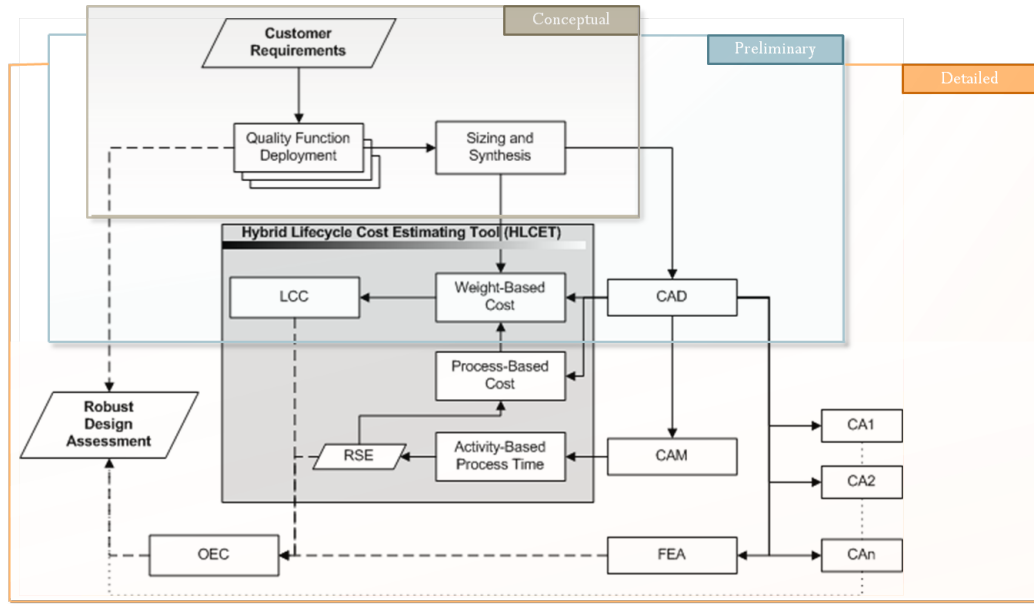
design concepts.

Producibility study is another area of interest. Knowledge gained through manufacturing consideration can be critical to the success of the project. Many factors such as production volume, time, available technologies, and manufacturing readiness level can differentiate a product on the shelf from a revolutionary product that is impractical.

#### *4.2.2.1 Modeling and Simulation Environment*

The modeling and simulation environment is setup in ModelCenter software. The integrated analysis framework consists of seven major analysis tools with linkages as show in Figure 19. Note that other Contributing Analyses (CA) are omitted for simplification. The centerpiece of the environment is the HLCET as described in the earlier section on this chapter. It generates the lifecycle cost element breakdowns that are used as one of the evaluation metrics in the OEC identified during the conceptual phase. Other contributing analyses, including computer-aided design (CAD), computer-aided manufacturing (CAM) and finite element analysis (FEA), provides specific engineering characteristics for the OEC evaluation.

**Vehicle Sizing and Synthesis** Flight Optimization System (FLOPS) is used as a physic-based vehicle performance simulation model. It is used to determine the fuel burn and total weight of the aircraft based on specified mission. FLOPS version 8, a derivative version of the original software developed by ASDL lab at Georgia Tech, will be used for demonstration purposes and integrated with the ModelCenter environment. The output from the analysis is in the form of vehicle configuration (sized vehicle) and its associated component weight breakdowns. The vehicle configuration parameters are then feed directly to computer-aided design module to generate basic vehicle geometry. The component weight breakdown is useful for initial LCC analysis.



**Figure 19:** Modeling and Simulation Environment

**Component Weight Breakdown** The most common form of presenting component weight breakdown is by using the standard form of weight and balance report commissioned by Society of Allied Weight Engineers Inc., Recommended Practice Number 8, SAWE-RP8 [50], a successor of Military standard, MIL-STD-1374 form which group the aircraft weight statements into 3 parts – Group Weight Statement, Detail Weight Statement, and Weight and Balance Status in a tabulated format. Example of the SAWE-RP8 Part I is shown in Figure 20 representing a generic breakdown of aircraft main components.

There exist many ways to come up with the component weight breakdown of a future system. One may use existing weight data from other system that resembles the future system being investigated. This method works well with fixed component, such as flight control system, and engine installations. One could also use weight allocation equations that proportionally divide the vehicle empty weight into individual component weights. These equations derived from weight data on previous aircraft



MIL-STD-1374 PART I - TAB  
 NAME  
 DATE

GROUP WEIGHT STATEMENT  
 WEIGHT EMPTY

PAGE  
 MODEL  
 REPORT

1	WING GROUP				
2	BASIC STRUCTURE-CENTER SECTION				
3	-INTERMEDIATE PANEL				
4	-OUTER PANEL				
5	-GLOVE				
6	SECONDARY STRUCTURE-INCL.WING FOLD WEIGHT			LBS.	
7	AILERONS - INCL. BALANCE WEIGHT		LBS.		
8	FLAPS - TRAILING EDGE				
9	- LEADING EDGE				
10	SLATS				
11	SPOILERS				
12					
13					
14	ROTOR GROUP				
15	BLADE ASSEMBLY				
16	HUB & HINGE - INCL. BLADE FOLD WEIGHT			LBS.	
17					
18					
19	TAIL GROUP				
20	STRUCT. - STABILIZER (INCL. LBS.SEC. STRUCT.)				
21	- FIN-INCL.DORSAL (INCL. LBS.SEC.STRUCT.)				
22	VENTRAL				
23	ELEVATOR - INCL.BALANCE WEIGHT		LBS.		
24	RUDDERS - INCL.BALANCE WEIGHT		LBS.		
25	TAIL ROTOR - BLADES				
26	- HUB & HINGE				
27					
28	BODY GROUP				
29	BASIC STRUCTURE - FUSELAGE OR HULL				
30	- BOOMS				
31	SECONDARY STRUCTURE - FUSELAGE OR HULL				
32	- BOOMS				
33	- SPEEDBRAKERS				
34	- DOORS, RAMPS, PANELS & MISC.				
35					
36					
37	ALIGHTING GEAR GROUP - TYPE **				
38	LOCATION		RUNNING	*STRUCT.	CONTROLS
39	MAIN				
40	NOSE/TAIL				
41	ARRESTING GEAR				
42	CATAPULTING GEAR				
43					
44					
45	ENGINE SECTION OR NACELLE GROUP				
46	BODY - INTERNAL				
47	- EXTERNAL				
48	WING - INBOARD				
49	- OUTBOARD				
50					
51	AIR INDUCTION GROUP				
52	- DUCTS				
53	- RAMPS, PLUGS, SPIKES				
54	- DOORS, PANELS & MISC.				
55					
56					
57	TOTAL STRUCTURE				

\* CHANGE TO FLOATS AND STRUTS FOR WATER TYPE GEAR.

\*\*LANDING GEAR "TYPE": INSERT "TRICYCLE", "TAIL WHEEL", "BICYCLE", "QUADRICYCLE", OR SIMILAR DESCRIPTIVE NOMENCLATURE.

Figure 20: Example of SAWE-RP8 Weight Statement

subjected to multiple linear regressions. The results are estimating relationships between weight and physical attributes that logically affect the weight of the component, e.g. rotational speed, horse power rating, wing aspect ratio, or total weight of the vehicle itself. Among the most popular equations, Prouty's weight allocation equations are used in many rotorcraft system preliminary designs [45]. Other industrial entities resort to their own historical data of their previous products, which in most cases, should give a more accurate account on the new component weight estimations since the historical data and the future system are likely to be based upon the same underlining assumptions, e.g. manufacturing facility, material fabrication technique, and technology level.

FLOPS also has its own weight allocation module which outputs component weight breakdowns resulting from the vehicle sizing routine. The resulting component weights are then automatically populated in the SAWE-RP8 format within ModelCenter environment.

**Computer-Aided Design** Computer Aided Three Dimensional Interactive Application (CATIA) is used as 3-dimensional product definition module in the design framework. It is a state-of-the-art geometry creation tool developed by Dassault Systemes. It is being used throughout Aerospace and Automotive industries, as well as other engineering communities like ship building, petrochemical, and biomechanical engineering.

CATIA is suitable for modeling high precision part geometry. It is an integral part in the design process since part design serves many purposes in engineering activities, such as, product visualization, material assignment, weight allocation, center of gravity and mass properties calculations, and in this particular study, *cost calculation*. 3D geometry can also be transformed into other useful format for subsequence

engineering analyses, such as Finite element Analysis (FEA), Computational Structural Dynamic (CSD), Computational Fluid Dynamic (CFD), Stability and Control analysis, and etc.

One important aspect of CATIA in this design framework is the use of CATIA product information to assist production cost calculations. To accomplish this task, the CATIA software is integrated into ModelCenter environment through a special plug-in called CAD Fusion. CAD Fusion is a robust tool that enables sharing of product information with downstream analyses. It can automatically extract any information inherent in 3D geometry such as weight, length, area, angle, spatial location and orientation, and etc. Furthermore, CAD Fusion can also import external input variables into CATIA file allowing for a complete automation of 3D geometry creation.

It is possible to setup the model such that the overall system geometry is driven by a set of external inputs. When the input file is changed, the product design gets updated automatically and returns new product information affected by those changes (e.g. area, length, weight, and etc.). This capability proves to be an important enabler for the successful use of ACCEM in integrated design environment since it allows for automatic update of geometry, then feeds new outputs to ACCEM cost calculation at the part level. Hence, cost implications from design changes can be analyzed in a more meaningful way. To accomplish this task, two design principles are applied namely Parametric and Relational Design principles.

**Parametric and Relational Design** Because traditional CAD tools are based on geometric objects, making a design change requires changing all constituent components in order to make the drawing correct.

Most current CAD/CAM/CAE software utilizes Parametric design principle. It is a method of linking dimensions and variables to geometry in such a way that when

the values change, the part changes accordingly. A parameter is a variable to which other variables are related, and these other variables can be obtained by means of mathematical formulations. In this manner, design modifications and creation of family of parts can be performed remarkably faster as compared with individual drawing required by previous generation CAD. Parametric modification can be accomplished by mean of spreadsheet, script, or manually changing dimension text in the user interface.

Relational design, on the other hand, is defined as method of linking part and product designs within a product structure with capabilities of parametric design and creation of parent/child relationships to control behavior [51].

In complex system design, pieces of the system may be designed and manufactured by several companies relatively independently.

Once the component design is done, the integrator will then combine the design of individual part from several vendors and make sure that all the parts function the way it is designed both physically and functionally.

The integrator faces a difficult task of creating standard design practices that must be exercised by individual vendor or engineer. This is to ensure that changes are appropriately captured and propagated throughout the entire system. This is to be able to maintain the part interactions, assembly constraints, as well as tolerances. Relational Design is a design practice that helps the integrator or designer to lay out the design roadmap, and quickly and effectively manage changes along the design process.

#### **4.2.3 Detailed Design Phase**

The design efforts will now focus on reducing uncertainties that might presence due to the lack of confirmed test data or unknown interactions among different components. This phase of the design deals with part-level decomposition.

3D product definition is now at a level of detail that manufacturing department can use to determine individual part fabrication method in detail. All the part features are defined in great detail.

Many changes in this phase focus more on part features rather than dealing with basic dimension. In terms of cost analysis, it is becoming more difficult to quantify impacts from this type of changes. For this reason, process-based cost model that was used in the previous phase may not have enough sensitivity to predict cost impacts from minute changes. Furthermore, process-based cost model can only estimate product costs that use the same manufacturing processes. To remedy some of the inherent deficiency from the process-based method, Activity-Based Costing (ABC) is used to replace certain portions of the cost results from ACCEM analysis. Specifically, the manufacturing time estimates of composite parts which are not applicable to existing ACCEM equations, i.e. parts that are made from difference manufacturing process, exhibit difference level of manufacturing complexity, and/or requires difference resources.

**Manufacturing Process Planner and Virtual Factory (CAM)** The purpose of simulating shop floor activities is to give more visibility to the very complicated and sheer amount of information involve in the process planning, especially in manual operation where the activities needed to be orchestrated in a manner that maximize the utility of all available resources.

DELMIA (Digital Enterprise Lean Manufacturing Interactive Application) is the state-of-the-art digital manufacturing software package that allows engineers to take 3D product definitions from CATIA and perform various studies on manufacturing process of the final product. Such areas of study are fabrication method, assembly sequence, factory floor layout, throughput determination, material and resources

planning, and etc. DELMIA and CATIA suites are operated under the same environment. It provides the direct linkage between product and process design, hence allowing both designers and manufacturing engineers to work together on the same data concurrently.

### ***4.3 Summary of Contribution***

Throughout this chapter a series of design and analysis tools used in this design framework are detailed. Explanations are also made on how these tools can be linked together such that output from one analysis can be fed to the next analysis tool via common set of parameters. Input parameters of the entire system are grouped and controlled by variable control module in ModelCenter.

The reader is reminded that not all of the tools are created by this work. Some of the commercially available tools deemed suitable for the design framework are chosen. These include the modeling environment software called ModelCenter 9.0 from Phoenix Integration is used. CATIA and DELMIA from Dassault Systemes are CAD-CAM simulation packages for creating product and process definitions. FLOPS is the vehicle synthesis and sizing tool used among researchers and graduate students at Georgia Tech.

All the works related to Hybrid Lifecycle Cost Estimating Tool (HLCET) including Excel-based TCM, ACCEM, and MaxiMOST, and the integration of the aforementioned analysis tools in ModelCenter is done exclusively by the author with the data acquired from public domains.

## CHAPTER V

### PROOF OF CONCEPTS

This chapter will demonstrate the validity of the elements in the Hybrid Lifecycle Cost Estimating Tool (HLCET) by comparing the result of various part of the analysis framework against published data. The three components of the tool will be treated separately. Weight-based lifecycle cost estimating model based on Tailored Cost Model (TCM) will be compared with existing LCC tool called MALCCA which has been used to estimate various military aircrafts. Process-based recurring manufacturing time estimate based on ACCEM methodology will be demonstrated on a simple composite part design to compare and contrast the validity of the tool against typical weight-based model. Lastly, the activity-based time measurement model based on MaxiMOST system will be demonstrated how the result from this detail analysis can be used to further increase the fidelity of the recurring manufacturing time estimate at the part level.

#### *5.1 Parametric Lifecycle Cost Estimate*

To be better integrated with current methodology, an excel-based TCM has been created for this evaluation. The equations used in the original TCM are retained. Inputs and assumptions that were scattered throughout the analysis are now consolidated into one sheet. This allow for a better visibility and user-oriented application. The analysis still depends almost entirely on the component weights breakdown which is now linked to the standard form MIL-STD-1374 implemented in the design framework. The inputs for the analysis includes MIL-STD-1374 component weight breakdown, learning curve slopes, test requirements, and other programmatic factors. The analysis then takes the inputs and estimates labor hours requirements for

research, development, testing and evaluation (RDT&E), first unit material, and manufacturing requirements. Then the learning curve slopes are applied to appropriate components to determine labor hours for subsequence production quantities. Finally support investment, and operation and support cost, and program management factors are applied to calculate support functions costs. The “System LCC Summary” block gathers the calculated cost elements from various modules and presents the results in a work breakdown structure (WBS) format.

The accuracy of TCM prediction has been demonstrated in the study done by Greg Bell who applied the tool to estimate the LCC of MV-22 aircraft [3]. The final result shows that unit acquisition cost is within 10% from the actual cost, RDT&E, and other cost categories are also show small deviation from published data of MV-22 project.

Further validation is done during this research by comparing the result of a vintage fighter aircraft F-86F Sabre LCC analysis using MALCCA and TCM-based calculations on the same weight breakdown structure. Figure 22 is the comparison between the two analysis results. Figure 21 shows the LCC summary for F-86F Sabre aircraft from TCM equations.

Comparable estimates on RDT&E and Total Production Cost can be seen from the result. However, a very large discrepancy in the Support Investment and Operation and Support can be observed, this large discrepancy may be resulted from various reasons. One of the cost elements in Support Investment category is the Training Equipment and Services where MALCCA estimate at \$1445.579M, while TCM only estimate at \$97.492M. This deviation came directly from the inherent assumption of the number of operational personnel required. Another possible explanation is in regard to the assumed operational structure and number of service personnel for operation and support activities. The number of personnel and salary at each level has been matched, but MALCCA estimates still give almost an order of magnitude



WORK EL NOMENCLATURE	CONTRACT FEE @	LCC (M\$)	REF
100 RDT&E		0.1	
110 ENGINEERING	121.780	12.178	133.959 Table 47
120 MOCKUP, TEST & DEVELOPMENT	120.079	12.008	132.087 Table 47
130 INITIAL TOOLING	99.711	9.971	109.682 Table 47
140 FLIGHT UNITS	81.328	8.133	89.461 Table 47
150 ILS PLANS & ANALYSES	17.664	1.766	19.430 Table 47
300 R&D ILS COMMODITY RDT&E	200.333	20.033	220.366 Table 32
160 PROJECT MANAGEMENT	15.013	1.501	16.514 Table 47
RDT&E TOTAL	655.908	65.591	721.499
200 PRODUCTION		0.13	
210 RATE TOOLING	12.841	1.669	14.510 Table 48
220 PRODUCTION A/C	5228.185	679.664	5907.849 Table 48
230 PROJECT MANAGEMENT	171.518	22.297	193.815 Table 48
PRODUCTION TOTAL	5412.544	703.631	6116.174
300 SUPPORT INVESTMENT			
310 PECULIAR GROUND SUPPORT EQUIPMENT			181.956 Table 32
320 TRAINING SERVICES & EQUIPMENT			166.360 Table 32
330 ENGINEERING & SUPPORT DATA			13.761 Table 32
340 INITIAL SPARES			397.551 Table 32
350 SITE ACTIVATION/FIELD SERVICES			8.991 Table 32
ILS INVESTMENT TOTAL			768.620
400 OPERATION & SUPPORT COST (AFR 173-13)/M			
410 UNIT MISSION PERSONNEL			3893.7 Table 40
420 UNIT LEVEL CONSUMPTION			60.35739 Table 40
430 DEPOT LEVEL MAINTENANCE			114.6644 Table 40
440 SUSTAINING INVESTMENT			113.0744 Table 40
450 INSTALLATION SUPPORT PERSONNEL			679.01 Table 40
460 INDIRECT PERSONNEL SUPPORT			571.7875 Table 40
470 PERSONNEL ACQ & TRAINING			1649.934 Table 40
O&S COST TOTAL	5 YR		7082.528
LCC TOTAL -- COST OF OWNERSHIP			14688.821
UNIT PRODUCTION FLYAWAY COST	1000 UNIT		6.116174
LCC SUMMARY -- FY89 M\$			
RDT&E COST			721.499
HARDWARE COST			6116.174
LOGISTIC SUPPORT			371.068
INITIAL SPARES			397.551
OPERATION & SUPPORT COST	5 YR		7082.528

Figure 21: F-86F Sabre LCC Summary

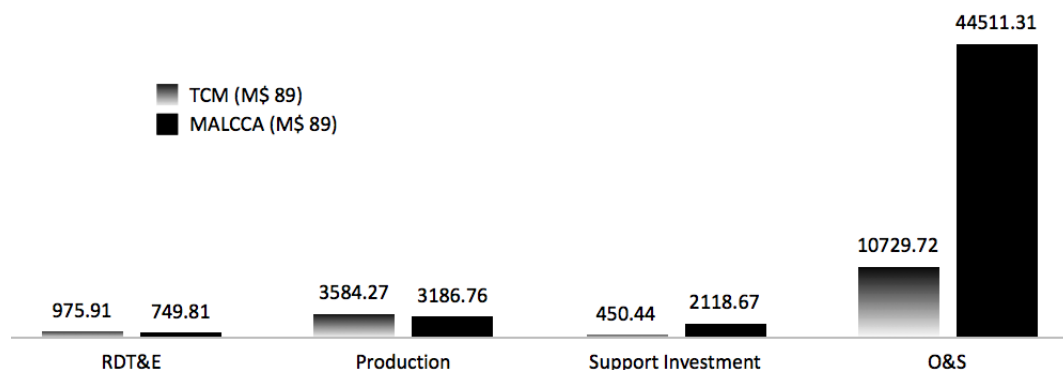


Figure 22: TCM and MALCCA Cost Comparison

higher than TCM. Lastly, the assumed flight hour per aircraft year is also one of the determining factors for Operation and Support cost. It is this factor that the author believes to be the major cause of discrepancy. Nevertheless, the focal point in the LCC estimate during conceptual and preliminary design are mainly on RDT&E and Production costs as they are directly related to aircraft component weights which are under direct provision of the designers at this early design period.

The Support Investment and O&S result exhibit large discrepancy which is taken from non-calibrated inputs and not very important at this point. But by looking at the result on MV-22 which is calibrated, TCM can give a good result within 10%.

In conclusion, from the user standpoint, TCM is a more versatile tool as compared with traditional LCC tool like MALCCA. At the very least, they can provide the same kind of analysis fidelity. All of the cost elements are the same, the same structure and attribute can be seen. The fact that TCM is created in excel provides great visibility to the user to see the sensitivity of the results to changing inputs. The results can be traced back to their origin, and the estimate relationships can be altered as more validated data become available. On the other hand, MALCCA represents input parameters by 5-letter acronyms, which is difficult to understand, often time, the user needs to consult with user manual to see the definition of each input. Then one by one, assign the value to those input. This is a very tedious process and prone to mistakes, and oversights.

Sensitivity analysis is sometime used to analyze the influence of input parameters to the LCC results. But this is not an easy task with MALCCA. Multiple layers of analysis setup and configurations are required, whereas the same analysis can easily be done in TCM as the sensitivity analysis tool, such as Crystal Balls or Matlab can be directly integrated with excel and the LCC sensitivity analysis can be done by just adding the distributions to the input parameters in one step.

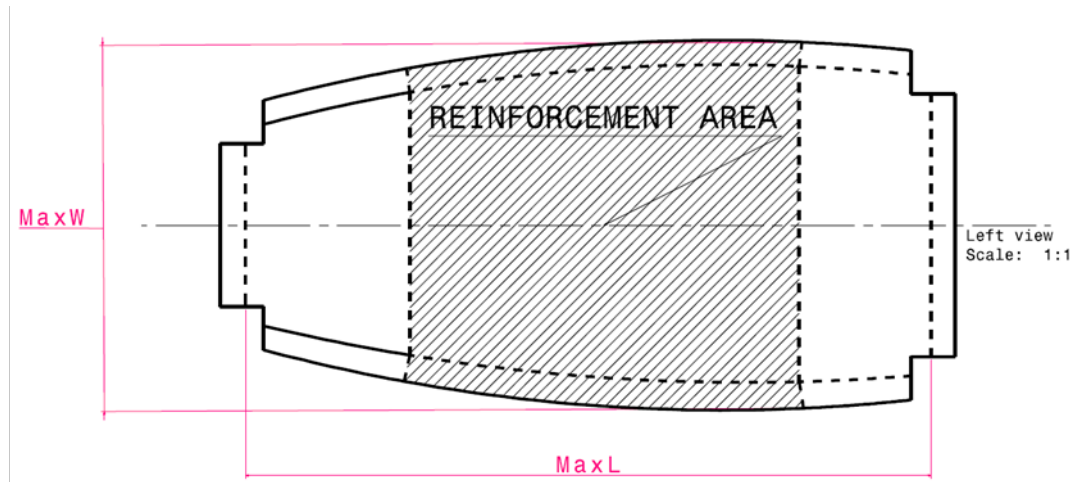
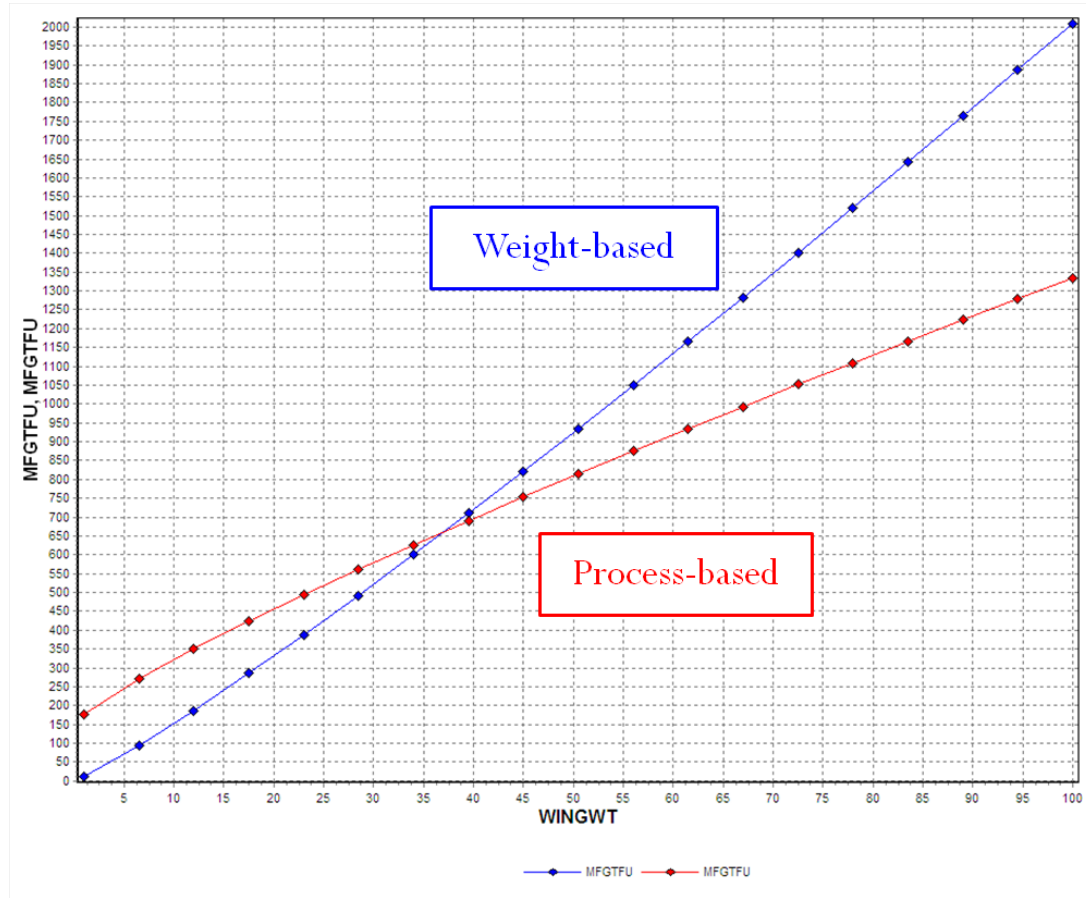


Figure 23: Generic Wing Rib Design

## 5.2 Recurring Manufacturing Labor Hours Estimates

The recurring manufacturing labor hours estimation is an integral part in the lifecycle cost estimation since all the recurring costs are calculated based on the labor hours, including manufacturing labor, engineering, quality assurance, and other support activities. The sensitivity of the recurring manufacturing labor hours estimates to detailed product and process parameters (as opposed to weight) is the main purpose for utilizing the Process-based Recurring Manufacturing (PbRM) Module. The following paragraphs focus the reader attention to usefulness of this module and how it can improve the sensitivity of the cost analysis. The demonstration will be done through a case study where a simple wing rib design, as shown in Figure 23, is first subjected to a cost estimating technique in the WbPL. Then the calculation is expanded to include the technique used in the PbRM module. The result from the shift in the dependent parameter from part weight to part features such as length, thickness, perimeter, is then compared and contrasted.

The rib part used in this example represent a simplest load carrying component in the wing box design. The part consists of rib web and flanges. The web portion forms the contour of the top and bottom skin and sustains shear load caused by the twisting



**Figure 24:** Comparison of the manufacturing times from WbPL and PbRM modules of the wing box due to aerodynamic loadings. The rib flanges are the features created to facilitate rib-to-skin and rib-to-spar connections. The rib thickness is made from laying up composite laminates with symmetrical plus/minus 45 degree plies. The manufacturing processes used for this part consist of first hand-laid the plies using mylar template, and reusable vacuum bag. The laid up part is then transferred to consolidation station where thermal expansion molding process is used. Finally, trimming and drilling process is performed to complete the process. The modelled part is then scaled to see the sensitivity of cost estimates from the two techniques to various scaling factors.

Figure 24 compares the estimating results from two estimating techniques in HLCET. First, the WbPL module is used to predict the part manufacturing time.

The existing equation for composite part is almost identical to equations used for predicting metallic part, except that higher value for complexity is used. The fact that WbPL module uses weight as a sole dependent parameter directly reflect on the chart. The weight-based result shows almost a linear relationship between part weight and cost, as shown in the blue line. Next, the PbRM module is used to predict the same composite part manufacturing hours. The result is then inserted back in the WbPL module, and the cost is then calculated in the same manner. The process-based result, represented by red curve, shows that as part weight (part size) increases, the rate of cost increase is not directly proportional to weight. As a result, the part that is large enough, in this case, more than 35 lb, can result in cheaper total cost due to lower manufacturing time. The phenomenon as seen in Figure 24 can be explained as the following. In composite manufacturing, the time it takes to setup the tool, layup plies, cure and final touch up the part can be significantly longer for small parts as compare to other material type such as aluminum. However, as part become larger, most operations are fixed except the operation that is related to layup of plies. The time it takes to lay down a strip of composite tape per unit length reduces as the length increases due to learning improvement that occur during the activity [34]. As part size increases in this study, the manufacturing time is a function of part size with an exponent factor of less than one. That is the manufacturing time is not directly proportional to part size (or weight) as is the case for weight based calculation. It can be concluded that it is possible to design a comparable composite part that resulted in shorter manufacturing cycle time than the metallic counter part.

### ***5.3 Work Measurement System for Manufacturing Time Estimate***

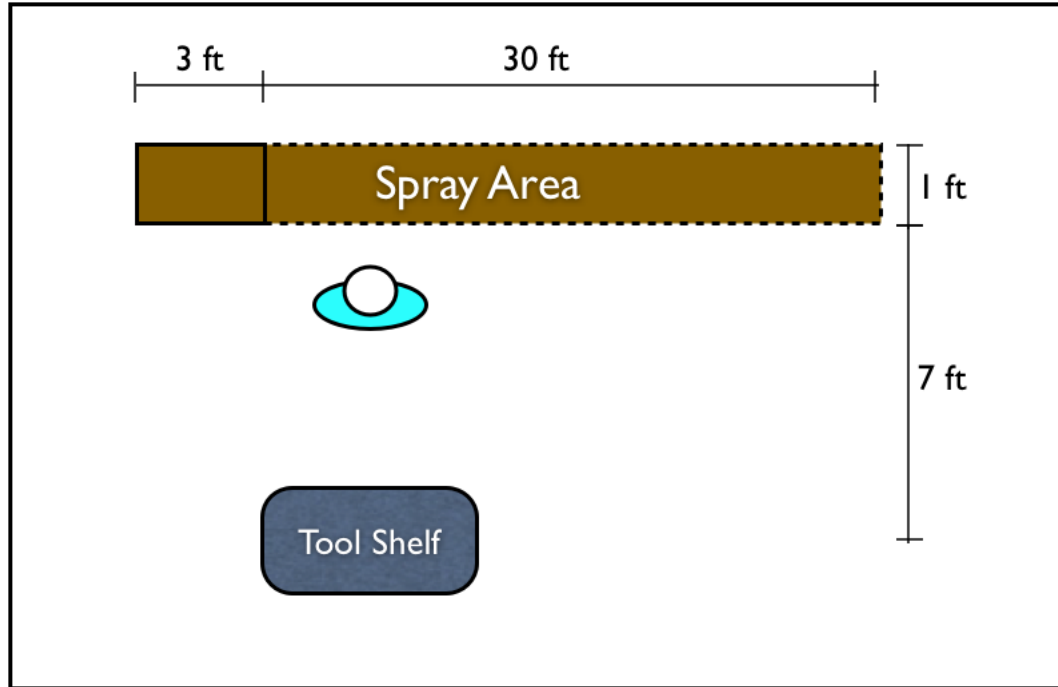
As described in the earlier section that ACCEM, a tool designed to be used as labor hour estimator for composite manufacturing, has some serious flaws that prevent its general use. Because of the fact that ACCEM based the manufacturing

processes on specific procedure done by Northrop Aircraft technologies and know-hows, the applicability become limited as the composite manufacturing technology advances. This problem has been shown during the GAC study where ACCEM is used to estimate hand layup hour for various GAC composite parts. The results provided by ACCEM proved to be inaccurate due to the fact that GAS processes are different from those used during ACCEM development. Adding insult to the injury, the preparation for the ACCEM calculation is very time consuming and requires many detail information on the part level which is not readily available during early product development process. All in all, there are two problems with ACCEM — long setup time, and accuracy issues. Both issues will be addressed in this section. The proposed methodology helps increase its generality, and reduce setup time and information required. Setting aside these shortcomings, ACCEM still provides a good starting point in the development of a true process-based cost model where the estimated labor hour, and hence cost, is dependent on the process and part configuration, rather than part weight as traditionally done.

The fact that the estimating relationships between part information and labor hour exist at the process breakdown level, provides the opportunity to select or omit certain procedures that are not relevant to the study at hand. This, in turn, increases the accuracy of the prediction. The inaccuracy caused by the case where the process steps do not exist in original ACCEM can be remedied by introducing activity time study method like Work Measurement System to add new, or modify existing estimating relationships to better represent current manufacturing process. A particular system called MaxiMOST will be used.

### **5.3.1 ACCEM and MaxiMOST Building Blocks Comparison**

MaxiMOST allows the user to build the manufacturing sequence from basic activities frequently referred to as building blocks. To demonstrate its use, a simple



**Figure 25:** Spraying Activity Layout

process of applying a release agent on tool surface will be constructed. Then, MaxiMOST study is performed to estimate processing time. The original ACCEM study dictates a simple linear equation of the processing time as a function of tool surface area. Upon closer look, this process sequence includes walking, grabbing and spraying activities as basic building blocks. Figure 25 shows the diagram of the process.

After examination of the definition of those predefined building block, it is found that the spraying activity of this type could be closely represented by an Air-Brush Activity, which described as an action of sweeping the area with an air gun with wrist rotations. By assuming that the tool surface area can vary from 3 - 30 square feet, the result shows an almost linear time response as a function of surface area. The fitted linear equation provide a very close coefficient of the linear equation, 0.00007 times tool surface area as compare to the 0.00006 from ACCEM model.

This demonstration shows that the application of MaxiMOST measurement analysis can be tailored to specific situation which give a lot of flexibility to the user to

improve accuracy of the estimation. It also allows process engineer to engage in the design process early. By the same token, it can be seen that MaxiMOST can provide even better level of visibility when combined with virtual manufacturing software like DELMIA to provide detailed account of the activity breakdown. This benefit also implicitly creates an opportunity for the design to be validated directly from manufacturing perspective.

### 5.3.2 Composite Layup Time Prediction Using MaxiMOST RSE

The purpose of this step is to compare the time estimates from two estimating techniques, ACCEM and MaxiMOST RSE, with actual time data collected by GAC on a simple composite part manufacturing. The calculation will only focus on the labor intensive processes including layup of composite plies, transfer of laid up plies to layup tool, debulking, and net trimming processes.

The composite part being study is a graphite epoxy plain web for B-1 Horizontal Stabilizer outboard closure rib as shown in the diagram below. Basic part descriptions are also provide in Figure 26 and 27. A complete process breakdown and processing times are documented in the report done by GAC in an effort to study the applicability of ACCEM estimates.

The rib construction represents the simplest load carrying component of the stabilizer torque box. The single channel elements consist of a basic 12-ply thick laminate, with six additional reinforcement plies covering 75% of the rib. Because of the simplicity of the part design, ACCEM process is very similar with that of GAC. Nevertheless, due to the difference in the layup practice between the two companies, not all equations can be applied. The table below shows the percentages of number of equations that match with the GAC's procedure along with the average percentages of total cost of part that are influenced by those equations. Figure 1 represents the breakdown of the operations that are subjected to study where ACCEM equations



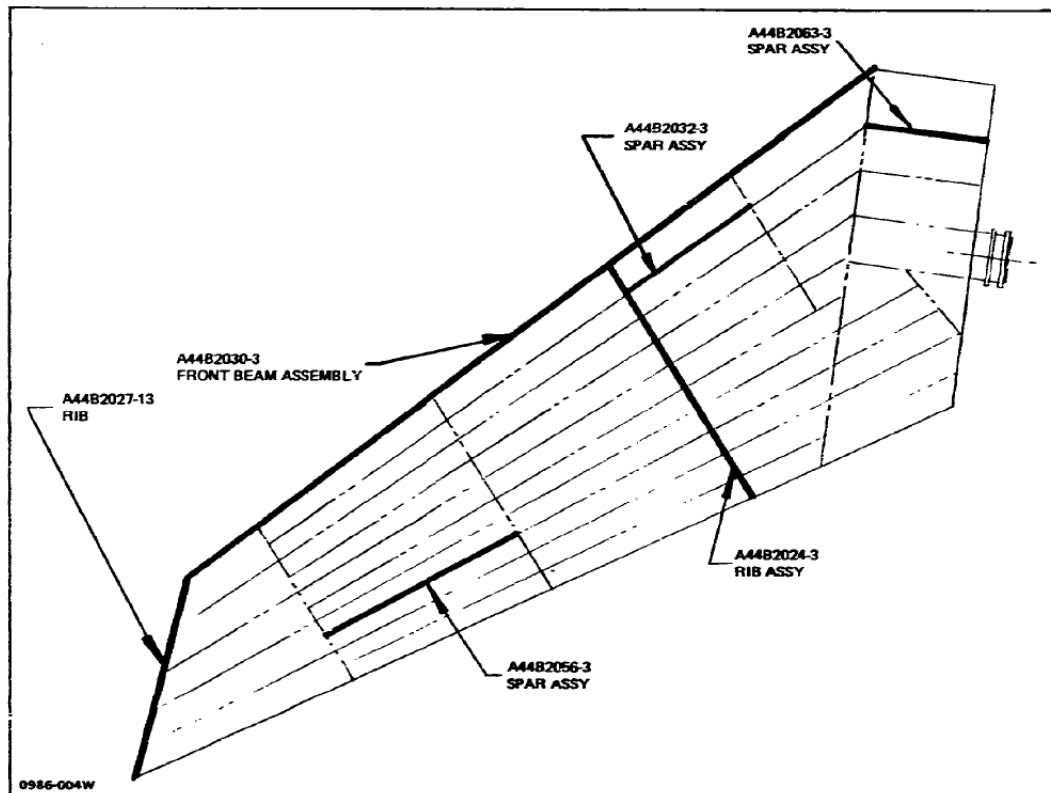


Figure 26: A-10 Horizontal Stabilizer Sturctural Layout

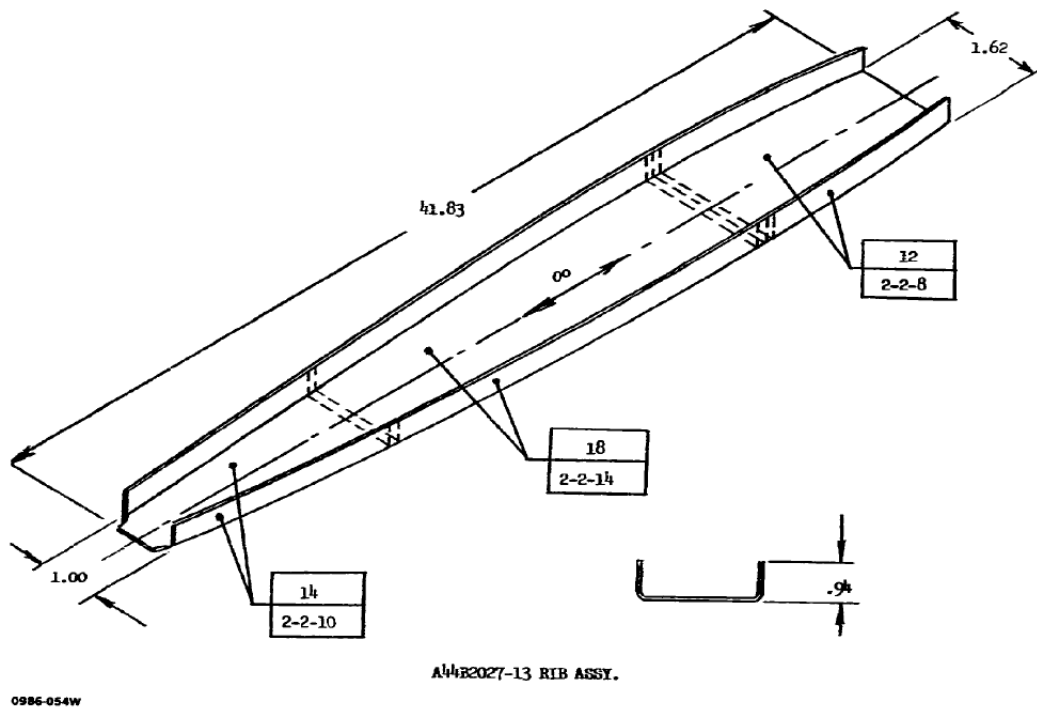


Figure 27: Composite Rib Design

are applicable.

It was found by GAC that some operations necessary to make the part could not be identified in the ACCEM program. As a result, a normalization process was utilized by purposefully omitting data of those procedures that cannot be accounted for by the ACCEM program for the comparison purposes. Figure 2 compares the result between the actual GAC process, normalized GAC process, and ACCEM predicted

Table 1: GAC Composite Operation Breakdown

<u>Manufacturing Operation</u>	<u>Number of Equations</u>	<u>Average Percentage of Total Cost of Parts</u>
Lay-Up	56%	72 - 93%
Core Preparation	59%	30 - 34%
Vacuum Bag/Autoclave Cure	100%	7 - 28%
Finishing	16%	1 - 4%

0986-002W

**Table 2:** Manufacturing Hours Comparison between GAC and ACCEM

<u>Manuf. Operation</u>	<u>GAC Actual (Person/Hours)</u>	<u>GAC Normalized (Person/Hours)</u>	<u>ACCEM (Person/Hrs)</u>	<u>Part Type/Number</u>
Lay-Up	16.41	16.41	13.99	Plain Web Rib A44B2027
Part Consolidation	5.87	4.88	2.92	
Total	22.08	21.29	16.83	

hours.

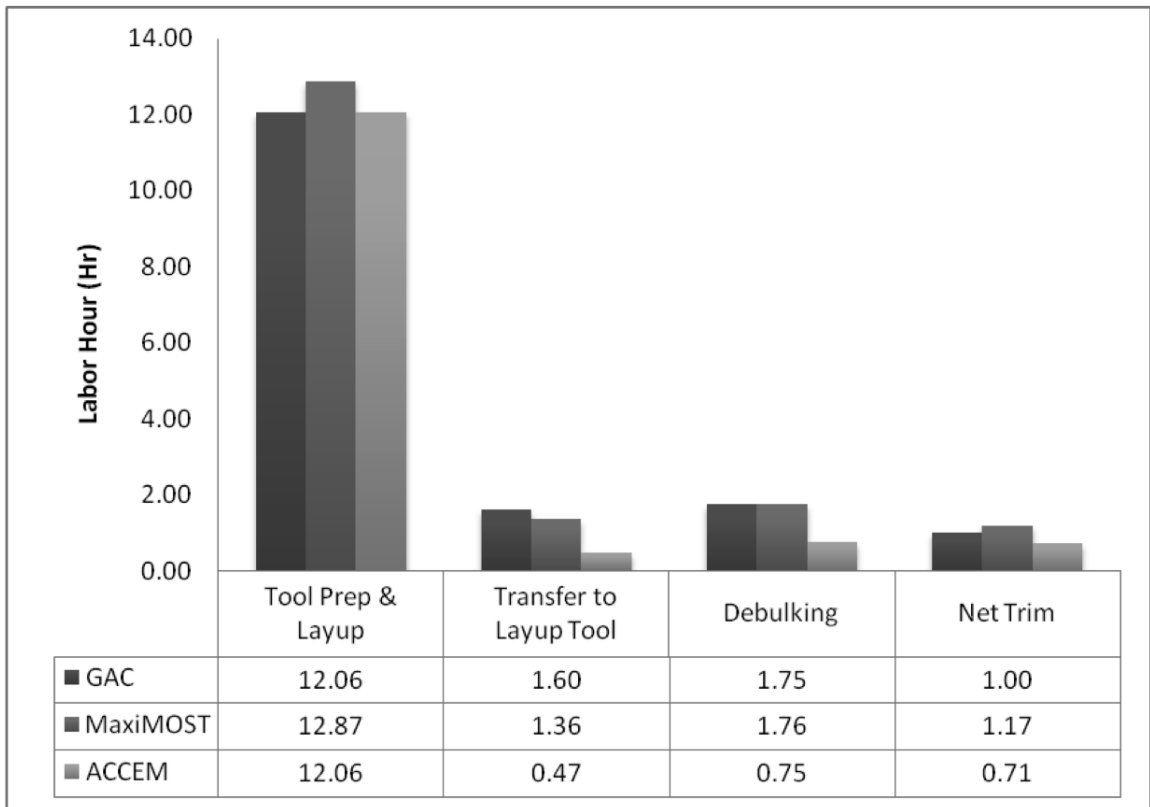
As can be seen from the comparison, although ACCEM equations can be fully utilized for layup process (based on the fact that GAC actual and normalized hours are equal), the prediction error is still significant, and too optimistic. With this in mind the next section will discuss the result of the estimation of this same manufacturing process using MaxiMOST.

Since MaxiMOST analysis is a generative estimating technique, the process is built from ground up. The work breakdown structure of the Graphite Epoxy fabrication found in the GAC report is used to build the manufacturing sequence. The four process steps that are included in this analysis are:

1. Tool Preparation and Layup
2. Transfer to Layup Tool
3. Debulking, and
4. Pre-Cured Trimming

Figure 28 presents the comparison between the actual time data from GAC, estimating result from MaxiMOST, and ACCEM, respectively. As can be seen, MaxiMOST analysis gives more conservative estimates as compared to ACCEM, except a slight optimistic estimate for the Transfer to Layup Tool process.

One disadvantage of using MaxiMOST is the amount of time required to complete each analysis. MaxiMOST requires more setup time and data than ACCEM. This is



**Figure 28:** Normalized Manufacturing Hours Comparison between GAC, ACCEM, and MOST

because of the fact than the entire work breakdown structure has to be created, than the appropriate activity type and an index value has to be assigned to each operation. Finally total time is calculated by summing up the processing time of all operations together. Although this technique gives a better result as compared to ACCEM, it is still impractical in reality. Next section outlines a way to rectify this disadvantage.

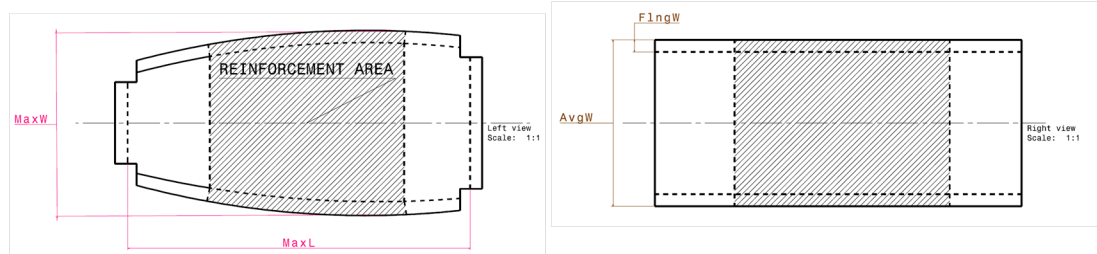
### 5.3.3 Response Surface Equation

The next step is to create a RSE of the processing time to turn individual analysis into reusable estimate relationship. This way, the setup need only be done once and the RSE can then be used for later analyses. Typical response surface equation is in the form

$$R = b_0 + \sum_{i=1}^k b_i k_i + \sum_{i=1}^k b_{ii} k_i^2 + \sum_{i=1}^{k-1} \sum_{j=i+1}^k b_{ij} k_i k_j \quad (2)$$

Where  $b_i$  are regression coefficients for linear terms,  $b_{ii}$  are coefficients for pure quadratic terms, and  $b_{ij}$  are coefficients for cross-product terms (second order interaction).

After considering geometry of the rib part, further simplification can be made to reduce the information needed to describe the geometry. Figure 29 depicts the unfolded shape of the part as seen at the beginning of the layup process. The drawing on the right is the simplified version of the same part. By replacing the actual geometry with simplified rectangular shape, the total number of parameters required to describe the complex geometry can be reduced to 10 parameters. At the same time, the simplification does not compromise the accuracy of the analysis. Figure 30 below lists these parameters. Also shown is the possible range of each parameter, referred to as design space, along with the baseline value that represents the original configuration. The design space will then be explored to get the response in terms of manufacturing time. In the case where geometry simplifications could affect the



**Figure 29:** Rib Design in Flat State, Actual Design vs Simplified Version

Input Parameter (Unit)	Variable	Min	Baseline	Max
Number of 45° Plies in Main Area (Ply)	45M	4.0	10.0	50.0
Number of 90° Plies in Main Area (Ply)	90M	0.0	2.0	10.0
Number of 0° Plies in Main Area (Ply)	0M	0.0	2.0	10.0
Number of 45° Plies in Reinforcement Area (Ply)	45R	0.0	4.0	20.0
Number of 90° Plies in Reinforcement Area (Ply)	90R	0.0	0.0	10.0
Number of 0° Plies in Reinforcement Area (Ply)	0R	0.0	0.0	10.0
Maximum Part Width (in Flat State, inch)	MaxW	0.0	0.6	1.0
Maximum Part Length (inch)	MaxL	12.0	41.8	72.0
Flange Width (inch)	FlngW	0.5	0.9	2.5

**Figure 30:** List of Parameters Involved in RSE Generation

accuracy, CAD geometry can be used to feed the geometric data directly to the analysis, the process which will be demonstrated in the next chapter.

First step in creating a RSE is to list all the input parameters and create a Design of Experiment (DOE) table. This technique is used to study the interactions between the variables and their effects on the response metrics. Another purpose of the study is to eliminate non-contributing variables which will reduce the complexity of the analysis. Based on Pareto Principle, only 20% of the variables are responsible for 80% of the effects. Figure 31 shows the result from the screening test in the form of Pareto plot.

As can be seen from Figure 31, only the first two out of ten variables, 45M and 45R are responsible for 80% of the response. Theoretically, we need only to include these two parameters in the RSE creation. The readers are reminded that for this demonstration, only hand layup process is included, downstream operations has been omitted such as autoclave curing, final trimming and machining, and some parameters

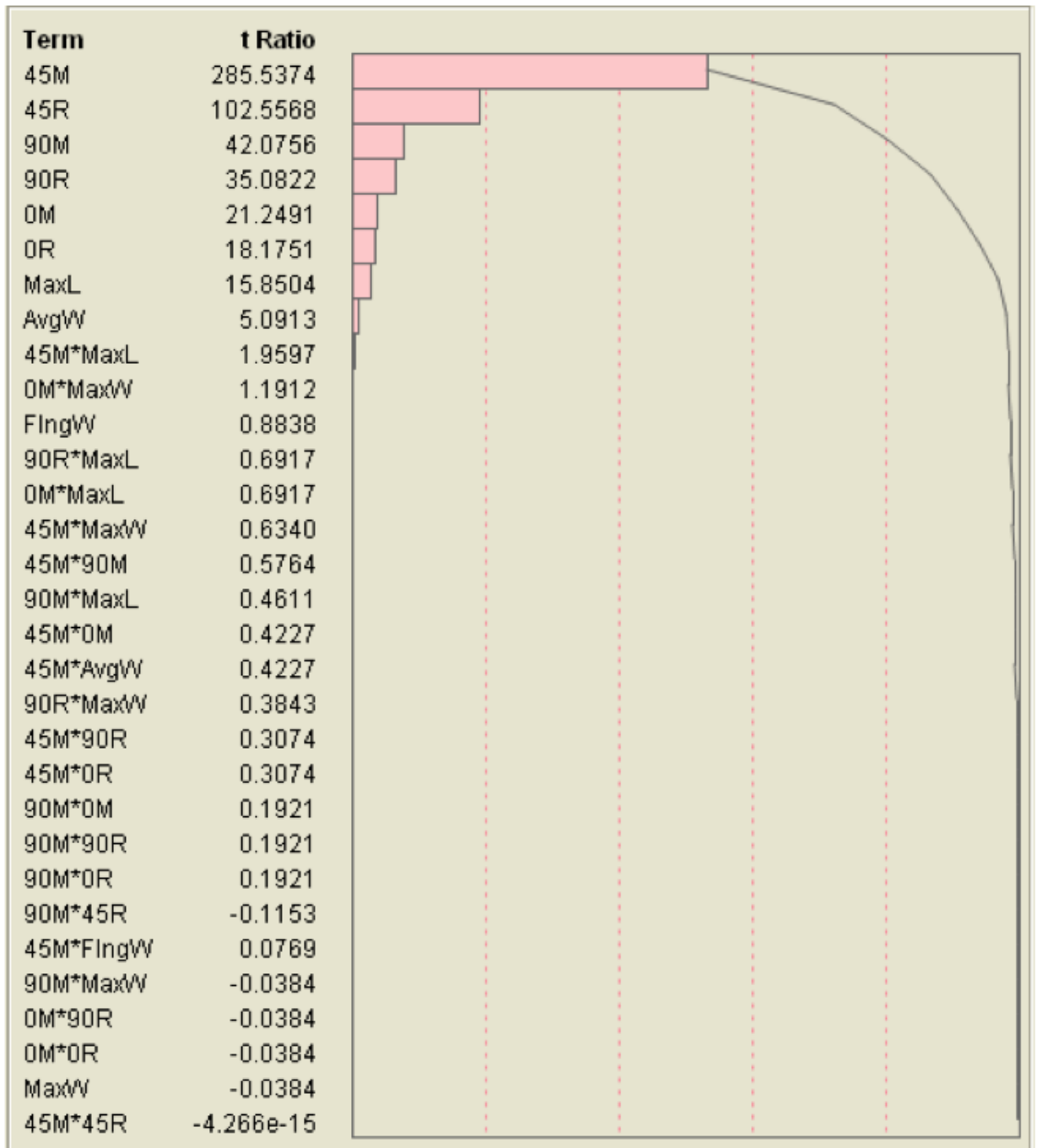


Figure 31: Pareto Plot Ranking the Influence of Each Parameter

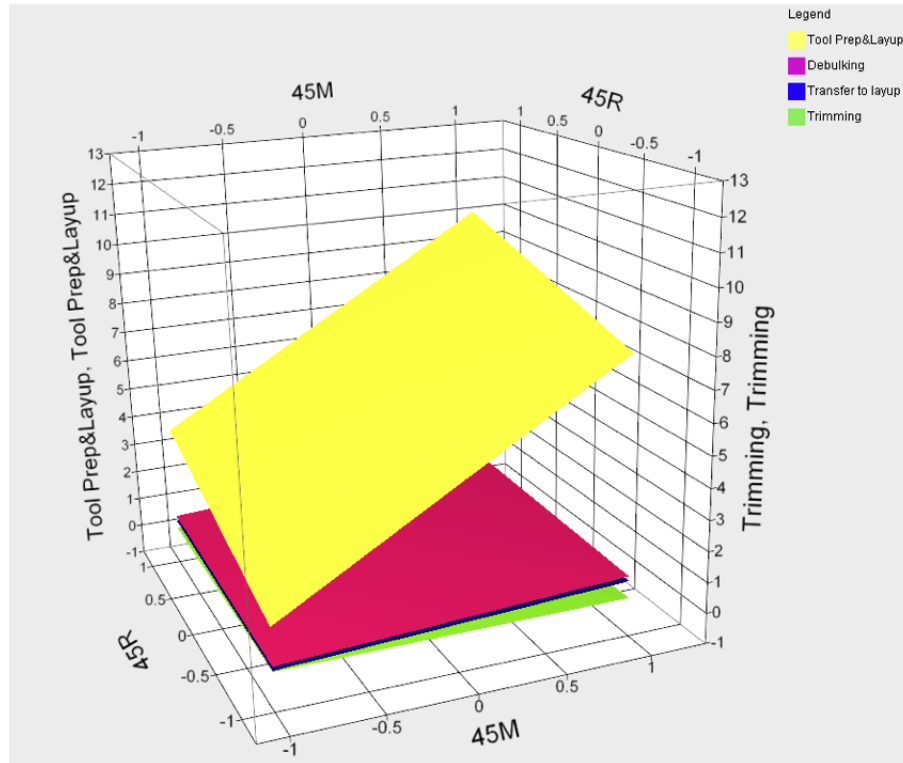
are also simplified. For practical use, more variables may be required for good RSE. For demonstration purposes, seven variables are included in this case, namely all six variables pertaining to the number of ply in each orientation, both in the main and reinforcement region, as well as the maximum length of the part, MaxL. With this decision, approximately 97% of the response should be captured by the RSE.

Once the down selection of parameters is complete, another DOE table will now be created. This table will include only the set of parameter values that are selected from the previous table, more precisely, the seven parameters selected earlier. More parameter values are generally better as the regression process can generate a more refined surface, however, more runs will also be required. Typically, a Central Composite Design (CCD) with 80 cases and 2 center points schema is used to identify the appropriate parameter values. Under this setup, a total of 79 different runs are needed. The picture below shows the response surface of the four operations; Tool Prep and Layup, Transfer to Tool, Debulking, and Trimming as a function of two most influential parameters; 45M and 45R. As can be seen, the more 45 degree plies used, the longer time it takes to finish the layup process. In any hand layup process, the majority of the work involves laying up plies on tool surface — as a result the total time is also influenced most by these two parameters as shown in Figure 32. This phenomenon can be logically explained by the fact that 45 degree ply layup process is much more involved as compared to other orientations.

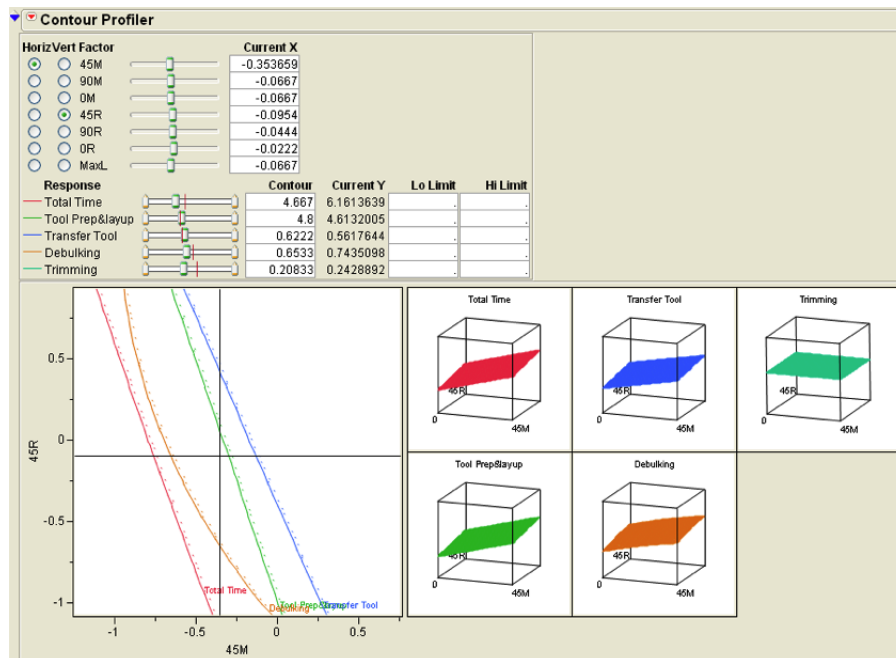
Figure 33 is another representation of the response surface as a function of 45M and 45R, while the other 5 parameters are fixed at their baseline values.

The response model is assumed to be fitted to the data based on a Taylor Series expansion of second order. One criterion for this assumption to be valid is that all higher effects are negligible and can be lumped into an error term with standard normal distribution with a mean of 0 and a standard deviation of 1 [31]. Figure 34 shows the distribution of error for the four processes, and the total time, as compared





**Figure 32:** Response Surface Plot for Estimating Labor Hours for Hand Layup Operation as a Function of Most Important Parameters



**Figure 33:** Response Surface Plot for Estimating Labor Hours for Hand Layup Operation as a Function of All Parameters

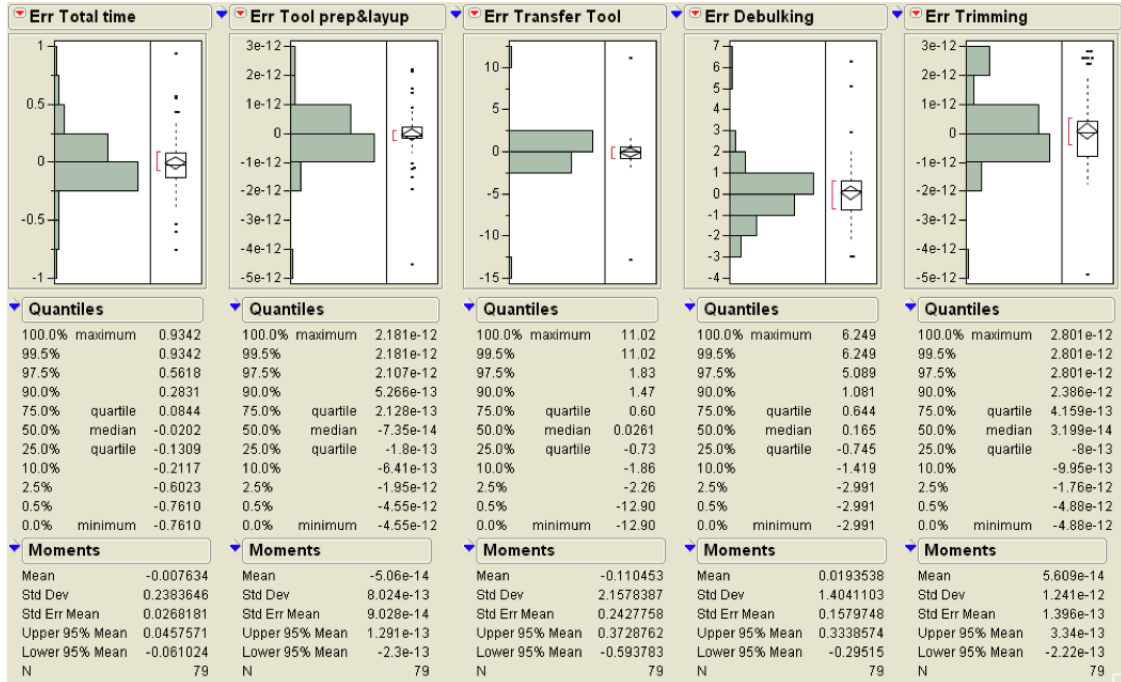


Figure 34: Prediction Error Distribution of RSE

to the actual data from MaxiMOST analysis. Notice that the shape functions of the errors resemble normal distribution with means of 0, with all standard deviations less than 1. This shows that the RSE can be used to estimated processing time for the manual composite layup processes under consideration.

## CHAPTER VI

# SOFTWARE TOOLS DEVELOPMENT AND INTEGRATION

This chapter describes the design tools and system integration required to support the design activity proposed in Chapter IV. Four off-the-shelf software packages were selected as design and analysis modules in the integrated design system. These analysis codes generate sized aircraft, produce 3-dimensional geometry, analyze structural integrity, and provide manufacturing process design support for the product development. An excel-based tool called Hybrid Lifecycle Cost Estimating Tool (HLCET) is created to provide multi-fidelity, flexible, and modular framework for product life-cycle cost calculation. The input information for LCC calculation can be gathered from the four design and analysis modules included in the integrated design system. Many source code modifications and analysis methodology implementations were required. After the individual developments were completed, integration work was done to facilitate concurrent use of the synthesis and analysis tools. The following sections describe the capabilities of the individual modules selected for this research. FLOPS, or Flight Optimization System, was selected as the aircraft sizing code. The FORTRAN source code was not modified, so the use of FLOPS is based on existing capabilities and no special modification is necessary to be used in the integrated framework. CATIA V5R19 was selected based on the availability at the time of the research. Other CAD software packages were reviewed, however, CATIA provides the most comprehensive knowledge-based and automation features, and can handle highly complex geometry creation and assembly constraints. Many advanced design methodologies such as parametric and relational features were implemented to

facilitate automation of geometry generation. Excel-based LCC simulation called Hybrid Lifecycle Cost Estimating Tool (HLCET) was developed based on three costing methodologies. First, the system-level lifecycle cost simulation was based on weight-based component cost estimate relationships found in Tailored Cost Model (TCM). The second methodology apply at the part-level using process-based approach from the study by Northrop Aircraft Corporation called Advanced Composite Cost Estimating Manual(ACCEM) to estimate recurring labor hours for composite parts. Lastly, the activity-based standard time measurement system approach was adopted from Maynard Operation Sequence Technique (MOST) called MaxiMOST as highest fidelity manufacturing standard time estimate. Future modifications and enhancements are encouraged since all the equations and Visual Basic codings were done in Excel spreadsheet which makes it more accessible to the user than typical “blackbox” development of software codes.

## ***6.1 Design Tools***

### **6.1.1 FLOPS**

The Flight Optimization System (FLOPS) is a multidisciplinary system of computer programs for conceptual and preliminary design and evaluation of advanced aircraft concepts. FLOPS is written in FORTRAN and consists of nine primary modules; weights, aerodynamics, noise footprint, propulsion data and scaling, engine cycle analysis, mission performance, takeoff and landing, cost analysis, and program control. The weights module uses statistical/empirical relationships to estimate the weight of components for a group weight statement. Drag polar can be internally calculated or can be user-defined and scaled with variations in wing area and engine size for performance calculations. Engine cycle definition decks are provided for several engines. The mission performance module uses the weights, aerodynamics, and propulsion data to determine the aircraft performance. Several types of missions

can be defined and flown with various climb, cruise, or descent schedules. An extensive takeoff and landing analysis can be performed. Noise footprint contour data can be calculated. The cost analysis module uses group weight statement to calculate RDT&E and production costs, direct and indirect operating costs, and combined total lifecycle cost. The program control module allows the user to analyze a point design, parametrically vary a set of design variables, or optimize a configuration with respect to these design variables for several objective function choices.

#### *6.1.1.1 FLOPS Developments*

The usage of FLOPS in this development is to analyze the fuel required for the aircraft to complete a specified mission schedule. The aircraft propulsion system and aerodynamic performance is defined and fixed over several design alternatives. The fuel required is then become a function of system component weights of the design configuration, among other parameters. The built in component weights module is used to analyze the baseline design. Then component weights of alternative designs are updated by geometric calculation of material volume from CATIA where appropriate. The existing LCC cost calculation functionality provide users with two options. First Johnson's cost model [29] can be invoked in FLOPS in the program control namelist by setting the variable flag  $ICOST = 1$ . Second option for cost calculation is done through a separate lifecycle cost code called ALCCA [40] which can be called directly by FLOPS through the program control by setting  $ICOST = 2$ . However, both cost modules are deactivated throughout the analysis since they are inherently weight-based. The only way to apply higher fidelity results is by modifying the complexity factors scattered throughout the analysis codes. This fact makes it difficult to manage and impractical when apply to design problems in general. It is determined that existing cost modules will not be applicable for the proposed costing methodology. The HLCET is used instead for LCC calculation. The integration of LCC cost

analysis is to be done outside FLOPS through integration software called ModelCenter. The software allows the mapping of FLOPS outputs to the appropriate input level in HLCET module.

### **6.1.2 CATIA**

Computer-Aided Three-Dimensional Interactive Application (CATIA) is a computer-aided design tool used throughout automotive and aerospace industries. It allows complex geometries to be created through a series of geometric manipulations. The basic building blocks for geometry creation are points, lines, sketches, and planes. Part features are then created or extracted by 3D operations such as extrusions, revolutions, surface thickness, pockets and etc. Assembly of parts is done by applying constraints of published part features. CATIA explicitly maintains all the parent/child relationships from the basic building blocks to the assembly constraints through product hierarchical product structure. In other words, the individual part, as well as the entire assembly, can be updated by modifying the associated parameters in the building blocks. Another capability of CATIA that makes it the tool of choice when it comes to automatic geometry creation is that, all the parameters associated with the parts and assemblies can be mapped and tabulated. As a result, the regenerations and modifications of 3D data can be done automatically through parameter updates.

#### *6.1.2.1 CATIA Developments*

the execution of geometry creation is commonly interactive by the nature of CAD system. The baseline wing design was created through Graphic User Interface (GUI) of CATIA environment with the intention to be able to reuse the geometry, and reconfigure it to produce a derivative product. As long as the wing derivative design is based on typical ribs and spars internal construction, and uses skin panels and stringers to create aerodynamic profile, the parametric and relational baseline

wing geometry can be reconfigured to a new design. The current limitations of this model are that the model can generate a wing with up to three spars and sixty ribs. Each spar has to start at the root station of the wing span and extend toward the tip, although two of the spars have to stretch the entire wing span, the third spar which is located in between the two spars does not. The number of ribs can go up to twenty ribs per row (i.e. leading edge row, the row between front spar and second spar, and the row between second spar and third spar). As mentioned earlier, the entire geometry parameter is first defined in an Excel input spreadsheet. The wing model is divided into three successive modules. First the module called “Reference Datums” is used to create a set of points, lines and planes that define the outline of the physical location of the wing. The inboard root profile is first defined with respect to the aircraft nose location, aircraft body x-axis, incident angle. The airfoil shape is constructed using the standard airfoil x-y coordinate locations imported as part of the input file. The wing plane is then created based on the anhedral or dihedral angle. The wing planform outline is then created using wing span, sweep angle, and taper ratio. The last object in the first module is the internal structural layout sketch. Individual lines in the sketch represent the center line of the ribs’ and spars’ locations. The user can activate and deactivate the individual lines based on the number of ribs and spars required. The second module in the wing geometry is the “Reference Surfaces.” The module creates wing Outer Mold Line (OML) based on the root and tip aerodynamic profiles. The ribs and spars reference surfaces are the extension of the centerlines perpendicular to the wing plane and limited by the top and bottom mold line. The last module contains the actual solid geometry of the wing model created by applying thicknesses as defined in the input sheet to reference surfaces. This method of parametrically generate the wing design through one single input file, using the steps outlined above, has proven to be the most effective way to create complex wing geometry in a relative short time. The number of interpart

operations are limited to a minimal in order to reduce possible errors and facilitate future modifications.

### 6.1.3 HLCET

The Hybrid Lifecycle Cost Estimating Tool (HLCET) consists of three modules namely Weight-based Parametric LCC Module (WbPL), Process-based Recurring Manufacturing Module (PbRM), and Activity-based Time Measurement Module (AbTM). One single excel file was created which contains the total of 29 worksheets that links the three modules during the LCC simulation. WbPL module takes in the group weight statement from FLOPS and user-defined system-level programmatic assumptions to calculate total LCC of the system (RDT&E, Production, Support Investment, and Operation and Support costs). Manufacturing labors are calculated based on the group weight. The labor hours are then used to calculate manufacturing and manufacturing support activity (QA, Engineering, Manufacturing Engineering, Tooling, Management, and etc.) costs by applying appropriate factors and rates. PbRM module can then be used to calculate more accurate manufacturing labors of composite parts by taking in part-level geometry information from CATIA and process selection inputs. Part weight subjected to PbRM module is then subtracted from the group weight statement and its subsequence calculations in the WbPL module. The new manufacturing labors are then inserted into the manufacturing labor field. The subsequence calculations are then performed to get the updated LCC. The last module, AbTM, serves as the process model modifier in PbRM. New process model can be constructed by the user. First, the operation activities are listed. Then, the activity types associated with the activities are defined. The tool then automatically assign time estimate equation based on the activity type selected, along with the independent variable required for the calculation (i.e. area, length, etc.) After the new process is created, the PbRM module is then populated with then new process



selection option.

#### *6.1.3.1 Weight-based Parametric LCC (WbPL) Module Development*

The development of WbPL module depend largely on the CERs and the hierarchical calculation taken from the Tailored Cost Model (TCM). The user is prompted with “INPUT” worksheet where a weight statement is populated by FLOPS outputs. The user can then modify individual component weights if difference weight information is desired. An example case is where new weight calculation from CATIA can be used to replace historical based calculation from FLOPS. The “Programmatic Factors” is the second worksheet that needs to be filled out, otherwise the default values will be assumed. Table 3 provides the list of all programmatic factors along with the default values. The “Learning Curve Factors” worksheet allows the user to define the learning curve slopes for the system elements to calculate recurring production costs. The system elements are grouped general characteristics of the process namely composite structures, conventional structures, propulsion, fixed equipments, avionic installation, armament installation, and integration/assembly/checkout. More shallow learning slopes are used for production units greater than 200 to represent reductions in learning improvement seen in the typical manufacturing system. Non-recurring engineering, and tooling costs are calculated from estimated engineering hours. Operational Flight Software (OFS) development costs are calculated based on thousands of lines of deliverable source instructions (KDSI). Once the input parameters are populated, several estimating routines are performed. Figure 35 and 36 provide heirarchical view of the several estimating routines within WbPL module and the breakdown structure of total system lifecycle cost elements, respectively.

The principal cost elements associated with test and mockup activity are test engineering and development labor. Ground test, flight test, and mockup activities are modelled separately, with algorithms for the engineering and development efforts.

**Table 3:** Programmatic Factors

PROGRAMMATIC FACTORS	VALUE
Quantity of Prototypes	0
Quantity FSD Fight A/C	6
Quantity Production A/C	652
Max Delivery Rate/Month	7
Test Requirements	
- Static Testing	Y
- Fatigue Testing	Y
- Iron Bird Testing	Y
- Wind Tunnel Occupancy	15000 HRS
- Misc Qual Testing	Y
- Flight Test Hrs	4000 FLT HRS
- Class II Mockups	Y
- Class III Mockups	Y
System Service (O&S) Life	20 YEARS
Quantity Force A/C	612
Flight Hrs per A/C Year	364
Quantity A/C per Squadron	9
Crew Ratio	1.5
Number of Engine	1
Shaft Horse Power (each engine)	6000

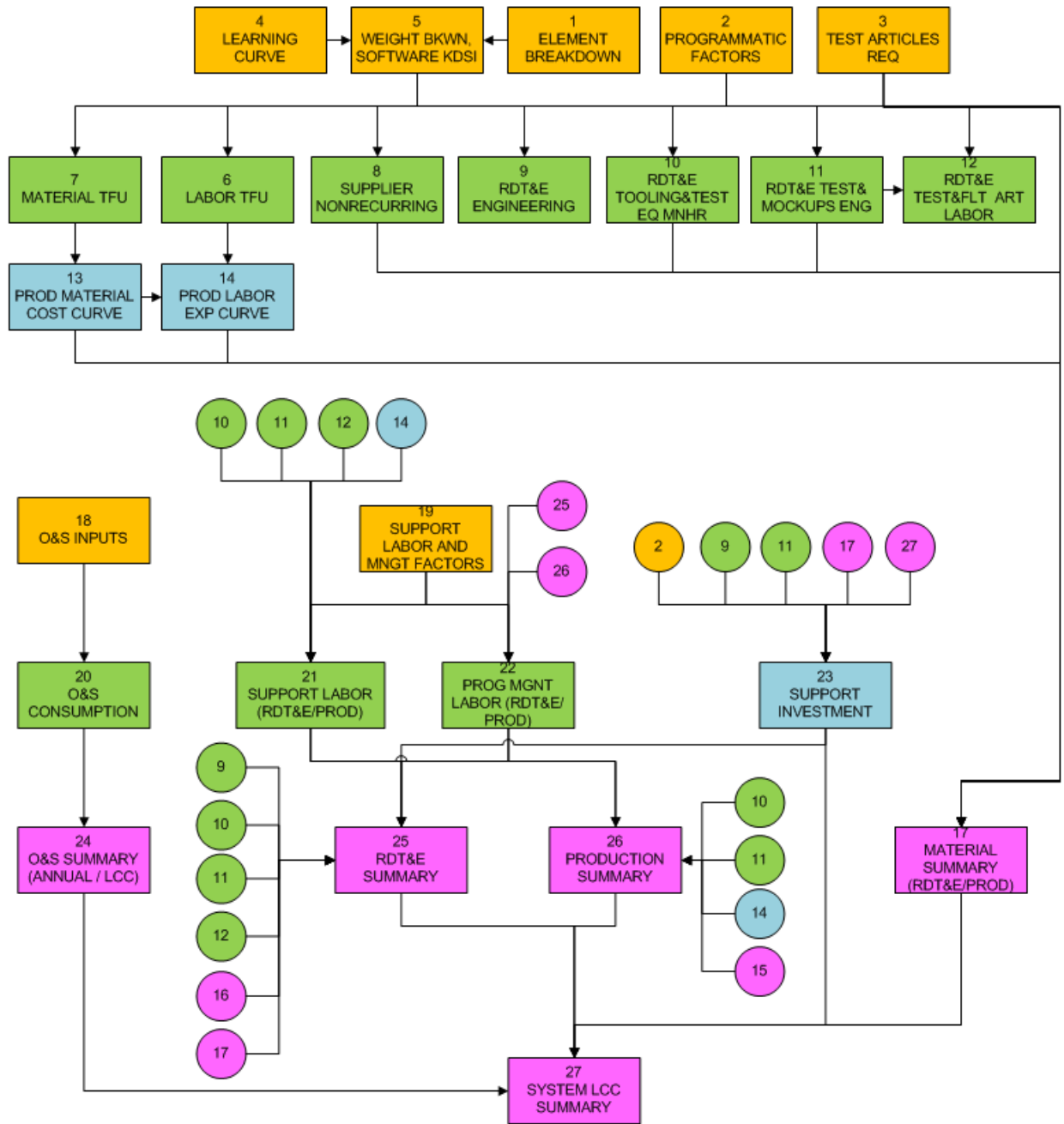


Figure 35: Diagram of Estimating Routines within WbPL Module

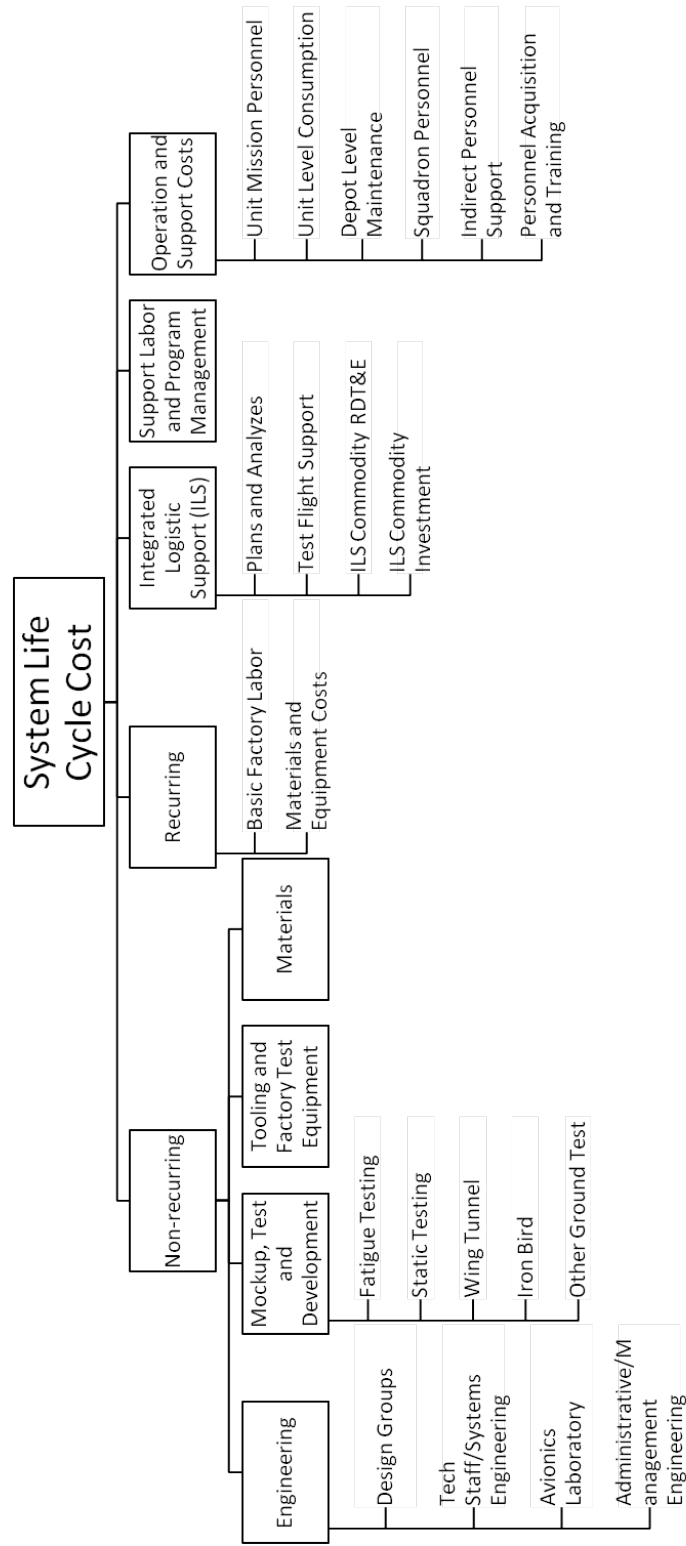


Figure 36: Cost Element Breakdown Structure of System Life Cycle Cost

**Table 4:** Learning Curve Slopes

SYSTEM ELEMENT	LEARNING CURVE SLOPES			
	PRODUCTION		MATERIAL	
	UNIT 1 - 200	UNIT 201 & Up	UNIT 1 - 200	UNIT 201 & Up
Composite Structures	82%	86%	92%	95%
Conventional Structures	80%	82%	92%	95%
Propulsion	82%	85%	92%	95%
Fixed Equipment	82%	85%	92%	95%
Avionic Installations	85%	85%	92%	95%
Armament Installations	82%	85%		
Integration/Assy/Checkout	76%	78%		

Five discrete test activities comprise the total ground test activities namely fatigue testing, static testing, wind tunnel, iron bird, and other ground tests. These tests are estimated as a group and use manufacturer's empty weight as the independent variable. Recurring manufacturing costs are developed by first estimate the Theoretical First Unit (TFU) labor hours. The learning curve slopes as listed in Table 4 are then applied to the appropriate system elements to calculate subsequent unit manufacturing labor hours called Basic Factory Labor (BFL). Finally labor rates are then applied to arrive at recurring costs. Material costs include the raw materials, casting/forgings, and purchased parts required to fabricate and assemble airframe structures. Operation and Support costs are the direct and indirect expenses associated with operating the system. WbPL module uses the architecture of the USAF Cost Oriented Resource Estimation (CORE) O&S model published in AFR-173-13 [27]. The CORE model develops annual squadron operation and support costs which can be used as a basis for estimating total O&S costs over the system service life.

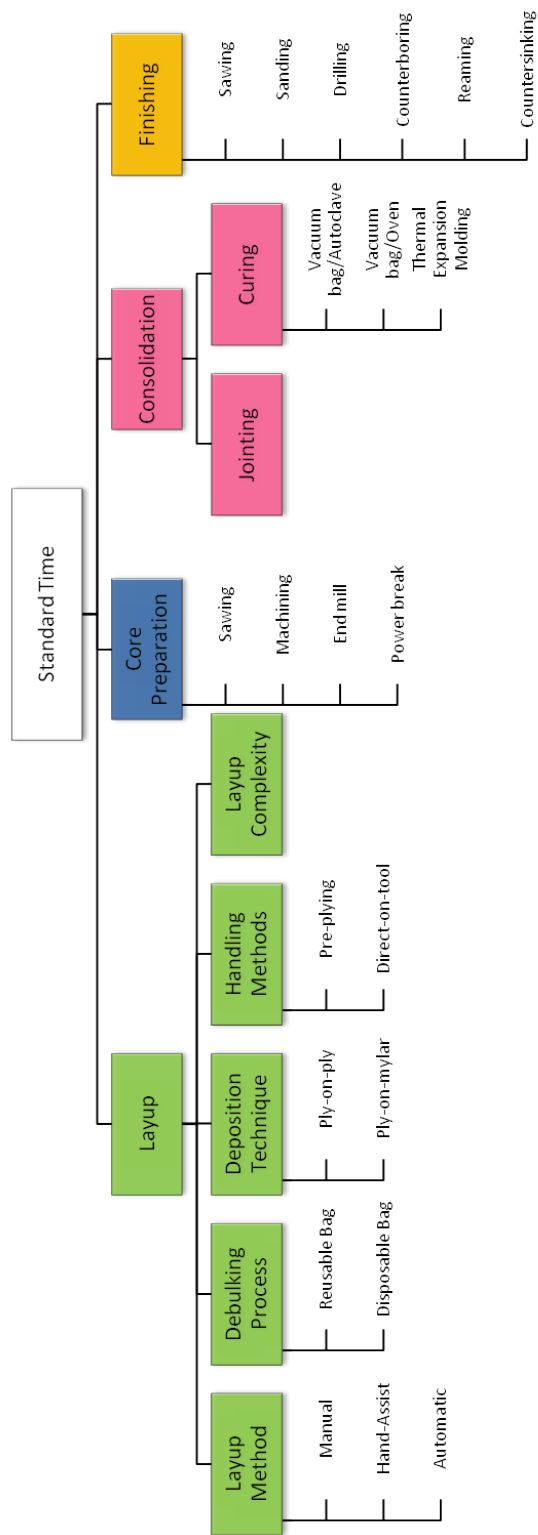
#### 6.1.3.2 Process-based Recurring Manufacturing (PbRM) Module Development

The main objective of the PbRM development was to supplement the weight-based parametric model with a model that is more appropriate for parts in which the costs to produce do not necessarily depend on weight, like composite parts. The PbRM module is tightly integrated with WbPL module. Parts that are subjected to

**Table 5: ACCEM Parameter Descriptions and Default Value**

SYMBOL	DESCRIPTION	VALUE / DEFAULT CALCULATIONS	UNIT
A	Area of ply, or greatest ply area of stack or layup, in square inches	0	sq. in.
PartLength	Longest dimension of part	=sqrt(A)	in
L	Total length of ply strip, in inches	=PartLength*CEILING((Area/PartLength)/TapeWidth*Plies	in
Lb	Length of bendline	=sqrt(A)	in
Ra	Radius of curvature	1	in
F	Flange width	1	in
P	Perimeter of Layup	0	in
PlyTh	Ply thickness	0.039	in
Th	Part thickness	0	in
Plies	Total number of plies in layup	=CEILING(Thickness/Plythickness,1)	plies

process-based calculations are automatically taken out from the weight-based calculations. The user is required to provide input information related to the part geometry and the manufacturing process specific to the part configurations. The outputs from PbRM are the updated part manufacturing labor hours which are then integrated back into the top-level life cycle cost calculation. The user-provided input are the area, layup perimeter, and thickness of part. These are the major parameters contributing to the analysis. Others are account for part complexity and extra process step that are less important. In the case where no detailed information is not available, default calculations is assumed. Process selections are done through dropdown lists. Layup type, debulking process, and layup complexity are the three categories of Layup operation needed to be defined. Consolidation type is the option related to part curing (solidification) and pre-cure assembly process. The available options for consolidation process are 1) Vacuum bag/Autoclave 2) Vacuum bag/Oven and 3) Thermal Expansion Molding. Lastly the Finishing operation are the activities related to any post-cure operations, such as drilling, reaming, and etc. Figure 37 provide the schematic of the composite manufacturing process and options available within PbRM module. Table 5 provides the list of input parameters for PbRM module.

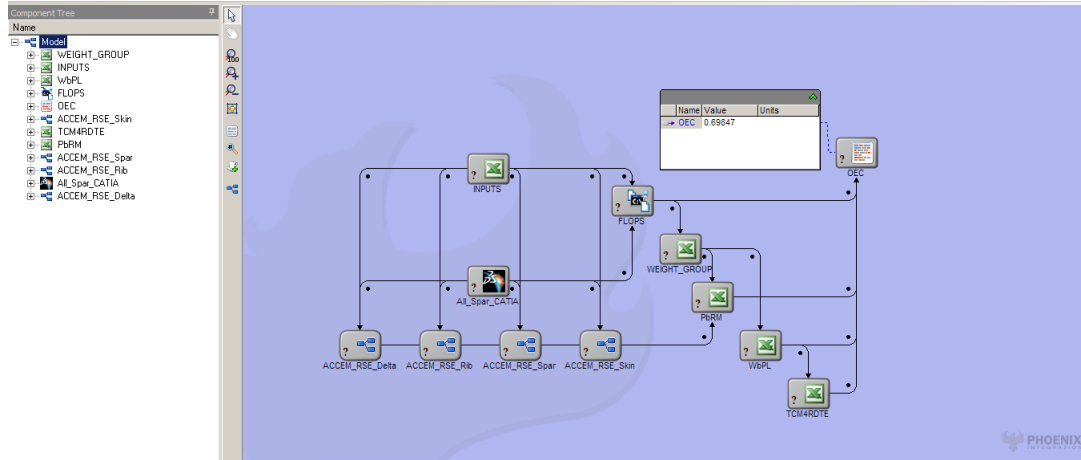


**Figure 37:** ACCEM Schematic of Process Selection Options

### 6.1.3.3 Activity-based Time Measurement (AbTM) Module Development

AbTM module was developed to be used as detailed manufacturing standard time estimation using a time measurement system called Maynard Operation Sequence Technique (MOST). The MOST procedure involve many manual inputs from the user. The selection of index values for the standard time calculation is done through form filling. To mitigate this cumbersome procedure, an excel VBA-based macro is created to provide knowledge database to help the user select the appropriate index value and automate the calculation of process standard times. The database is divide into three sections corresponding to the activity type namely A, B, and P which stand for Action Distance, Body Motion, and Part Handling, respectively. The user is then select the category and sub-category of of the activity type that correspond the to activity in question. The macro then matches the input and return the corresponding Time Measurement Unit (TMU) to the user. Once the value is accepted by the user, subsequence activity can then be analyzed. The index values from all the activities are summed up and converted into actual time automatically. The simply table lookup feature called “VLOOKUP” in excel is used to populate the correct sub-category options based on the preceeding selection. Appendix D provides the Microsoft Visual Basic macro that acts as a reference engine accompanying the activity detabase. The last input before the macro can retrieve the data from the database is the frequency of action, or the number of repetitions. In some activities, such as Walk, Applying tape, and Wipe area, the index values range in a contineous fashion with respect to the frequency of action, such as length of walk, length of tape, and area to be cleaned, respectively. The index value calculation for these types of activity can be simplified to the estimate relationships through regression analysis. When the activity in this category is selected, the user is then prompted with the dependent parameter to be input in the adjacent field.





**Figure 38:** ModelCenter Environment and Analysis Integration

## 6.2 System Integration

This section discusses the integration of all the analysis tools together in a single environment that allows information to be transferred effectively. Each analysis module is guaranteed to be performed on the most up-to-date information. Modelcenter software is selected for the implementation of analysis tools integration. It provides the ability to link several analysis tools that can be executed in sequential or parallel fashion. The execution control manages the flow of information as specified by the designer. Any parameter changes will trigger the execution of affected modules. The overall information flow is depicted in Figure 38. The figure shows the fully integrated analysis environment consisting of 9 modules, namely INPUT, FLOPS, CATIA, WEIGHT\_GROUP, PbRM, WbPL, TCM4RDTE, and OEC module.

### 6.2.1 Execution Control

The process starts from defining aircraft configuration as well as wing design parameters within *INPUTS* module. *FLOPS* then analyzes the design configuration based on a mission profile to calculate fuel required and group weight statement. At the same time, *CATIA* takes the basic aircraft configuration defined in the *INPUTS* module and parametrically constructs the wing structure model. The resulting 3D

data from CATIA can be used to validate group weight produced by FLOPS and updated as necessary. The corresponding weight output plays a crucial role in predicting composite wing weight. *WEIGHT\_GROUP* module plays an important role in the analysis framework by collecting weight output from FLOPS and CATIA modules, and then parsing the appropriate weight elements to the corresponding cost analysis modules. Composite components from CATIA are first analyzed by parsing geometrical measures to the four blocks on the lower left corner in figure 38. These blocks represent metamodel for manufacturing time estimates for the various wing structural components. The total manufacturing time estimate is then fed into Process-based Recurring Manufacturing (PbRM) module for composite production cost calculations. At the same time, CATIA model representing metallic parts provide weight data to Weight-based Parametric LCC (WbPL) module through *WEIGHT\_GROUP* block. The combined production cost output is then fed into TCM4RDTE which provides aggregated LCC results corresponding to the product life cycle cost elements — RDT&E, Production, Support investment, and Operation and Support cost. The final step in the design evaluation is to form a value function, *OEC* from multiple design characteristics, including Mission Capability Index (MI), Structural Quality Index (SI), and Ownership Cost Index (OI). The environment setup as described can be used to analyze all five design alternatives. The modules involving composite material calculation can be deactivated when metallic construction is selected for the design.

### 6.2.2 Practical Consideration of Software Integration and Automation

Several discrete design alternatives can be simultaneously analyzed through the design environment setup as described in the previous section. Component weight estimates from the sizing code are based on empirical data. When possible, this estimates should be replaced by detail analysis on specific structural layout for the

design. A finite element analysis results in determination of the proper weight of the modeled structure. The idea of having a structural analysis code linked with the design environment is considered but dismissed for two reasons. First, the time-intensive development of finite element models of the design alternatives prevent direct integration of the software package to the system. Each analysis requires generation of finite elements representing the parts, define connection configuration between the part interfaces, and assigning material type from the material library, and finally setting up the boundary condition for the analysis. The time it takes for an analysis cycle is on the order of several days as oppose to several seconds for other analysis modules in the system. Second, the quality of the mesh generated by macro function cannot be easily and consistently controlled without human intervention. The poor mesh generation can result in invalid solution, and excessively long analysis time. As far as the determination of design value through OEC is concerned, a majority of FEA analysis can be automated, but not completely. The user needs to confirm the quality of the auto-generated mesh and modify if necessary. The connection interfaces and material assignment need to be provided. Finite element analysis in this study is performed manually for each design alternative. The result of the analysis is then included in the OEC module.

### ***6.3 Summary***

This chapter described the computer implementation of the proposed design methodology in Chapter IV. Developments and extensions of all codes were discussed. The functionality and effectiveness of the system is demonstrated in the next chapter for system and model validation on several wing structural layouts for hypothetical aircraft wing.

## CHAPTER VII

### IMPLEMENTATION

The application of Stochastic Process-based Cost Integration with IPPD methodology is demonstrated in this chapter. The content follows the Systems Engineering method of synthesizing a new or derivative product from customer requirements definition through conceptualization of design alternatives, preliminary and detailed design stages.

#### **7.1 Introduction**

The rapidly changing world market today make for an increasingly intense competition in all economic sector. Increasing globalization requires rapid product development cycle, utilization of advance technologies both in material science and manufacturing process, while maintaining affordability through robust design solution. Complex aerospace system design has undergone many transformations over the decades. The most prominent being the paradigm shift from Performance-at-Any-Cost to Affordability-Based Design and Value Driven Design. These new design philosophies came about when advance materials become one of the main focus in many, if not all, new aerospace system developments. The performance increase can sometime mislead the fact that the final product must be affordable, and the benefit from integrating new technology does not compensate for the lack of knowledge in terms of manufacturing and product quality.

One of the biggest challenges in modern system design is how to find the best solution from a family of solutions, all of which meet or succeed the fuzzy customer requirements. The consideration of the solution needs to also stay abound by technological, economical, and environmental constraints. The best solution could be one

of the following;

- one that meets the requirements (performance based requirement)
- one that performs the best (highest performance)
- one that cost less (lowest cost)
- one that has highest chance of realization (lowest risk)

The likely answer is the one that is the blend of all the above. But it is becoming more difficult as the criteria become more complex. Many solutions seem to work well and difficult to distinguish. In cases where small variations in the problem statement can lead to vastly difference solution, we want to look at the design that is robust to those variations both internal and external. In this case study we shall look at the variations in customer-stated requirements and their weighted importance, as well as engineering uncertainties stem from lack of complete knowledge and error of predicted outcome.

### 7.1.1 Value Driven Design

No one weapon system can be operated alone. They are part of the overall system-of-systems architecture where each small piece plays a critical role that attributes the success of the overall objective. As a result, one best aircraft is not likely to attribute to the success of the overall objective. it is an interplay between difference parts of the whole system. This argument is trying to lead the reader to the subject of robust design methodology where the optimal design is not necessary the best performer, but the one that remain optimal or near optimal even when the objective or requirements have changed. An example is the tradeoff between an ultimate weapon system that is very expensive to make, as oppose to less optimal system, but more efficient and can be mass produced. Example of this is the number of aircraft produced. More aircraft

produced, less cost per aircraft from economics of scale, more potential sorties, but the aircraft itself may have to be less advanced to minimize risk in terms of scheduling, and technology readiness level.

This methodology expands traditional multi-attribute utility function to include risk at the top level and propagate throughout the system components. It is in line with the philosophy of value-driven design approach being investigated by the AIAA Value-Driven Design Program Committee [12] to increase awareness to design teams to create a higher performance, more affordable product through a clear and unified set of Design Values.

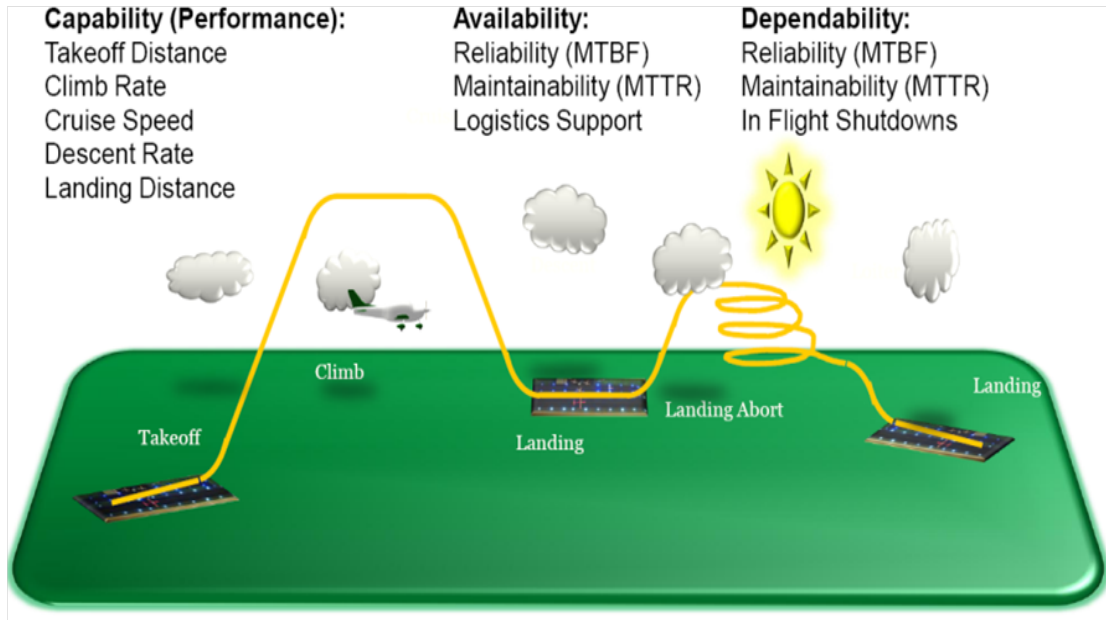
For these reasons, the overall design integration framework taken in this dissertation makes the redesign of a generic fighter aircraft wing an excellent case study to demonstrate the applicability of the design environment for quantifying the manufacturing and cost implication of alternative wing design concepts. The remaining of this chapter takes the reader through the systems engineering process of alternative evaluation outlined in Chapter IV using F-68F Sabre aircraft as example. The demonstration will conduct IPPD tradeoff at all three levels from system-level to part-level, identify and manage risk over the design iterations.

### **7.1.2 Define the Problem**

#### *7.1.2.1 Assumption*

A hypothetical aircraft redesign problem representing typical scenario of today aerospace and defense industry paradigm is examined. The need for improvement over existing wing design which is predominantly metal based to incorporate more advance materials and manufacturing technology has been one of the fascinating areas of interest for over a decade and still ongoing.

The conflicts between various customer requirements are inherent in any product development and product going through an update cycle. Most notably is the issue of higher performance at lower or affordable cost. Aircraft design environment is



**Figure 39:** Generic Mission Description and Performance Metrics

no difference. The numerous potential stakeholder issues can be filtered through and determined their relative importance among each other. Typical customers' desires for improvement can be grouped into following four main areas; Availability, Dependability, Capability, and Affordability.

Figure 39 shows a simple aircraft mission profile which includes takeoff, climb, cruise, and landing with some contingency on landing abort mission. Also shown in the figure are the elements of customer desires grouped into the four categories as mentioned, although affordability is not explicitly shown, it is an inherent requirements for any realizable project.

#### 7.1.2.2 Relative Importance among Stakeholder Issues

Treatment of the stakeholder issues is likely to be prioritized due to the fact that the various requirements have different levels of importance since they come from different voice-of-the-customers. In order to determine the relative importance among the issues as well as the distribution of those relative preferences, Prioritization matrix has been utilized as shown in Figure 40 below.

Prioritization Matrix	Reliability	Maintainability	Logistics Support	Survivability	Endurance	Payload	Maneuverability and Agility	Range	Speed	RDT&E	Acquisition Cost	Operations & Support Cost	Disposal Cost	RELATIVE IMPORTANT
Reliability	5	5	0.2	1	0.2	0.1	0.2	0.2	1	5	1	10	0.055	
Maintainability	0.2	10	0.1	0.1	0.1	0.1	0.1	0.1	0.1	1	5	1	5	0.044
Logistics Support	0.2	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.2	0.2	1	1	0.006	
Survivability	5	10	10	5	1	1	5	1	5	10	5	10	0.130	
Endurance	1	10	10	0.2	0.2	0.1	1	0.1	5	10	10	10	0.110	
Payload	5	10	10	1	5	0.2	0.2	0.2	5	5	10	10	0.118	
Maneuverability and Agility	10	10	10	1	10	5	5	1	5	5	5	10	0.147	
Range	5	10	10	0.2	1	5	0.2	1	5	5	10	10	0.119	
Speed	5	10	10	1	10	5	1	1	5	5	10	10	0.140	
RDT&E	1	1	5	0.2	0.2	0.2	0.2	0.2	0.2	0.1	1	5	0.027	
Acquisition Cost	0.2	0.2	5	0.1	0.1	0.2	0.2	0.2	0.2	10	10	10	0.070	
Operations & Support Cost	1	1	1	0.2	0.1	0.1	0.2	0.1	0.1	1	0.1	0.1	0.010	
Disposal Cost	0.1	0.2	1	0.1	0.1	0.1	0.1	0.1	0.2	0.1	10	10	0.023	

**Figure 40:** Prioritization Matrix of Customer Requirements

The result from the customer requirement prioritization matrix revealed that all area of capabilities; Endurance, Payload, Maneuverability, Range, and Speed are among the top matrices as well as all Cost elements with respect to the overall importance. This finding is typical with today paradigm of Value-Driven design and affordability based acquisition, where customers are no longer willing to pay whatever fee stipulated in order to get outstanding performance as in the case of the former performance driven paradigm. Instead a trade has to be made between performance and lifecycle costs.

### 7.1.2.3 Quality Function Deployment (QFD)

Quality Function Deployment (QFD) or The House of Quality (HOQ) is a formal method for capturing the user's requirements and mapping them into product and process attributes. The method relies on constructing a series of complementary matrices describing the association between the voice-of-the-customer and many product



characteristics, such as the product features, manufacturing processes, support characteristics, and etc. The objective of QFD is to separate the important parameters based upon the customer's desires and to understand the effect of product design on downstream processes.

The QFD as shown in Figure 41, is used to aggregate and give visual representation to the relationships between the customer's requirements (WHATs) and the product and process metrics (HOWs).

Customer requirements (WHATs) are shown on the left column with their relative importances came from the brainstorming sessions and tools like Affinity Diagram to collect all the ideas from all stakeholders, and rank them through the use of Prioritization Matrix similar to the one previously shown. Across the top part are the engineering characteristics that characterize the system under development. The Direction of Improvement identify potential tradeoffs among the engineering characteristics, most notably are the product and process/cost parameters that are always competing in the opposite direction. The far right column is the assessment of competitors or products with similar range of capabilities. The main part of the QFD HOQ correlates between pairs of customer desires and engineering characteristics. This provides important information about which parameters are more important than the others based on the relative important of the customer requirements. The relationships include Strong, Medium, and Weak with values 9, 3, and 1 respectively. The effect of the correlations can be graphically seen in the Relative Important row. The bottom most row shows the Difficulty Weighted Importance (DWI) of engineering characteristics when risks of achieving the target are incorporated.

In the secondary level QFD, Figure 42, the engineering characteristics from system level are mapped onto the wing level requirement (WHATs), along with their respective organizational difficulty weighted importance weightings. The same process of constructing the QFD at the wing level mirrors that of system level. However,



the focus is instead on wing level characteristics in response to system level requirements definitions. The Alternatives Assessment compare qualitatively how the design alternatives stack up among each other in the various area of product and process metrics.

**Incorporating Risks in Customer Requirements** Since several voices of the customers can be included; user, buyer, builder, acquisition expert, and many others, ranking these needs are a team effort. QFD that incorporates needs from all area of customer viewpoint can be regarded as an effective communication medium for the product development team.

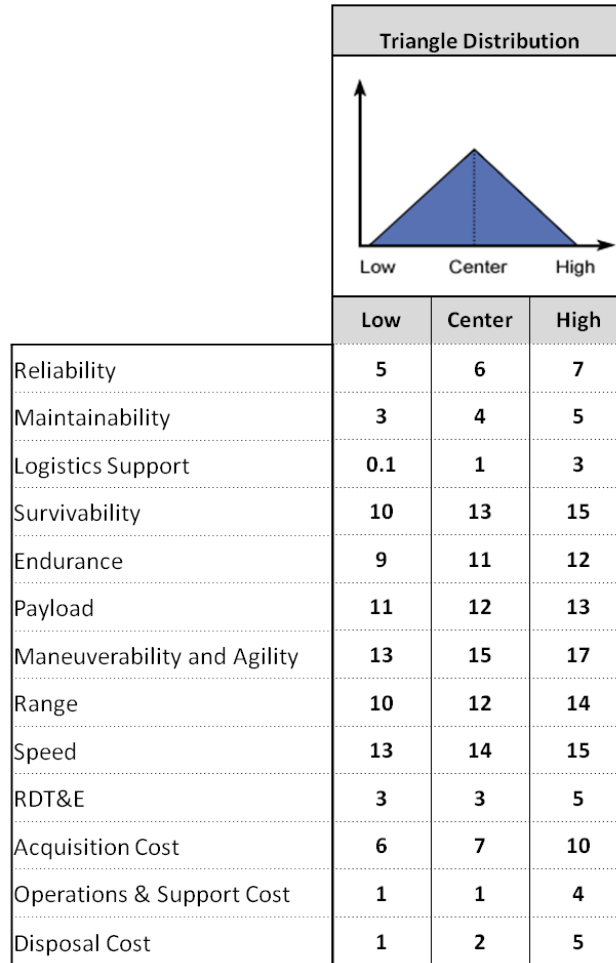
In this case, the QFD can be modified to handle uncertainties associated with difference voices of the customers, rather than using the average effect of the combined requirements as one single point of reference. The inclusion of uncertainties at this level help emphasize the less important ideas that otherwise may have been thought of as not important. This study can potentially point out those secondary metrics that may have high variation of preferences among different types of customers.

Figure 43 shows the result from the interview of various target customers, and theirs rating of relative importances between the same set of metrics. After the interview, the results are summarized in terms of the relative importance midpoint and the corresponding low and high points. The distributions can be represented by Triangular distributions as follow.

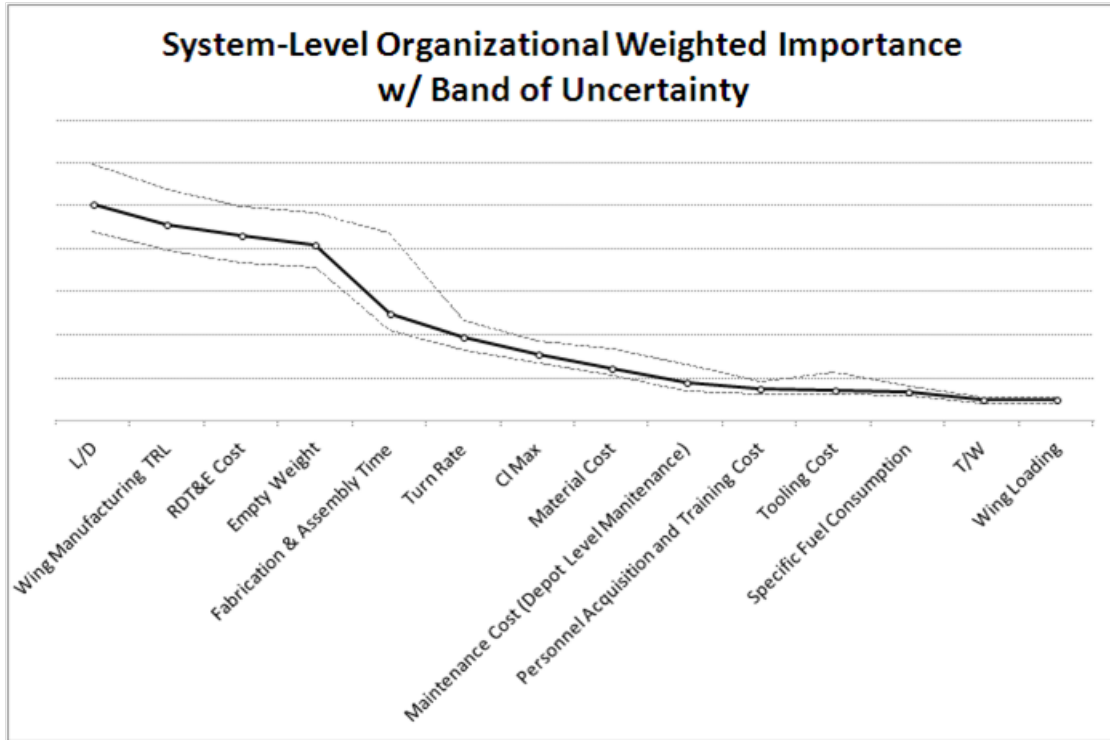
Based on the variations of relative importances generated from the interview session, these values can then be incorporated in the original QFD to generate an interval of weighted importance for each product and process metrics. Figure 81 below shows the uncertainty band of system level Difficulty Weighted Importance (DWI) rearranged from most importance metrics. As with typical interpretation of the QFD result, the top four metrics are perceived as more important than other issues, however

Customer Importance		HOWs (Title)																			
		Product Metrics										Process Metrics									
		Aerodynamics and Weights										Structural Integrity			Cost						
		Wing Area	Skin Weight	Rib Weight	Spar Weight	Fuselage Weight	Fuel Weight Required	Systems Weight	Paint Weight	Wing Loading	Thrust-to-Weight Ratio	Structural Factor of Safety	Max. Linear Deformation	Max. Strain	Max. Stress	R&D Costs	Manufacturing Cost	Support Investment Cost	Wing Level Maintenance Cost	MTTR	Production Rate
Direction of Improvement		↑	↓	↓	↓	↓	↑	↓	↓	↓	↑	↓	↓	↑	↓	↓	↓	↑	↓	↑	
WHATs (Title)	CI Max	5.3	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	
	Empty Weight	14.0	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	
	Turn Rate	6.8	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	
	L/D	17.2	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	
	SFC	2.3	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	
	T/W	1.7	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	
	Wing Loading	1.7	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	
	RDT&E	14.7	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	
	Material	4.2	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	
	Tooling	2.5	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	
F&AT - Fabrication & Assembly Time	6.6	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕		
Maintainability	3.0	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕		
PA&T (Personnel Acquisition & Training)	2.8	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕		
Cost	Wing Manuf TRL (Technology Readiness Level)	15.8	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕		
Alternative Assessment	Design 1: All Metallic	1	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	
	Design 2: Comp. Skin	2	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	
	Design 3: Skin and Spar	3	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	
	Design 4: Black Au.	4	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	
	Design 5: All Comp.	5	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	⊕	
Baseline		315 sq ft	248.9 lb	103.6 lb	127 lb	82.15 lb	3352 lb	986.34 lb	115.01 lb	54.85	0.39	2.355	1.72 in	0.461	120 Mpa	2255 \$	12632 \$	1587 \$	22686 \$	0.5 h/flight	2155 min/s/wing
Target Values		320 sq ft	230 lb	75 lb	100 lb	30 lb	3200 lb	930 lb	100 lb	52	0.408	5	0.5 in	0.187	50 Mpa	2500 \$	13000 \$	1900 \$	23000 \$	0.45 h/flight	2000 min/s/wing
Organizational Difficulty		3	5	3	3	3	5	3	1	5	3	5	5	3	3	5	3	3	5	3	3
Weighted Importance		421	259	300	300	291	105	275	241	328	395	632	136	118	190	487	136	97	328	56	188
Relative Importance		0.123	0.079	0.093	0.093	0.087	0.033	0.083	0.071	0.097	0.119	0.193	0.041	0.035	0.057	0.143	0.042	0.023	0.080	0.016	0.054
Organizational Weighted Importance		1263	1294	900	900	874	527	826	241	964	1185	1897	680	363	570	2437	408	290	1040	167	564
Organizational Relative Importance		0.123	0.129	0.090	0.090	0.087	0.033	0.083	0.071	0.097	0.119	0.193	0.041	0.035	0.057	0.143	0.042	0.023	0.080	0.016	0.054

Figure 42: Wing-level Quality Function Deployment



**Figure 43:** Triangle Distributions for Customer Requirements Uncertainties



**Figure 44:** System-level Organizational Weighted Importance with Integrated Uncertainty Interval

due to high uncertainties in how the customers view cost issues, the fifth characteristic on the list can potentially become as important as the other top four issues. This finding is impossible to be detected with traditional QFD.

The band of uncertainty at the system level can then be propagated throughout all level of deployments from system- to subsystem-level. The result is a better decision aid that helps define the area of focus under the presence of customer uncertainties at any level in the system hierarchy. In other words, difference Voices-of-the-Customers create distribution of preferences, which can then be propagated throughout system characteristics.

Typically, in the design process the manufacturing issues would often be under-represented or even ignored until later stages of the design cycle. It is especially

important to ensure that this does not happen for a design utilizing advanced materials and manufacturing processes. QFD construction with incorporation of manufacturing authorities is an excellent enabler that helps to ensure that the voice of the manufacturer is heard throughout the design process so as to avoid costly changes before, and even after the production begins.

### 7.1.3 Established Value (OEC)

The focal point in this step of the process is to develop an Overall Evaluation Criterion (OEC) in order to gauge the design goodness. The OEC is a function designed to illustrate the ratio between system effectiveness and cost. As such, the OEC forms a standardized basis for the objective comparison of design alternatives. The overarching goal of the OEC function is to provide a quantitative measure of how well a design meets the system requirements. Design alternatives are subjected to the same criterion as a basis of comparison. In order to evaluate different wing design concept without changing anything else about the system, i.e. propulsion, airframe, and etc., the study will focus on the wing-level tradeoff analysis, hence the OEC will be evaluated using engineering characteristics at the wing level.

The OEC equation is formulated based on the product and process characteristics found in the wing-level QFD with emphasis on the most important metrics. As a result the OEC for the current problem can be described as a function of three main indexes; Mission Capability Index (MI), Structural Performance Index (SI), and Total Ownership Cost Index (OI). Below is the OEC equation constructed for this problem.

$$OEC = \lambda(MI) + \mu(SI) + \nu(OI)$$

Where;

MI = Mission Capability index

SI = Structural Quality index

OI = Ownership Cost index

Each index comprises of several engineering characteristics and weighting factors which are the direct results from the Wing-Level QFD Difficulty Weighted Importances as follow;

$$MI = \alpha\left(\frac{FOS}{FOS_{BL}}\right) + \beta\left(\frac{DEFORM_{BL}}{DEFORM}\right) + \gamma\left(\frac{STRAIN_{BL}}{STRAIN}\right) + \delta\left(\frac{STRESS_{BL}}{STRESS}\right)$$

$$SI = \epsilon\left(\frac{WFUEL_{BL}}{WFUEL}\right) + \zeta\left(\frac{WWING_{BL}}{WWING}\right) + \eta\left(\frac{TW}{TW_{BL}}\right) + \varepsilon\left(\frac{LOADING_{BL}}{LOADING}\right)$$

$$OI = \theta\left(\frac{RDT\&E_{BL}}{RDT\&E}\right) + \kappa\left(\frac{PRODUCTION_{BL}}{PRODUCTION}\right) + \xi\left(\frac{INVESTMENT_{BL}}{INVESTMENT}\right) + \tau\left(\frac{O\&S_{BL}}{O\&S}\right)$$

Where;

FOS	= Structural factor of safety
DEFORM	= Max. wing bending deformation
STRAIN	= Max. strain energy
STRESS	= Max. von Mises stress
WFUEL	= Mission fuel weight required
WWING	= Wing primary structural weight
TW	= Thrust-to-weight ratio
LOADING	= Wing loading
RDT&E	= Research, development, testing, and evaluation costs
PRODUCTION	= Production costs
INVESTMENT	= Support investment costs
O&S	= Operation and support cost

#### 7.1.4 Feasible Alternatives

Several design alternatives can now be conceptualized. Morphological matrix is utilized to generate feasible alternatives. This is a functional or characteristic breakdown of a product. For each function or characteristic, all possible alternatives are listed. Figure 45 below shows the Morphological matrix for this problem. As can be seen from the table below, the focal point in this analysis is to capture characteristics pertaining to fabrication and assembly methods for wing primary structure.



Wing Criteria			Options			
Surface Finish	Coated	Painted				
Spar Material	CFRP	Aluminum	Aluminum	Aluminum	Aluminum	Aluminum
Rib Material	CFRP	Aluminum	Aluminum	Aluminum	Aluminum	Aluminum
Skin Material	CFRP	Aluminum	Aluminum	Aluminum	Aluminum	Aluminum
Number of Ribs	30	20	10	8	2	
Number of Spars	All-Spar	5-Spar	3-Spar	2-Spar		
Spar type	C-spar	Combo-spar (C & I)	Sine Wave Spar	Tube		
Aerodynamic sealing	Yes	No				
Spar Fabrication	Automated Composite Layup	Manual Composite Winding	Automated Machining	Machining	Automated Casting	Manual Sheet Forming
Skin Fabrication	Automated Composite Layup	Manual Composite Winding	Automated Machining	Machining	Automated Casting	Manual Sheet Forming
Rib Fabrication	Automated Composite Molding	Manual Composite Molding	Automated Machining	Machining	Automated Casting	Manual Sheet Forming
Chemical bonding	Chemical bonding	Fasteners	Rivets	Hilok	Welding	
Fasteners	Fasteners	Fasteners	Rivets	Hilok	Welding	
Determinant Assembly (DA holes)	Jig	Jig	Rivets	Hilok	Welding	
Determinant Assembly (DA holes)	Jig	Jig	Laser Tracking			
Determinant Assembly (DA holes)	Jig	Jig	Laser Tracking			
Determinant Assembly (DA holes)	Jig	Jig	Laser Tracking			
Major Assembly Locating Features	100% Manual	40% Auto	60% Auto	80% Auto	100% Auto	
Drilling	100% Manual	40% Auto	60% Auto	80% Auto	100% Auto	
Fastening	Moving Line	Pulse Line	Conventional Line	Stationary Positions		
Plant layout						

Figure 45: Morphological Matrix

#### 7.1.4.1 Wing Structural Concepts

Five design configurations can be formulated using information from Morphological matrix as described below, Figure 46.

**Design 1** The first design option represents the baseline metallic wing design. All of the wing structural components are made from aluminum. The wing box design consists of 30 ribs components that are attached to the front and rear C-spars. The skin panels are used to form aerodynamic envelope. The manufacturing process selected for this design represents typical metal forming and machining process commonly used for aluminum components. Drilling and riveting processes are used to construct wing box, and attach skin panels to the wing box. Parts that requires access for maintenance operations are assembled through fastening process. The fabrication and assembly processes are performed with manual labor.

**Design 2** The second design introduces one-piece Graphite-Epoxy composite skin cover panel using manual composite layup process. The wing box design utilizes 20 ribs that lie between 3 spars. The rib and spar constructions are done through automated machining process. The assembly process for the wing box are done using determinate assembly which helps reducing assembly time, as well as quality assurance cost.

**Design 3** The third feasible design alternative utilizes composite skin and spar design. Ten titanium ribs are machined from solid titanium block. The skin panel and spar constructions utilize automated tape laying process. The spar layups then go through a compaction and compression processes to form sine wave shape for added strength. The assembly process is similar to design 2 where drilling, riveting, and fastening processes are utilized.

**Design 4** The fourth design alternative represents the “black aluminum” design where traditional aluminum parts are replaced with composite parts of similar design. The skin panel and spars are fabricated using automated tape laying process. The composite ribs are fabricated using compression molding process. The wing box assembly is chemically bonded together. The skin panels are then fastened with the wing box.

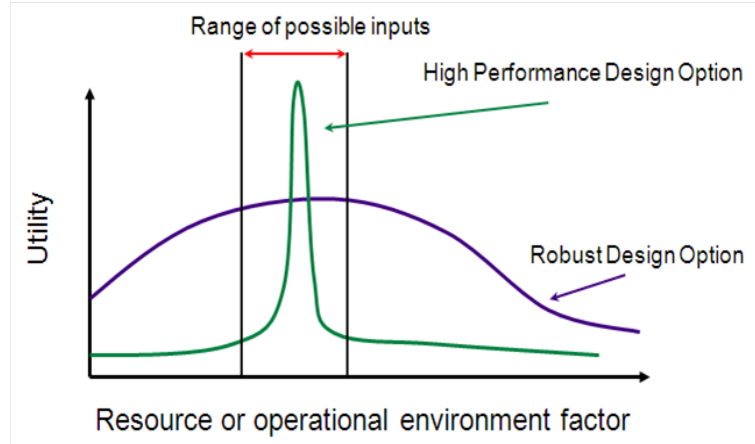
**Design 5** The last design alternative represents a more innovative structural concept is adopted from [1] where the wing ribs are eliminated and replaced with multi-spar structure where the spars are placed next to each other and extended in a span direction. A single rib is used to connect wing structure with the fuselage. Filament winding process is used to construct individual spar. The multi-spar structure is then formed through composite curing process.

The design options progress by their increase in manufacturing complexity (RDT&E, tooling support investment), increase in level of composite use, increase in the use of co-curing of part which reduce fastener and assembly time, and at the same time reduce total weight which will increase performance. All the progression may cross at some point where the benefit and cost intersect which dictate the optimal amount of composite use, manufacturing process, as well as weight reduction potential.

Most design and optimization methodologies utilizing Response Surface Methodology, and Gradient Based Optimization breakdown if applied to this type of problem where the design options are highly discretized. The assumption of *smoothness* of the system parameters cannot be applied as traditionally done in many conceptual design frameworks. Individual design alternative has to be treated separately with appropriate analysis setups. The integrated design framework proposed in this study remedies this shortfall.

	Baseline: All Metallic	Design 2: Composite Skin	Design 3: Skin and Spar	Design 4: Black Aluminum	Design 5: All-Spar Composite
Surface Finish	Painted	Coated	Coated	Coated	Coated
Spar Material	Aluminum	Aluminum	CFRP	CFRP	CFRP
Rib Material	Aluminum	Aluminum	Titanium	CFRP	Titanium
Skin Material	Aluminum	CFRP	CFRP	CFRP	CFRP
Number of Ribs	30	20	10	8	2
Number of Spars	2 spar	3 spar	2 spar	5-Spar	All-Spar
Spar type	C-spar	Combo-spar (C & I)	Sine Wave Spar	C-spar	Tube
Aerodynamic sealing	Yes	Yes	Yes	Yes	No
Spar Fabrication	Machining	Automated Machining	Automated Composite Layup	Automated Composite Layup	Manual Composite Winding
Skin Fabrication	Manual Sheet Forming	Manual Composite Layup	Automated Composite Layup	Automated Composite Layup	Automated Composite Layup
Rib Fabrication	Manual Sheet Forming	Automated Machining	Automated Machining	Automated Composite Molding	Automated Machining
Rib-to-Spar Assembly	Rivets	Rivets	Rivets	Chemical bonding	Chemical bonding
Rib-to-Skin Assembly	Fasteners	Fasteners	Fasteners	Fasteners	Chemical bonding
Spar-to-Skin Assembly	Rivets	Fasteners	Chemical bonding	Chemical bonding	Chemical bonding
Rib-Skin Locating Features	Jig	Laser Tracking	Laser Tracking	Jig	Jig
Rib-Spar Locating Features	Jig	Jig	Laser Tracking	Jig	Jig
Spar-Skin Location Features	Jig	Laser Tracking	Jig	Jig	Jig
Major Assembly Locating Features	Jig	Determinant Assembly (DA holes)	Determinant Assembly (DA holes)	Determinant Assembly (DA holes)	Determinant Assembly (DA holes)
Drilling	100% Manual	60% Auto	80% Auto	60% Auto	80% Auto
Fastening	100% Manual	60% Auto	80% Auto	60% Auto	80% Auto
Plant layout	Stationary Positions	Moving Line	Conventional Line	Pulse Line	Pulse Line

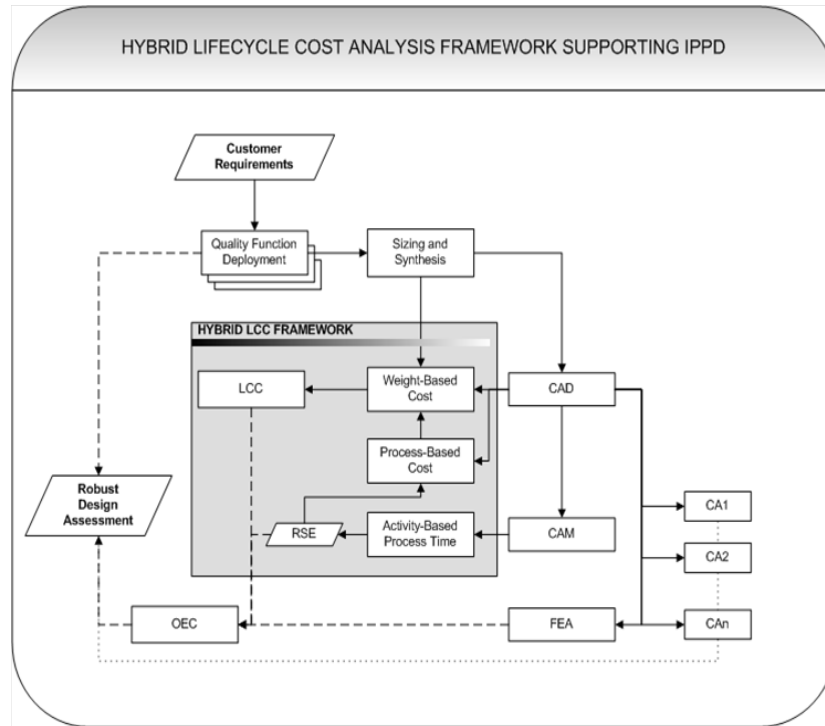
Figure 46: Feasible Design Alternatives



**Figure 47:** High Performance vs. Robust Design Options

## 7.2 *Robust Design Assessment*

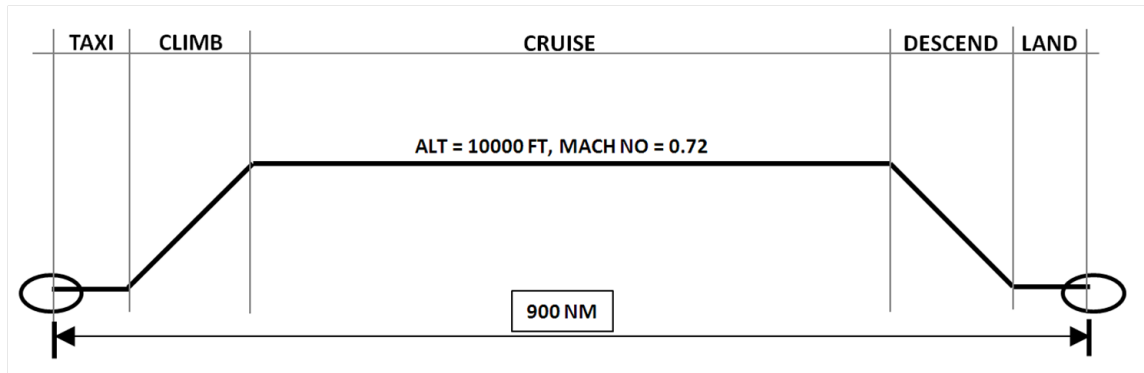
In order to evaluate the wing alternatives and their impacts on overall system performance and cost, a modeling and simulation environment as described in Chapter IV is applied. The proposed multidisciplinary modeling and simulation environment allows the designer to define product definitions, verify their performance characteristics as subjected to the specific mission profile, while simultaneously assess the producibility and cost considerations at difference level of knowledge available and analysis fidelities. The 5 design alternatives are analyzed and compared in terms of product and process characteristics as well as design robustness, where robustness is defined as a measure of the ability of a system to absorb changes in requirements, constraints or failures while reducing the impacts on the performance, functionality, or composition of the mission or system. Two different design options are shown as an example in Figure 47 - one with high performance, and the other with robust performance. The final selection of the best design alternative will depend on the design value based on an Overall Evaluation Criterion (OEC) as well as how much the design value deviates from its nominal value because of the uncertainties caused by the customers requirements, as well as by the simulation errors at the system-level characteristics.



**Figure 48:** Hybrid Lifecycle Cost Analysis Framework Supporting IPPD

### 7.2.1 Integrated Design and Manufacturing Environment

ModelCenter<sup>®</sup> is a virtual environment for complex systems design exploration utilizing process integration of various design and analysis tools. It can automate the process of running multiple executions of series of analysis codes and applications providing fast design iteration, reduced error and minimized information lost during data transfers. Moreover, ModelCenter<sup>®</sup> can also provide design exploration tools including parametric studies, optimization, response surface modeling, and many others which are beneficial during concept evaluation phase. Another useful feature is the ability to capture discipline-related information from individual analysis tool and made available for all other tools to be utilized. Figure 48 below shows the complete ModelCenter<sup>®</sup> environment setup for generating, and analyzing generic wing design concepts during conceptual and preliminary design phases. Chapter 6 provides detailed explanation for the software development and integration effort.



**Figure 49:** Mission Profile

#### 7.2.1.1 Sizing and Synthesis: FLOPS

Figure 49 shows a simple mission profile used in the sizing analysis. The aircraft goes through basic warm-up and taxi, then initiate 4 segment climb to altitude 10,000 feet above sea level. It then cruises at 0.72 MACH speed for 900 NM with 10% reserve fuel available after landing. The sizing code takes the wing geometry from CATIA and size the aircraft and fuel required based on the mission profile given. All five design alternatives are sized based on the same mission requirements. The only variation among the design alternatives are the internal structural layout and their material compositions, with everything else about the aircraft remains fixed over all design options. As a result, the design option with lower wing weight will require less fuel to complete the mission.

**ModelCenter Integration and Automation** FLOPS is fully integrated in ModelCenter environment allowing for a transfer of wing geometry directly from CATIA, such parameters are wing span (SPAN), dihedral angle (DIH), and etc. Wing bending component weights can also be imported from CATIA 3D geometry instead of using built-in weight build-up equations which sometime are not applicable for all wing type. Composite material considerations are accounted for via the parameter FCOM. This parameter tells FLOPS the weight fraction of composite used in a particular

design. All of the parameters vary throughout the 5 design alternatives.

**Constant Payload-Range Aircraft Sizing** The system performance is calculated for the constant payload-range aircraft. The design range of 900 NM (DESRNG) is applied as a constraint at the beginning of the performance sizing routine. Flops is then iterate on the gross weight until the range flown is equal to the Design Range [IRW=1]. Structural weight is one of the importance metrics that affects range.

**Outputs** The outputs that are useful for the downstream analysis tools are component weight breakdowns and total fuel weight required for the specified mission. Appendix A provides the list of input parameters and output file generated by Flops execution. Note that, to expand this analysis to the full extent of the system optimization, many performance attributes can be generated and included in the OEC calculation, including but not limited to Climb rate, Time to climb, load factor, turn rate, and turn radius. However, to demonstrate to tradeoff between metallic and composite wing design as described earlier, these parameters are of secondary importance.

#### 7.2.1.2 Computer-Aided Design: CATIA

CATIA V5 software by Dassault Systemes is used as CAD module that is also fully integrated within ModelCenter through CAD Fusion plug-in interface. The full scale wing geometry generation is driven by an excel file using Relational Design concept. The model creates simple thickness plates to represent skins, ribs, and spars from reference surfaces. Various measurements inside CATIA model, e.g. surface area, part volume, circumferential length, etc. can be transferred between modules within ModelCenter environment. The following procedure is the simplification of the creation process.

First, the entire wing shape is defined through a set of input parameters including



basic geometry data, unit airfoil x-y coordinates and thicknesses of individual structural elements as shown in Figure 50. The input data also indicates the reference position of the wing from aircraft body frame of reference. The Reference Datum section identifies basic aircraft wing dimension including distance from aircraft nose, wing root and tip chord length, dihedral angle, wing span, sweep angle, twist and built-in incident angle. Reference Surfaces, and Wing Geometry sections define thicknesses information for each elements. Lastly, the Airfoil Coordinates section is used to create aerodynamic profiles. This tabulated data is directly linked to the CATIA module which allows automatic generation of wing geometry.

The wing model consists of three main parts; Reference Datum, Reference Surfaces, and Solids for each structural components. The creation of the wing geometry starts with the reference datum by assigning a point representing the wing inboard root profile tip offsetting from the fuselage nose tip in Cartesian coordinate system. Wing planform layout is then created based on the chord lengths at the root and tip, wing half span, sweep angle, and dihedral angle. Next step is then to create a sketch of internal structural elements that offsets the plane that defines wing planform shape. This step provides easy access for the designer to modify structural layout of any element within the wing in one combined sketch. Figure 51 below illustrates the sketch of internal structure of one of the design alternatives, where the structural sketch is shown on the top of the wing planform area. Each line in the sketch represents individual ribs and spars that form the wing box structure.

Next, the airfoil coordinate is imported to generate the unit-chord airfoil shape for wing root and tip profiles using standard airfoil x-y coordinates. The final profiles are then scaled based on the actual chord lengths. At this point, the skeleton of the wing is defined. The next step involves generating reference surfaces of individual elements. First, wing skin surfaces are generated using Multi-Section Surface feature in CATIA. The inputs required for this step are the airfoil shapes at the wing root

**F86 Wing Input Parameter List**

Reference Datum:		
distanceFromNose	1520	mm
rootChordLength	3113.23	mm
dihedralAngle	0	deg
wingHalfSpan	5638.8	mm
lampda	40	deg
tipChordLength	1575.82	mm
twist	0	deg
incidence	0	deg

Reference Surfaces:		
SkinThickness	4	mm

F86 Wing Geometry:		
skinThickness	4	mm
Spar1WebThicknessatRod	6	mm
Spar2WebThicknessatRod	6	mm
Spar3WebThicknessatRod	6	mm
Rib0.0Thickness	3	mm
Rib0.01Thickness	3	mm
Rib0.1Thickness	3	mm
Rib0.2Thickness	3	mm
Rib0.3Thickness	3	mm
Rib0.4Thickness	3	mm
Rib0.5Thickness	3	mm
Rib0.6Thickness	3	mm
Rib0.7Thickness	3	mm

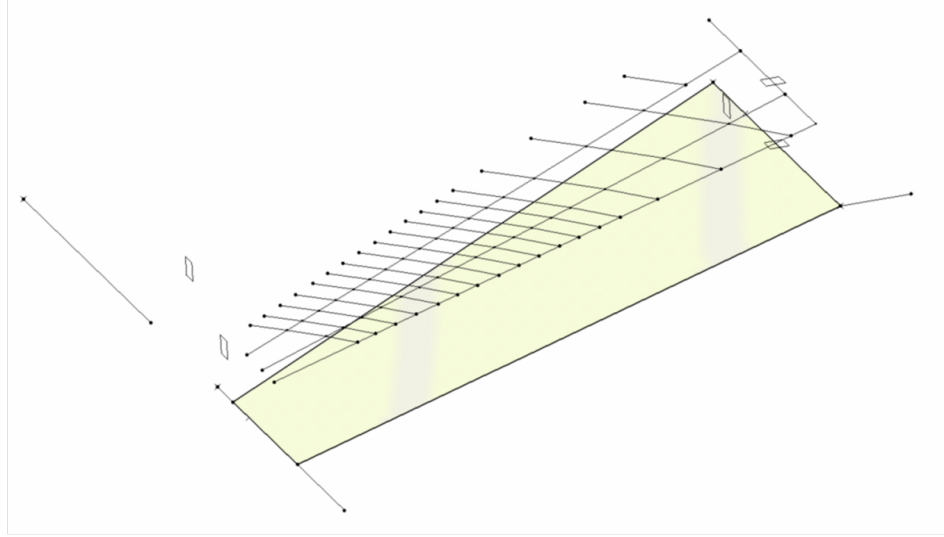
Rib2.5Thickness	3	mm
Rib2.6Thickness	3	mm
Rib2.7Thickness	3	mm
Rib2.8Thickness	3	mm
Rib2.9Thickness	3	mm
Rib2.10Thickness	3	mm
Rib2.11Thickness	3	mm
Rib2.12Thickness	3	mm
Rib2.13Thickness	3	mm
Rib2.14Thickness	3	mm
Rib2.15Thickness	3	mm
Rib2.16Thickness	3	mm
Rib2.17Thickness	3	mm



Airfoil Coordinates:	
'PartBody\Sketch.2\Offset.1\Offset' (mm)	1
'PartBody\Sketch.2\Offset.2\Offset' (mm)	0.98296
'PartBody\Sketch.2\Offset.3\Offset' (mm)	0.93301
'PartBody\Sketch.2\Offset.4\Offset' (mm)	0.85355
'PartBody\Sketch.2\Offset.5\Offset' (mm)	0.75
'PartBody\Sketch.2\Offset.6\Offset' (mm)	0.62941
'PartBody\Sketch.2\Offset.7\Offset' (mm)	0.5
'PartBody\Sketch.2\Offset.8\Offset' (mm)	0.37059
'PartBody\Sketch.2\Offset.9\Offset' (mm)	0.30866
'PartBody\Sketch.2\Offset.10\Offset' (mm)	0.25
'PartBody\Sketch.2\Offset.11\Offset' (mm)	0.19562
'PartBody\Sketch.2\Offset.12\Offset' (mm)	0.14645
'PartBody\Sketch.2\Offset.13\Offset' (mm)	0.10332
'PartBody\Sketch.2\Offset.14\Offset' (mm)	0.06699
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'PartBody\Sketch.2\Offset.16\Offset' (mm)	0.01704
'PartBody\Sketch.2\Offset.17\Offset' (mm)	0.00428

'PartBody\Sketch.2\Offset.52\Offset' (mm)	0.00767
'PartBody\Sketch.2\Offset.53\Offset' (mm)	0
'PartBody\Sketch.2\Offset.54\Offset' (mm)	-0.00767
'PartBody\Sketch.2\Offset.55\Offset' (mm)	-0.01646
'PartBody\Sketch.2\Offset.56\Offset' (mm)	-0.02395
'PartBody\Sketch.2\Offset.57\Offset' (mm)	-0.03023
'PartBody\Sketch.2\Offset.58\Offset' (mm)	-0.03564
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'PartBody\Sketch.2\Offset.60\Offset' (mm)	-0.04295
'PartBody\Sketch.2\Offset.61\Offset' (mm)	-0.04466
'PartBody\Sketch.2\Offset.62\Offset' (mm)	-0.04509
'PartBody\Sketch.2\Offset.63\Offset' (mm)	-0.04431
'PartBody\Sketch.2\Offset.64\Offset' (mm)	-0.03978
'PartBody\Sketch.2\Offset.65\Offset' (mm)	-0.03247
'PartBody\Sketch.2\Offset.66\Offset' (mm)	-0.02384
'PartBody\Sketch.2\Offset.67\Offset' (mm)	-0.01522
'PartBody\Sketch.2\Offset.68\Offset' (mm)	-0.0077
'PartBody\Sketch.2\Offset.69\Offset' (mm)	-0.00218
'PartBody\Sketch.2\Offset.70\Offset' (mm)	0

**Figure 50: Tabulated Input Parameter for Wing Design**

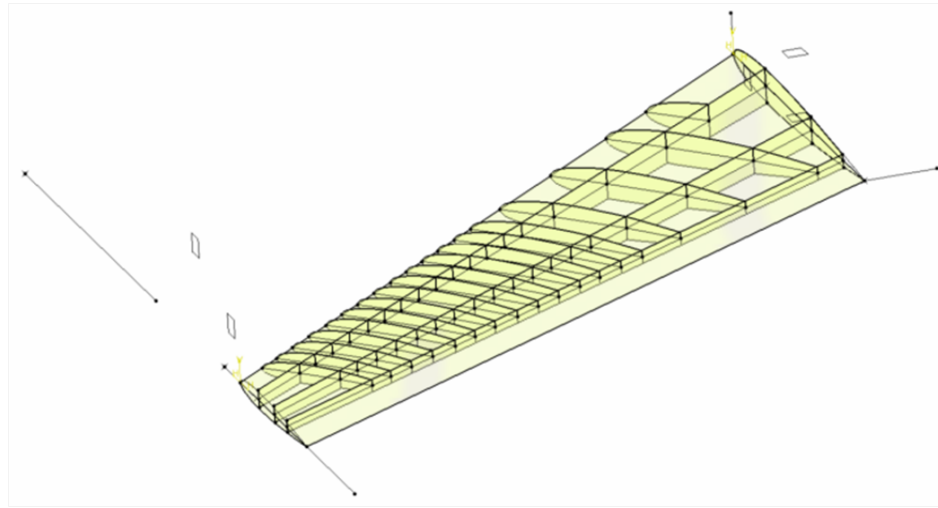


**Figure 51:** Relational Design CAD: Wing Planform and Structural Layout Definitions

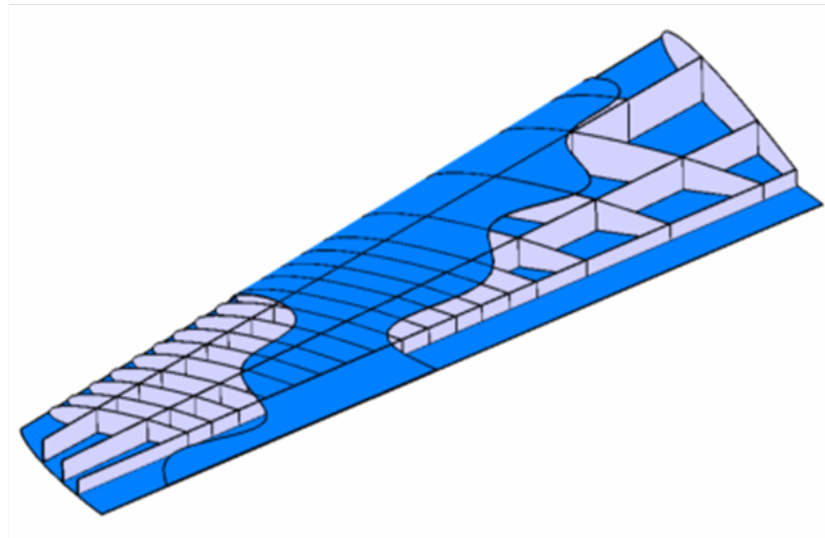
and tip defined earlier. These surfaces represent the Inner Mold Line (IML) for the top and bottom surfaces of the wing. The rib and spar surfaces are the extrusions of the internal structural layout sketch with the limits defined by the IML surfaces. Figure 52 below shows the result of the reference surfaces generated at this step.

The final step in the conceptualization of the wing 3D definition is to assign thicknesses to individual components as defined in the input file, Figure 50. Figure 53 below is the final wing geometry automatically generated using Relational Design concept. It shows a complete wing geometry with part of the top skin peeled off to expose the internal structure. The resulting geometry information such as part area, circumferential length, and volume can be extracted and used for downstream analysis including finite element analysis, and process-based cost estimate. One of the enabling features in CATIA that helps make this relational design philosophy possible is the ability to provide feedback measurements, i.e. weight, length, surface area, and etc. This information is captured by ModelCenter CATIA plug-in and made available for other analysis tools to be utilized.

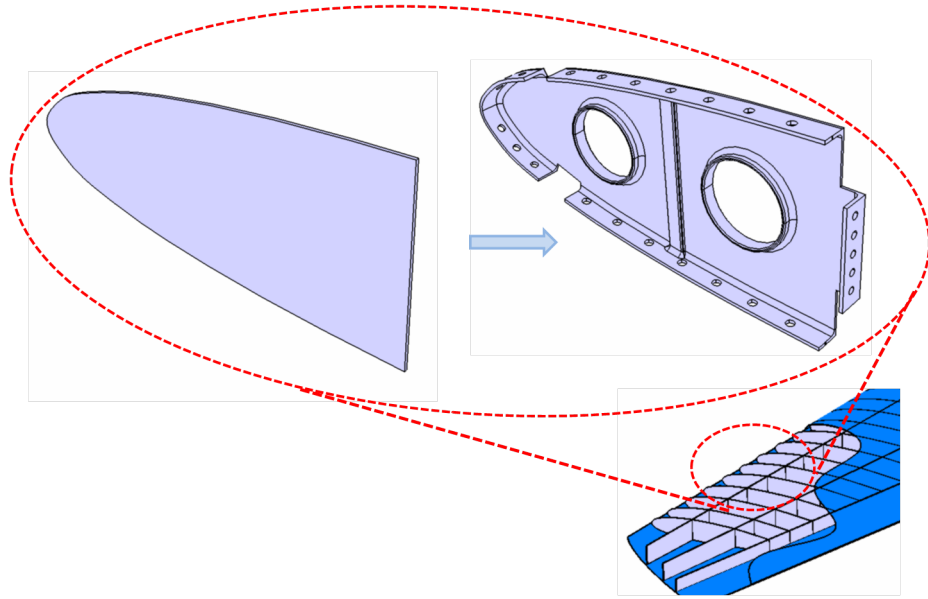
The reader is noted that since all the solid parts representing the elements in



**Figure 52:** Relational Design CAD: Reference Surfaces Generation



**Figure 53:** Relational Design CAD: Final Geometry

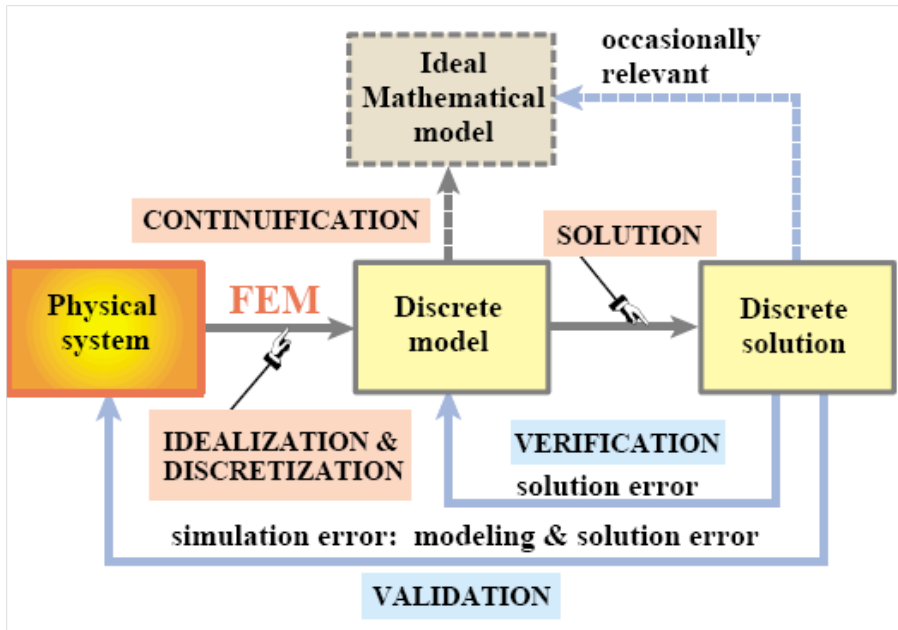


**Figure 54:** Relational Design CAD: Detailed Part Design

the wing are individually created, as a result, they can be separately updated and modified to add more details and manufacturing features as design process progresses and more information is available to the designer. In other words, although the model is created at the level of fidelity for conceptual and preliminary design, it can be further refined to the level of detail suitable for detailed design phase. Figure 54 shows how one of the leading edge ribs can be modified to reflect the machining characteristics as well as assembly features.

#### 7.2.1.3 Finite Element Analysis (FEA): ANSYS

FEA is included in this study because of the fact that in order to compare different wing structural layout, one need to determine the underlining structural attributes like bending and torsional stiffness, strength, and material factor of safety, as a function of material composition. This allows designers to determine how much weight can be saved by introducing composite constructions to different structural arrangements as determined by the 5 design alternatives. This way we can make certain that the various design alternatives are structurally comparable. A commercially available

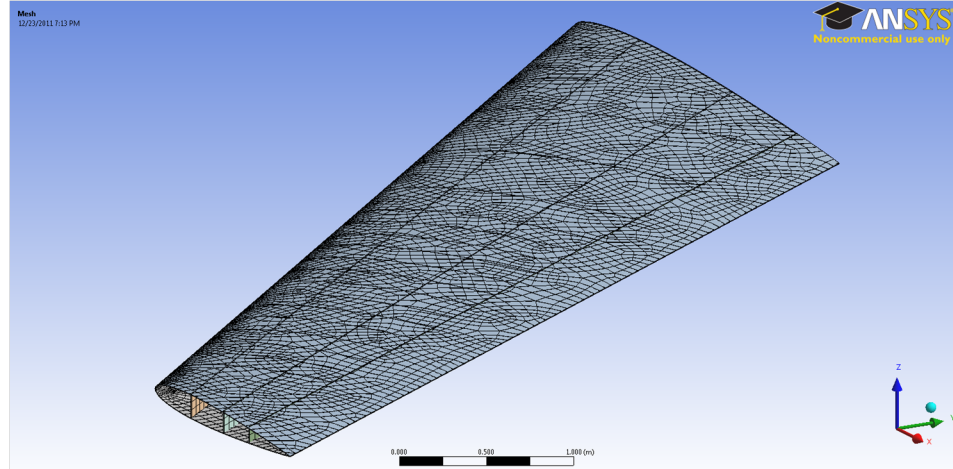


**Figure 55:** Finite Element Analysis Methodology

FEA packages called ANSYS 13.0 is selected as the tool of choice when it comes to Finite Element Analysis. It is a Computer-Aided Engineering (CAE) software capable of Model-based simulation of multi-physics and structure mechanics problems. Figure 55 show the idealization and discretization process used by the Finite Element Method.

Unfortunately, integrating FEA package to the framework with the ability to automatically update the model has proven to be too cumbersome and impractical. Moreover, the design alternatives has now become highly discretized that Response Surface technique is also ineffective. With this in mind, the FEA model for each design alternative is developed and analyzed separately.

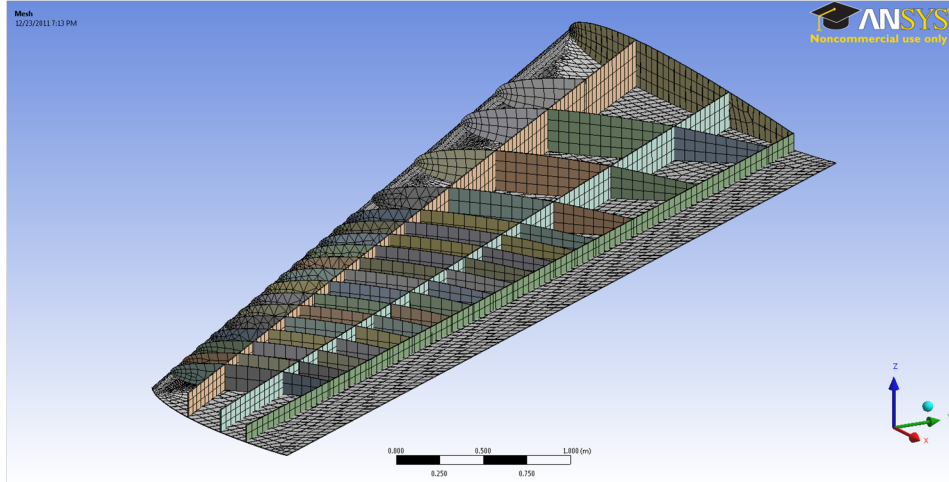
**Anatomy of Wing Finite Element Modeling** A static structural analysis determines the displacements, stresses, strains, and forces in structures or components caused by loads that do not induce significant inertia and damping effects. Steady loading and response conditions are assumed; that is, the loads and the structure's response are assumed to vary slowly with respect to time.



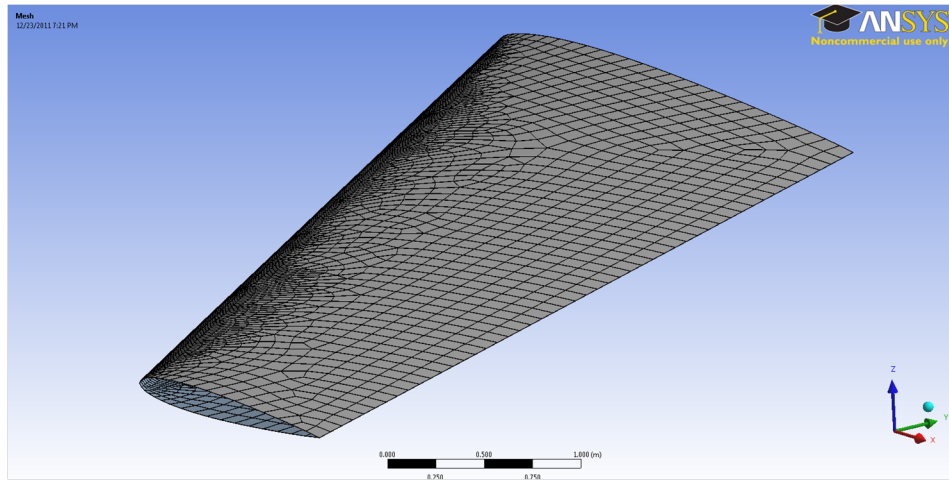
**Figure 56:** Design 1 Skin Meshing for FEA

**Simplifications** External force is applied to the wing structure to represent one of the adverse operating conditions; 7Gs maneuver. The wing is assumed to be rigidly connected to the fuselage. This boundary condition help reduce the problem to a simple cantilever beam type analysis, with steady loading condition instead of aerodynamic pressure exerted on the wing skins. The problem can be idealized further by assigning appropriate idealized elements (2D) to represent actual 3D geometry, i.e. a skin panel can be represented by shell elements. The assembly of different components is also simplified by using rigid connection as opposed to rivet or bolt joints. The consequences of the aforementioned simplifications help shorten the analysis and setup time whilst maintaining the physical ramifications.

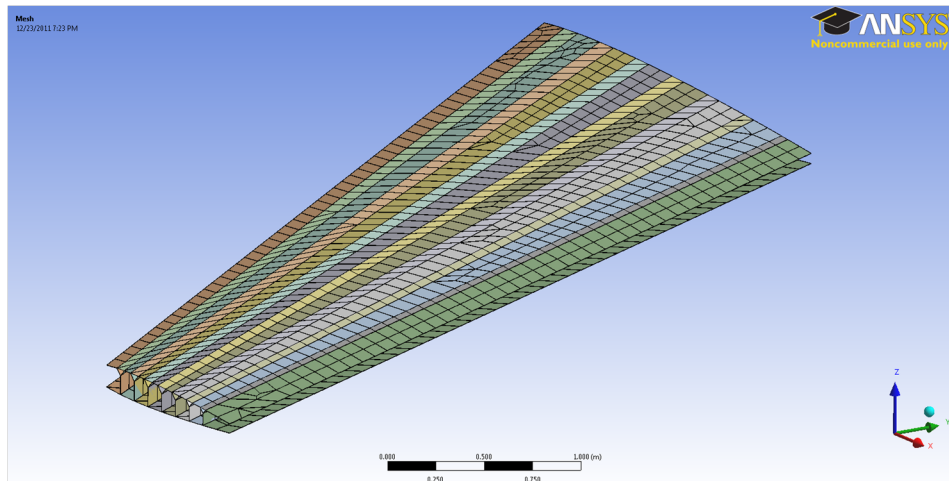
**Meshing** ANSYS Workbench is a CAD-neutral environment that supports bidirectional, direct, and associative interfaces with CAD systems. The Relational CAD model in CATIA can be directly imported without translating into intermediate geometry format. Once imported, meshing is performed on the global parameter setting, and element type is assigned to mesh sections to represent the idealization of actual structural components. Figure 56,57,58,and 59 show several views of meshes generated for design 1 and 5.



**Figure 57:** Design 1 Internal Structure Meshing for FEA



**Figure 58:** Design 5 Skin Meshing for FEA



**Figure 59:** Design 5 Internal Structure Meshing for FEA



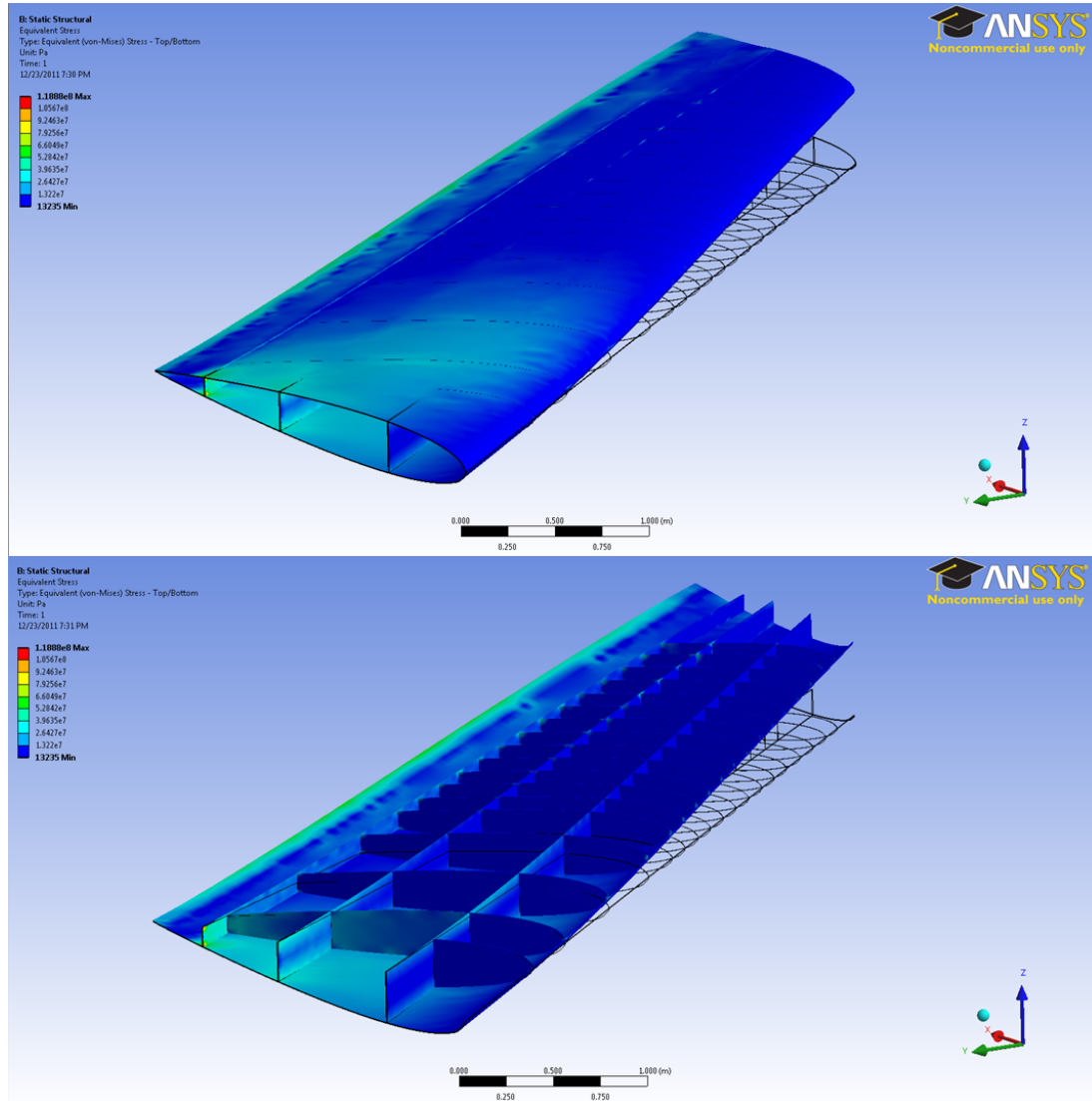
Properties	Unit	Value	
		Carbon/Epoxy Sheet	Aluminum 6061-T6
Coefficient of thermal expansion - Longitudinal	x10-6 K-1	2.1	23.6
Coefficient of thermal expansion - Transverse	x10-6 K-1	2.1	23.6
Compressive Strength - Longitudinal	MPa	570	310
Compressive Strength - Transverse	MPa	570	310
Density	g.cm <sup>-3</sup>	1.6	2.7
Shear modulus - in-plane	GPa	5	26
Shear strength - in-plane	MPa	90	207
Tensile strength - Longitudinal	MPa	600	310
Tensile strength - Transverse	MPa	600	310
Tensile yield strength	MPa	N/A	276
Ultimate compressive strain - Longitudinal	%	0.8	12
Ultimate compressive strain - Transverse	%	0.8	12
Ultimate shear strain - in-plane	%	1.8	17
Ultimate tensile strain - Longitudinal	%	0.85	12
Ultimate tensile strain - Transverse	%	0.85	12
Volume fraction of fibers	%	50	N/A
Young's Modulus - Longitudinal	GPa	70	68.9
Young's Modulus - Transverse	GPa	70	68.9
Poisson's Ratio		N/A	0.33

**Figure 60:** Material Properties for Metallic and Composite Design

**Material Properties** Two types of materials are used; Aluminum alloy 6061-T6, and Carbon/Epoxy composite sheet. The Figure 60 below lists key material properties for both materials. The construction of composite laminate in this study is assumed to have symmetry at the mid plane with the  $[0,90, \pm 45]_S$  configuration.

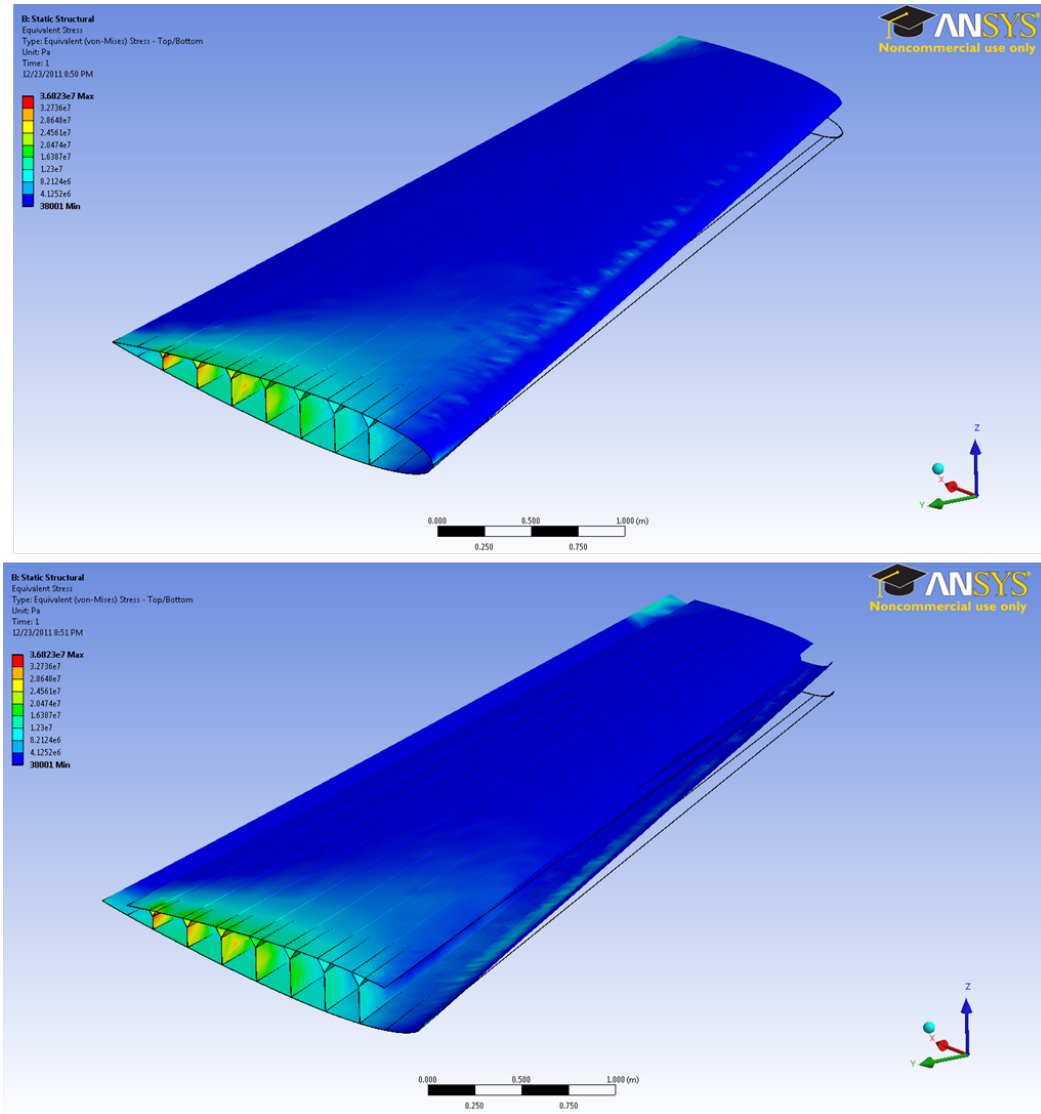
**Post-Processing** The linear static structural analyses can now be performed with the boundary conditions and externally applied load as described earlier. The purpose of this study is to look at structural characteristics due to changes in material composition of the 5 design alternatives. The metrics of interest in this study are the following;

- Maximum bending stress,
- Maximum strain energy,
- Maximum displacement, and
- Minimum material factor of safety



**Figure 61:** Equivalent Stress Contour for Design 1: All Metallic Design

These attributes will then be combined into a value function that represent the structural quality measure, and will be used to compare alternatives through Overall Evaluation Criterion (OEC). Figure 61, and 61 show results of Equivalent Von Mises Stress on Design 1 and 5. The rest of the results are not shown here. For further detail, please refer to Appendix B, FEA Reports.



**Figure 62:** Equivalent Stress Contour for Design 5: Composite All Spar Design

#### 7.2.1.4 Manufacturing Modeling

Apart from weight savings that are the direct results from the choices of difference material usage, fabrication and assembly processes corresponding to those materials need to be taken into account as well. The necessity of this work will become apparent when the lifecycle cost estimate of composite parts cannot be easily handled using weight-based cost estimate approach.

The difference use of material, i.e. advance composite primary structure leading to product designs that is significantly differ from typical aluminum counterpart. The direct consequence of this is the manufacturing processes that have to be tailored appropriately before any cost estimating activity can be performed.

**Work Breakdown Structure** Whenever composite material is applied to the wing structural component, manufacturing work breakdown structure has to be constructed to describe the process for layup, consolidation, assembly, and finishing operations. The starting point in this study is by using generic composite processes based on processes used by Northrop Corporation, Aircraft Division to create Advance Composite Cost Estimating Manual (ACCEM). Any parts that are not conformed to the generic processes can be modified through the use of Activity-Based Manufacturing Process Time Estimating tool, MaxiMOST, to add any activities that are not included. The reader is referred to the subject discussions in Chapter 4 and proof of concept in Chapter 5.

**Virtual Manufacturing: DELMIA** Since the generic composite processes in ACCEM are commonly used during 1970s. These processes are being optimized through new technologies, and cycle time reduction techniques. Modernized composite processes can be generate by removing obsolete steps and replacing them with alternative steps involving new procedure, or new machines, like Automated Tape Laying (ATL)



**Figure 63:** Automated Tape Laying Process

machine, Figure 63, or compression molding machine as shown in Figure 64.

In order to construct new process activities, virtual manufacturing tool like Dassault Systemes' DELMIA can be used to simulate process activities as well as relevant products and resources that are involved. This step ensures the completeness of constructing updated work breakdown structure. It also provides necessary inputs parameters for cycle time estimation for AbTM Module. Figure 65 shows the DELMIA Wing manufacturing process layout and simulation which includes the use of manual labor, automated drilling, compression molding and automated tape laying machine depending on which design alternative is being analyzed. The new workbreak down structures are constructed in the form of PERT chart. It can then be mapped to a spreadsheet form necessary for activity time estimates in AbTM module of HLCET.

**Customized Process Breakdown: MaxiMOST** Once the graphical representation of the shop floor activities is generated, a new work breakdown structure follows.

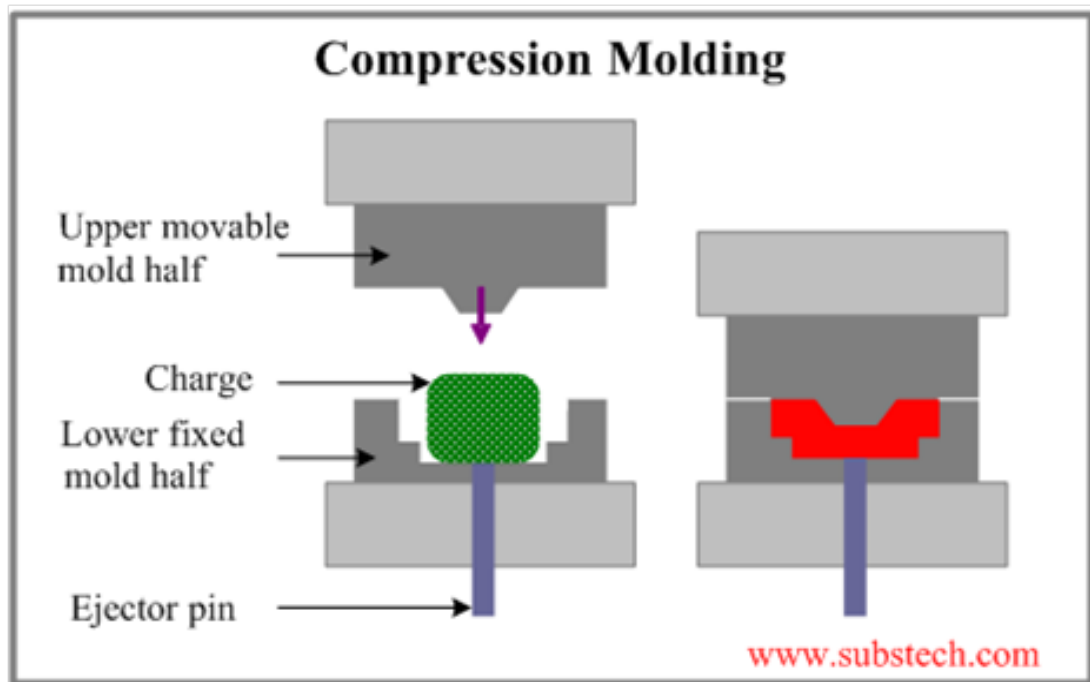


Figure 64: Compression Molding Process for Composite

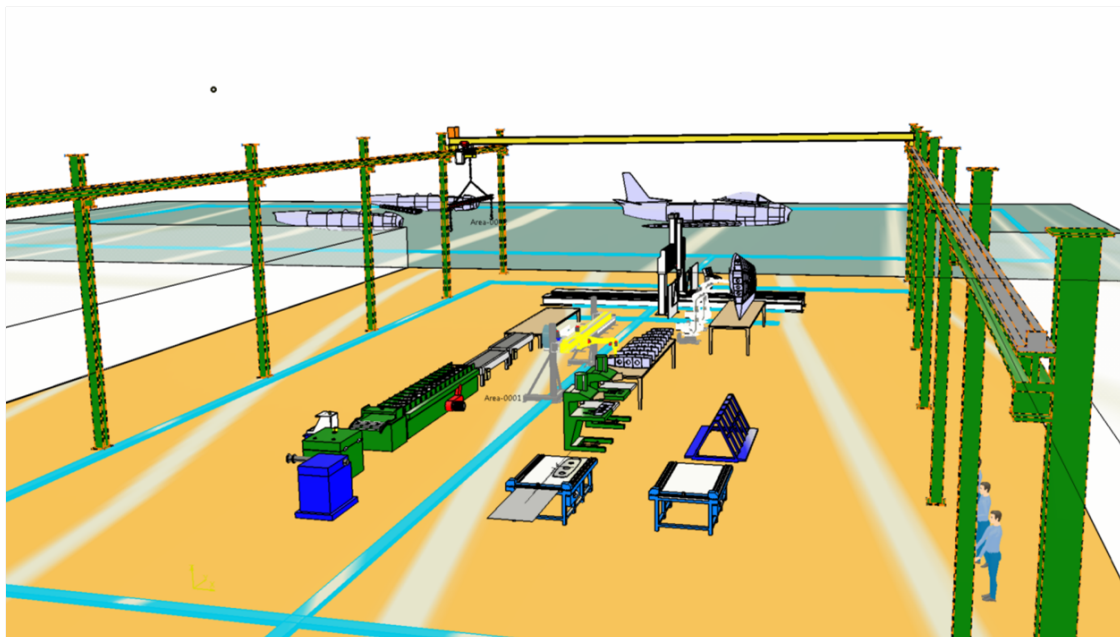
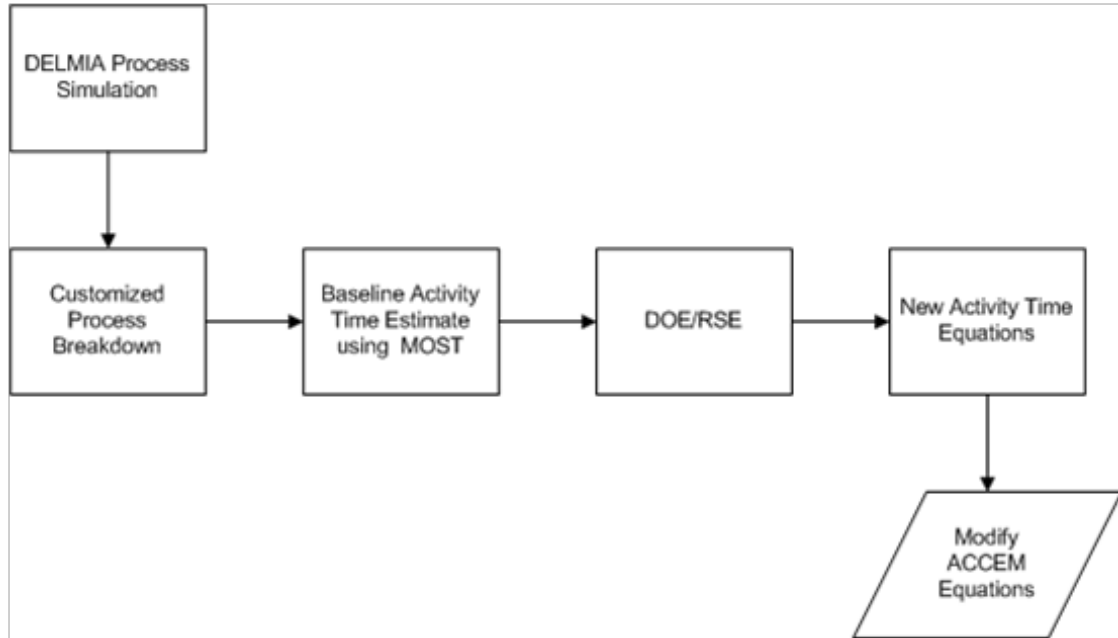


Figure 65: Virtual Plant Layout



**Figure 66:** Procedure for Creating Customized Process Breakdown

Appendix C provides a list of work breakdown structure for composite rib construction adopted from Grumman Corporation Aircraft. Each activity is assigned the appropriate standard time calculation using Maynard Operation Sequence Technique (MOST). Once baseline activity times are calculated, ranges of possible variation from baseline values are then assigned to each activity. Design of Experiment (DOE) in conjunction with Response Surface Methodology is used to generate a customized activity time equation for each activity. The new equations are then used to modify existing recurring manufacturing time model. The diagram 66 below graphically describes the process.

#### 7.2.1.5 Lifecycle Cost Analysis: Hybrid Cost Model

Hybrid Lifecycle Cost Estimating Tool (HLCET) developed in this study is one of the major contributors in this integrated design framework. It enables real time estimates of total ownership cost of a product that is sensitive to material and process selection. The estimate fidelity can be increased depending on the available knowledge at the time of estimation. It is a tool that can evolve along with the design cycle

from conceptual to detailed design. It also maintains compatibility between metallic and other material types since the cost model is subjected to multiple processes, and materials utilizations.

**Weight-Based Parametric LCC (WbPL) Module** The weight-based parametric lifecycle cost estimate provide top level estimates of the total ownership cost of the system. The input parameters necessary to general the results are provided in Table 6, 7, and 8. Table 6 shows component weight breakdown for F-86F baseline design. The integration of HLCET in Modelcenter environment allows the component weights generated by FLOPS sizing analysis to be fed directly to WbPL module. The analysis of design alternatives can be done by reconfiguring the vehicle configurations in FLOPs module. the simulation schedule is initiated and new components weights automatically updated. Table 7 provides generic programmatic factors assumed for all alternatives. Table 8 shows production and material learning curve slopes. Difference learning curve slopes are assigned to various system elements depending on the nature of the manufacturing process, i.e. the more automation in the process, the higher value for learning curve slopes (slower learning). Once all the inputs are inplace, the simulation schedule automatically perform calculations and populate the results in the summary page. Table 9 shows the tabulated LCC summary based on the specified inputs. Table 10, and 11 show the detailed cost breakdown for RDT&E and Production costs, respectively

The weight-based module still have typical shortfall of traditional cost estimating tools that prevent its general applicability in that, all the cost values are solely driven by group weight statement as per MIL-STD-1734, provided that assumptions are completely defined. The dependency on weight alone makes it difficult to apply the tool to any other product that is not analogous in terms of product and process characteristics. The next section extends the current capability of weight-base LCC



**Table 6: F-86F Baseline Group Weight Statement**

F-86F GROUP WEIGHT STATEMENT		F-86F GROUP WEIGHT STATEMENT	
<b>STRUCTURE</b>	<b>4752.0</b>	<b>FIXED EQUIPMENT</b>	<b>1663.0</b>
Wing Group	1643.0	DFCS Computer	0.0
Rotor/Hub	0.0	Surface Controls	673.0
Tail	194.0	APU	0.0
Tail Rotor Group	0.0	Instruments	77.0
Body	2147.0	Hydraulics/Pneu	174.0
Nacelle	202.0	Electrical	426.0
Air Induction	0.0	Environmental Cntl	106.0
Lighting Gear	566.0	Anti-Ice	0.0
Other Structure	0.0	Furnishing & Equip	207.0
<b>PROPULSION</b>	<b>3689.0</b>	Load/Handling	0.0
Engines	2950.0	Other Fixed Equipment	0.0
Accessories and Drive	57.0	<b>AVIONICS</b>	<b>490.0</b>
Exhaust	0.0	Group B (Equipment)	490.0
Engine Start & Controls	0.0	Mission Avionic Sys	0.0
Thrust Reversers	0.0	Group A (Provisions)	0.0
Propeller Install	0.0	Mission Provisions	0.0
Drive System	0.0	<b>MFR's EMPTY WEIGHT</b>	<b>10594</b>
Exh Mgt System	0.0	Crew	215.0
Fuel System	682.0	Cargo	
		Fuel	3873.1
		Trapped POL	101.0
		Std/Op Items	594.0
		<b>TAKE OFF GROSS WEIGHT</b>	<b>15377.1</b>

**Table 7:** Generic Programmatic Factors for LCC Analysis

PROGRAMMATIC FACTORS	VALUE
Quantity of Prototypes	0
Quantity FSD Fight A/C	6
Quantity Production A/C	652
Max Delivery Rate/Month	7
Test Requirements	
- Static Testing	Y
- Fatigue Testing	Y
- Iron Bird Testing	Y
- Wind Tunnel Occupancy	15000 HRS
- Misc Qual Testing	Y
- Flight Test Hrs	4000 FLT HRS
- Class II Mockups	Y
- Class III Mockups	Y
System Service (O&S) Life	20 YEARS
Quantity Force A/C	612
Flight Hrs per A/C Year	364
Quantity A/C per Squadron	9
Crew Ratio	1.5
Number of Engine	1
Shaft Horse Power (each engine)	6000

**Table 8:** Learning Curve Slopes for Various System Elements

SYSTEM ELEMENT	LEARNING CURVE SLOPES			
	PRODUCTION		MATERIAL	
	UNIT 1 - 200	UNIT 201 & Up	UNIT 1 - 200	UNIT 201 & Up
Composite Structures	82%	86%	92%	95%
Conventional Structures	80%	82%	92%	95%
Propulsion	82%	85%	92%	95%
Fixed Equipment	82%	85%	92%	95%
Avionic Installations	85%	85%	92%	95%
Armament Installations	82%	85%		
Integration/Assy/Checkout	76%	78%		

**Table 9: F-86F Baseline Overall LCC Summary**

SYSTEM LIFE CYCLE COST SUMMARY (FY89 M\$)				
WORK ELEMENT	NOMENCLATURE	CONTRACTOR COST	FEE	LCC (M\$)
100	RDT&E		0.10	
110	ENGINEERING	217.15	21.71	238.86
120	MOCKUP, TEST & DEVELOPMENT	403.71	40.37	444.08
130	INITIAL TOOLING	106.75	10.67	117.42
140	FLIGHT UNITS	236.34	23.63	259.98
150	ILS PLANS & ANALYSES	45.86	4.59	50.44
300 R&D	ILS COMMODITY RDT&E	348.75	34.87	383.62
160	PROJECT MANAGEMENT	35.08	3.51	38.59
	<b>RDT&amp;E TOTAL</b>	<b>1393.64</b>	<b>139.36</b>	<b>1533.00</b>
200	PRODUCTION		0.13	
210	RATE TOOLING	12.21	1.59	13.80
220	PRODUCTION A/C	9227.10	1199.52	10426.62
230	PROJECT MANAGEMENT	183.11	23.80	206.91
	<b>PRODUCTION TOTAL</b>	<b>9422.42</b>	<b>1224.91</b>	<b>10647.34</b>
300	SUPPORT INVESTMENT			
310	PECULIAR GROUND SUPPORT EQUIPMENT			316.76
320	TRAINING SERVICES & EQUIPMENT			289.61
330	ENGINEERING & SUPPORT DATA			23.96
340	INITIAL SPARES			692.08
350	SITE ACTIVATION/FIELD SERVICES			15.65
	<b>ILS INVESTMENT TOTAL</b>			<b>1338.05</b>
400	OPERATION & SUPPORT COST (AFR 173-13)/M			
410	UNIT MISSION PERSONNEL			6742.09
420	UNIT LEVEL CONSUMPTION			1115.14
430	DEPOT LEVEL MAINTENANCE			1363.08
440	SUSTAINING INVESTMENT			1260.46
450	INSTALLATION SUPPORT PERSONNEL			738.76
460	INDIRECT PERSONNEL SUPPORT			1178.62
470	PERSONNEL ACQ & TRAINING			1942.55
	<b>O&amp;S COST TOTAL</b>	<b>20 YR</b>		<b>14340.69</b>
	<b>LCC TOTAL -- COST OF OWNERSHIP</b>			<b>27859.08</b>
	<b>UNIT PRODUCTION FLYAWAY COST</b>	<b>1000 UNIT</b>		<b>10.65</b>
	<b>LCC SUMMARY -- FY89 M\$</b>			
	RDT&E COST			1533.00
	HARDWARE COST			10647.34
	LOGISTIC SUPPORT			645.97
	INITIAL SPARES			692.08
	OPERATION & SUPPORT COST	<b>20 YR</b>		<b>14340.69</b>

**Table 10:** F-86F Baseline Research, Development, Testing and Evaluation (RDT&E) Costs

RDT&E COST SUMMARY (FY89 M\$)				
WORK ELEMENT	NOMENCLATURE	CONTRACTOR COST	FEE	LCC (M\$)
110	ENGINEERING	2245124.84	93.00	208.80
ENGR	0.04 ODC \$	6.85	1.22	8.35
110 TOTAL ENGINEERING				217.15
120	MATERIAL (HIGH VALUE) \$	4.08	1.05	4.28
MOCKUP	MATERIAL (MFG) \$	16.31	1.25	20.39
TEST & DEV	ENGINEERING TEST DEVELOPMENT	2005988.32	80.00	160.48
	ENIGNEERING LIAISON	46233.29	93.00	4.30
	MANUFACTURING	327895.66	55.00	18.03
	MANUFACTURING SUPPORT	58085.11	62.00	3.60
	QUALITY ASSURANCE	336729.05	64.00	21.55
	TOOLING M & R	96243.68	68.00	6.54
	0.04 ODC \$	12.73	1.22	15.53
120 TOTAL MCKUP TEST & DEV				403.71
130	MATERIAL (MFG) \$	6.32	1.25	7.90
INITIAL TOOLING	TOOLING	1264209.99	68.00	85.97
	MANUFACTURING SUPPORT	63210.50	62.00	3.92
	QUALITY ASSURANCE	75852.60	64.00	4.85
	0.04 ODC \$	3.37	1.22	4.11
130 TOTAL INITIAL TOOLING				106.75
140	MATERIAL (HIGH VALUE) \$	54.88	1.05	57.62
FLIGHT ARTICLES	MATERIAL (MFG) \$	68.65	1.25	85.81
	ENGINEERING	130111.21	93.00	12.10
	ILS	21223.81	83.00	1.76
	MANUFACTURING	922774.54	55.00	50.75
	MANUFACTURING SUPPORT	88586.36	62.00	5.49
	QUALITY ASSURANCE	101505.20	64.00	6.50
	TOOLING M & R	106119.07	68.00	7.22
	0.04 ODC \$	7.45	1.22	9.09
140 TOTAL FLIGHT ARTICLES				236.34
150	MATERIAL (HIGH VALUE) \$	4.41	1.05	4.63
ILS	MATERIAL (MFG) \$	2.33	1.25	2.91
	ILS	440388.02	83.00	36.55
	0.04 ODC \$	1.45	1.22	1.76
150 TOTAL ILS				45.86
160	PROJECT MANAGEMENT	362702.80	93.00	33.73
PROJECT MGT	0.04 ODC \$	1.11	1.22	1.35
160 TOTAL PROJECT MGNT				35.08
TOTAL RDT&E COST				1044.89

**Table 11: F-86F Baseline Production Costs**

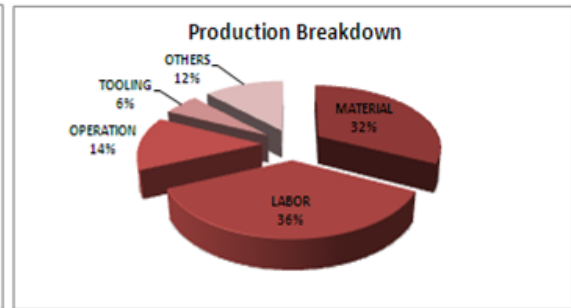
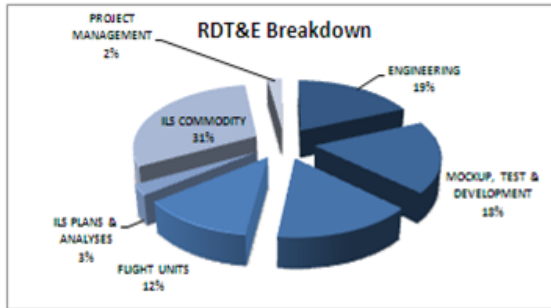
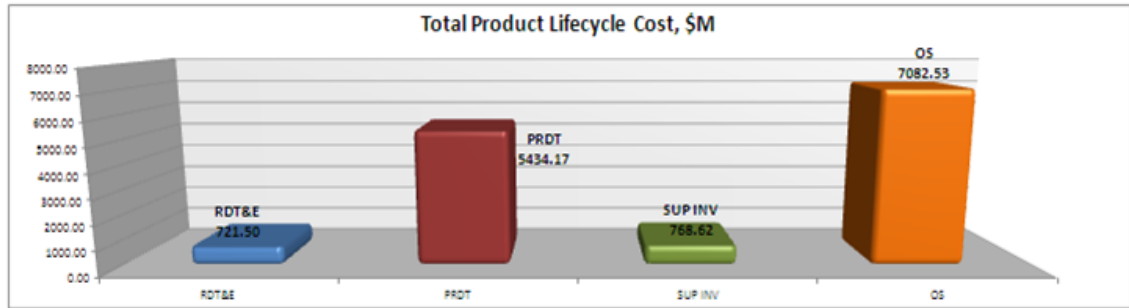
PRODUCTION COST SUMMARY (FY89 M\$)				
WORK ELEMENT	NOMENCLATURE	CONTRACTOR COST	FEE	LCC (M\$)
210	MATERIAL (MFG) \$M	0.72	1.25	0.90
RATE	TOOLING	144640.36	68.00	9.84
TOOLING	MANUFACTURING SUPPORT	7232.02	62.00	0.45
	QUALITY ASSURANCE	8678.42	64.00	0.56
	0.04 ODC \$	0.39	1.22	0.47
	210 TOTAL RATE TOOLING			12.21
220	MATERIAL (HIGH VALUE) \$	2365.87	1.05	2484.17
PRO-	MATERIAL (MFG) \$	2307.73	1.25	2884.67
DUCTION	ENGINEERING	5350161.65	93.00	497.57
	TEST ENGINEERING	102053.76	80.00	8.16
	ILS	872721.40	83.00	72.44
	MANUFACTURING	37944408.85	55.00	2086.94
	MANUFACTURING SUPPORT	3642663.25	62.00	225.85
	QUALITY ASSURANCE	4932773.15	64.00	315.70
	TOOLING M&R	4363607.02	68.00	296.73
	0.04 ODC \$	290.89	1.22	354.89
	220 TOTAL PRODUCTION			9227.10
230	PROJECT MANAGEMENT	1893175.02	93.00	176.07
PROJECT	0.04 ODC \$	5.77	1.22	7.04
MGNT	230 TOTAL PROJECT MGNT			183.11
	TOTAL PRODUCTION COST	1000 EACH		9422.42
	UNIT PRODUCTION COST (LESS FEE - FY89 M\$)			9.42

model by incorporating higher fidelity cost/time estimating results.

**Process-Based Recurring Manufacturing (PbRM) Module** Process-based recurring manufacturing model is the first detail analysis tool to be used as a complementary analysis to weight-based model. The first step is to get an accurate production plan of the part. This can be done using simple excel spreadsheet to populate all the operations required. Then each operation is assigned an equation that represents the operation time. This portion of the analysis should be done by a manufacturing expert so as to ensure that the process options are chosen correctly and the right equations are used. The analysis is made easier with incorporation of database of RSEs. The user is presented with list of input with associated options. The RSEs are populated automatically once all the options are selected. Once the right equations are chosen, the input can be acquired directly from CAD and other sources. Many times new design iteration result in weight changes, whether it be the whole aircraft weight or the part weight, the system can handle changes effectively through central input data sheet. Bill of Material (BOM) is used to populate specific part costs to be estimated through ACCEM. Figure 67 below illustrate how ACCEM modify TCM results. The top bar chart represents total LCC of the system. The two pie charts in the middle provide detailed cost breakdowns for RDT&E and Production cost respectively. The bottom part of the figure shows BOM structure of the individual parts being analyzed through process-based model.

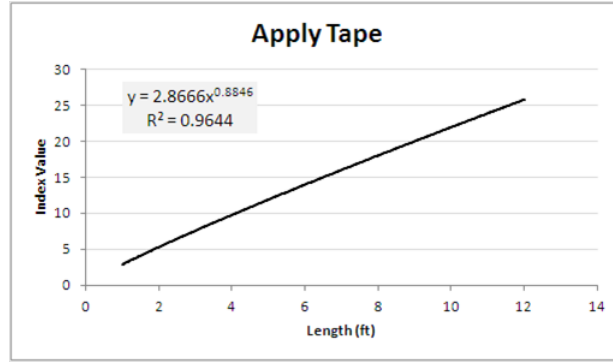
**Activity-Based Time Measurement (AbTM) Module** The equations available in PbRM module may not be applicable or not appropriate for a particular design. In such cases, new RSE has to be made. For advanced composite design concepts, customed process analysis may be required to represent more closely the actual process necessary. This option involve populating process plan, assign process characteristic as per MaxiMOST guidelines, then determining the require input for

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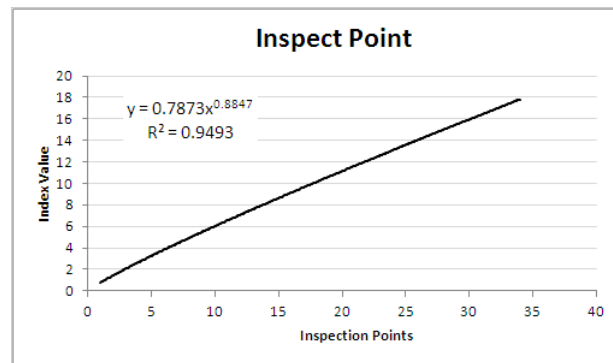


BOM										YEARLY							
COMPOSITE	Confidence Level	Material l\$/lb of part	Labor/l min cycle	Default Cycle time	Material l/(50 lb part)	Labor\$/ part	Operati ng Cost/P	Tooling	Other		Material	Labor	Operati on	Tooling	Other	#part	VT
											3374670	6451250	3059680	5889648	2852328	9200	306
GlassThermose	90	25.05	0.8438	8308.58	1866.23	309.38	90.133	480.76	295.74	559867.5	92812.5	27040	144228	88722	300	43	
GlassThermose	90	25.05	0.8438	8308.58	1866.23	309.38	90.133	480.76	295.74	559867.5	92812.5	27040	144228	88722	300	43	
GlassThermose	90	25.05	0.8438	8308.58	1866.23	309.38	90.133	480.76	295.74	559867.5	92812.5	27040	144228	88722	300	75	
GlassThermose	90	25.05	0.8438	8308.58	1866.23	309.38	90.133	480.76	295.74	559867.5	92812.5	27040	144228	88722	300	75	
NoneAluminium	95	3.3	0.76	8308.58	141.90	760	368.94	664.09	312.18	141900	760000	368940	664092	312180	1000	9	
NoneAluminium	95	3.3	0.76	8308.58	141.90	760	368.94	664.09	312.18	141900	760000	368940	664092	312180	1000	9	
NoneAluminium	95	3.3	0.76	8308.58	141.90	760	368.94	664.09	312.18	141900	760000	368940	664092	312180	1000	9	
NoneAluminium	95	3.3	0.76	8308.58	141.90	760	368.94	664.09	312.18	141900	760000	368940	664092	312180	1000	9	
NoneAluminium	95	3.3	0.76	8308.58	141.90	760	368.94	664.09	312.18	141900	760000	368940	664092	312180	1000	9	
NoneAluminium	95	3.3	0.76	8308.58	141.90	760	368.94	664.09	312.18	141900	760000	368940	664092	312180	1000	9	
NoneAluminium	95	3.3	0.76	8308.58	141.90	760	368.94	664.09	312.18	141900	760000	368940	664092	312180	1000	9	

Figure 67: Integrating Process-based Cost to Weight-based LCC Estimate



**Figure 68:** Processing Time for Apply Tape vs. Length in Feet

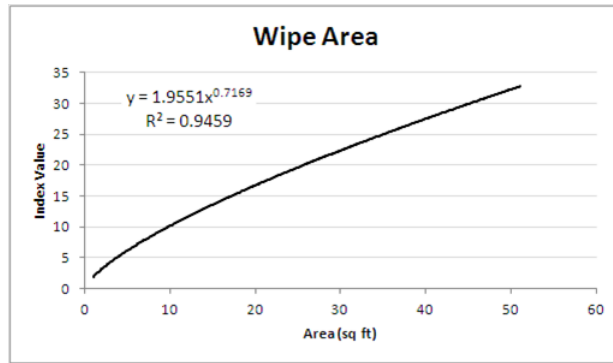


**Figure 69:** Processing Time for Inspect Point vs. Number of Points

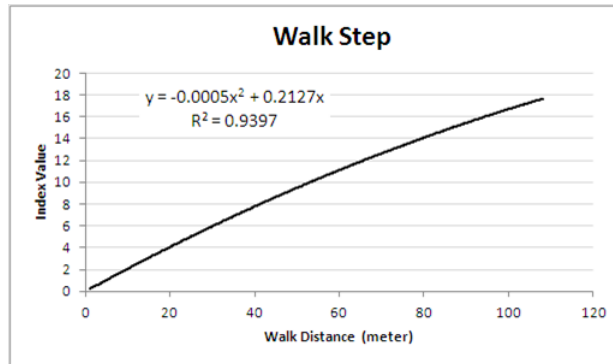
each operation, defining the range of those inputs, and finally running cases from Design of Experiment table to generate RSEs.

The concept of integrating activity-based analysis tools like MaxiMOST in the early design phase is quite complicated considering the fact that all the activities in the shop floor has to be accounted for in order to determine the actual time. Nevertheless, this analysis if done correctly and in a timely manner can be an important enabler to determine the actual cost driver and provide path forward to process improvement and cycle time reduction effort in the future. Figure 68, 69, 70, 71, and 72 are some examples for the activity time equations resulted from response surface equation generation. These building block activities can be combined into a new process sequence and converted into a new RSE.

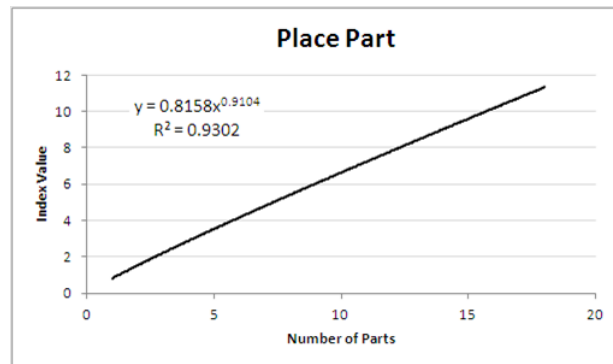




**Figure 70:** Processing Time for Wipe Area vs. Area in Square Feet



**Figure 71:** Processing Time for Walk Step vs. Length in Meters



**Figure 72:** Processing Time for Part Placement vs. Number of Parts

## Manufacturing Complexity and Determination of Main Cost Drivers

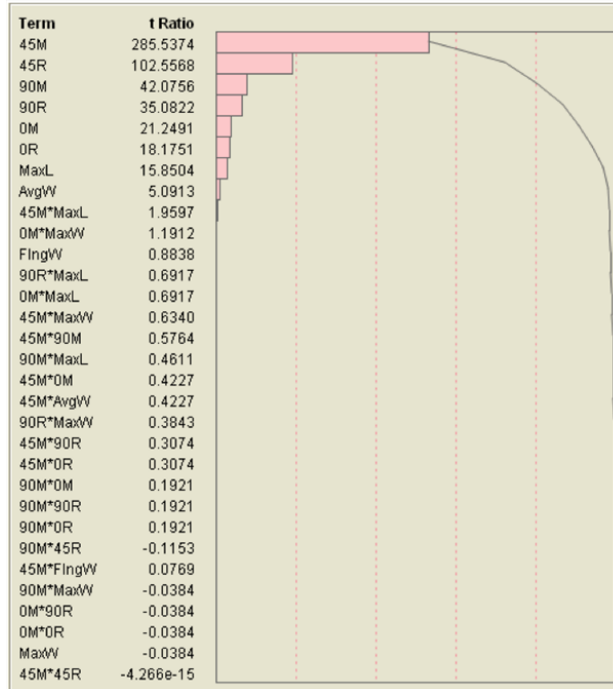
It has been found that the main cost drivers in modern Aerospace system product can be categorized into two domains; one that is dependent on *weight* and the other on *manufacturing cycle time*. Factors that influence part weight are mainly material selection, and part volume. Conversely, factors that influence cycle time are such as, process selection, geometry, feature, and part complexity. HLCET This new methodology can predict cost as a function of not only weight, as traditionally done, but also take into account material and process selection, part feature and complexity. It can also be tailored to specific knowledge at a particular time in the design process as the knowledge about the design evolves over time.

Each manufacturing process has a unique set of main cost drivers. For example, typical Aluminum structure cost is mainly driven by part weight. On the other hand, composite hand lay-up cost is driven, not by weight, but by cycle time that is dependent on the number of layers of composite plies, and orientation of each ply as shown by the Pareto plot of main effect below 73. As can be seen,  $\pm 45$  degree plies are the main cost drivers which account for almost 60% of total effects on part manufacturing cost.

### 7.3 Case Study

The paradigm shift from *Performance at Any cost* to *Value Driven Design* (VDD) together with advances in computing and software technology enable the creation of this new tightly integrated, moderate to high fidelity design and analysis environment deserving of today needs for ever more highly-coupled complex systems that requires rapid and informed decision making.

Through case studies, this section identifies several advantages of the integrated design environment that facilitates product and process trades. The cornerstone of this methodology is the ability to differentiate the impact of composite material



**Figure 73:** Pareto Plot of Main Drive for Composite Layup Processing Time Estimate

usage on various wing structural components in both *product metrics* such as weight, mission capability, structural integrity and design complexity, and on *process metrics* such as manufacturing time and complexity, and ultimately, total ownership cost (LCC).

The first case study is the identification of the limitation of the current weight-based cost model that do not have enough sensitivity to differentiate the variation in material and process variations for the different designs, and how HLCET can remedy this shortfall. In the second case study, the feasibility of each design alternatives is analyzed and compared. The overall *value* of each design is identified through the use of OEC which is a mechanism for selecting the best design option. The third case study focuses on the sensitivity analysis of each design to see how changes in design parameters affect the design effectiveness from its norm. Lastly, Fuzzy Front End analysis can be applied to each alternative to see how uncertainties from various sources can be introduced and propagated throughout the system hierarchy in search

of a balanced design alternative that is both *high value* and *robust*.

### 7.3.1 Limitation of Weight-based LCC Models

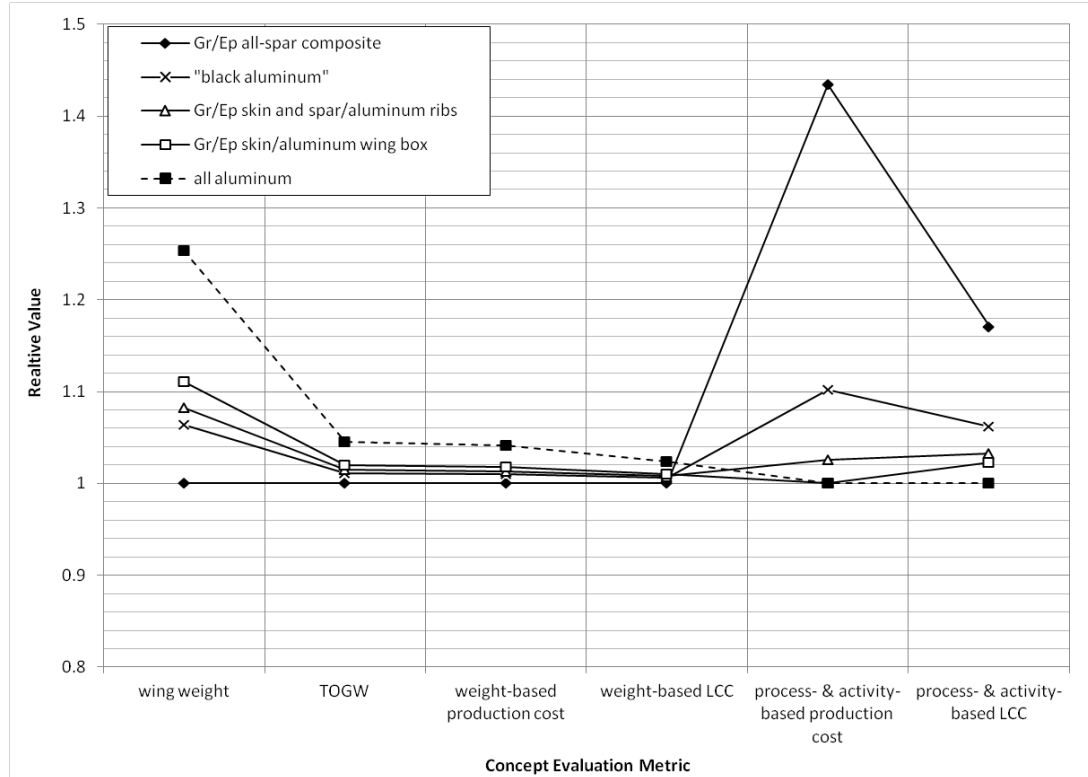
To illustrate the limitations of current weight-based cost models with respect to material and process variations, the result of the F-86 sizing and analysis were used in weight-based LCC analysis in the WbPL module of HLCET. The calculated production and total LCC costs do not reflect the process-dependent material, fabrication, and assembly costs. Figure 74 shows the incorrect weight-based system production cost and LCC cost generated with the weight-based module. The highest weight concept, the all aluminum design, is also the highest cost concept using a weight-based LCC model (the third and fourth column, respectively), which is incorrect in this case. The Gr/Ep all-spar composite design is actually the most expensive concept, even though its wing weight is substantially lower than those of the other concepts.

Hence, the product decomposition and process recomposition in Figure 14 of Chapter 4 must be enabled if the LCC estimates are to reflect material and process variations. This must include a preliminary structural analysis and a process evaluation to generate data beyond the major component weights from preliminary sizing tool. If the LCC analyses are based on component weights only, process variations will have little effect on cost.

The added sensitivity shown in the fifth and sixth columns of Figure 74 is achieved by bringing in the results from structural analysis and process evaluation to influence LCC. The materials and their compatible processes can be analyzed to produce more realistic LCC estimates.

### 7.3.2 Alternative Wing OECs

Typical process for analysis of alternatives is done through the use of Overall Evaluation Criterion (OEC). Its sole purpose is to quantify the design *value* normalized to its baseline design. It requires moderately high level of engineering design and



**Figure 74: Weight-based LCC Model Limitation**

analysis to evaluate all engineering characteristics under consideration. As a result, most design process only utilize this type of analysis only for a selected few design options and use as a go/no go type decision making rather than to compare alternatives. The resulting integrated design framework from this thesis provides a way to evaluate design alternatives using detailed engineering analysis tools and presents the result in a meaningful way. At the same time, it does not restrict the designer from choosing the design based only on one particular value. Another advantage of the integrated framework is the fact that uncertainties from difference sources can be included in the analysis process to compensate for the lack of knowledge about the requirement or the design itself.

Five feasible design alternatives are identified through various brainstorming techniques. The design alternatives are the compilation of design progression between two design extremes. On one end, the design represents traditional, off-the-shelf, low risk

design using technologies that are readily accessible. An example of such design is a typical metallic wing construction. On the other, the design represents novel, technologically advanced, and high risk design, such as an all-composite design. The design framework provides the decision support information. It allows the designer to choose a well-balanced solution which takes into account all aspects of product and process characteristics as viewed from customer's perspective. The framework also provides mechanism for the designers to make rapid iterations and tradeoffs as more knowledge about the design is acquired throughout the development cycle. Figure 75 illustrates a simple design tradeoff between cost and performance. The abscissa represents Cost Importance on the scale of zero to one, where zero means cost is not at all important as compare to performance. The ordinate represents the design value, OEC. The shaded areas in the plot differentiate the OEC values for the five design options considered. If cost is not an important factor, then design 5 dominates the other options and is chosen as the best alternative to be further analyzed in more detail.

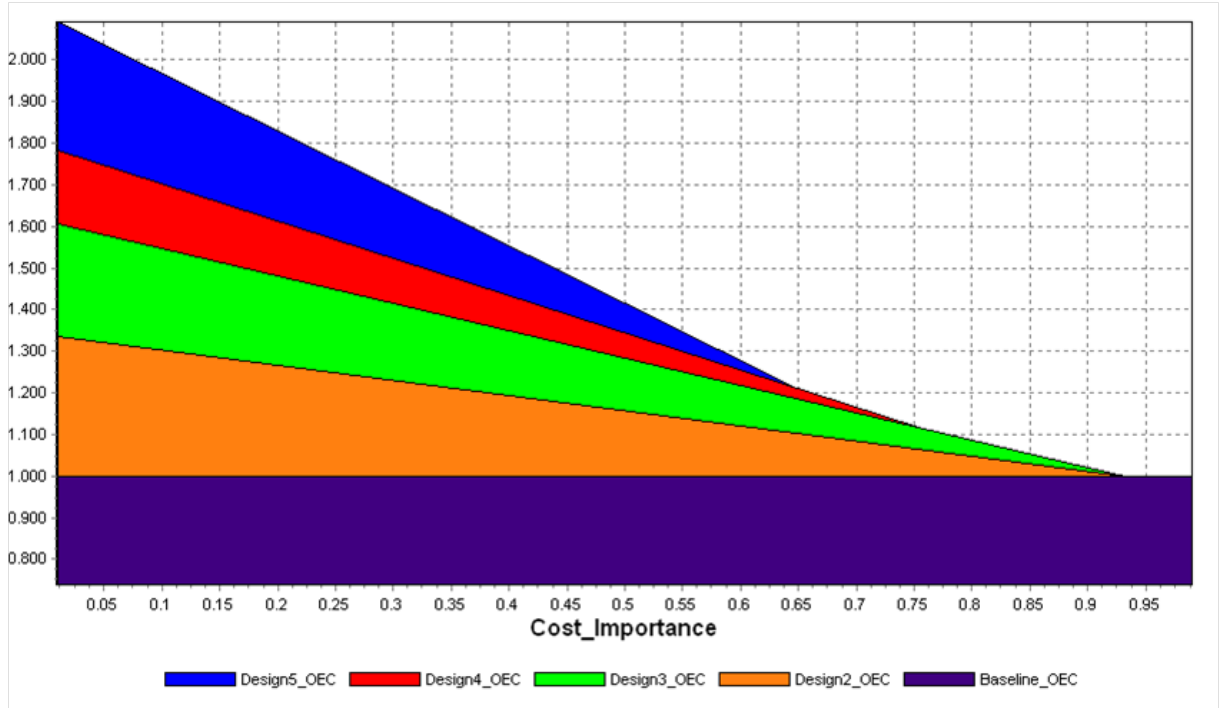
### 7.3.3 Distribution of Evaluation Metrics Value

The design and analysis environment setups as described in Section 6.2 – “System Integration” are used to evaluate all five design options to generate the list of engineering characteristics as shown in Table 12. Also shown in the table are the weighted importances resulting from the QFDs analyses.

Figure 76 below shows several product and process evaluation metrics that are used to evaluate concepts during conceptual design. The values are normalized with respect to the baseline design in order to show their relative importances rather their absolute values. The data points above datum value represent superiority as compare to the baseline, i.e. all cost metrics of advance designs exhibit less desirable values as compare to the baseline. The graph shows that structural metrics, i.e. FOS,

**Table 12:** Engineering Characteristics of Design Alternatives

	Fuel Required (lb)	Wing Weight (lb)	Wing Loading (lb)	Thrust-to-Weight Ratio	Structural Factor of Safety	Max. Linear Deformation (in)	Max Strain Energy (J)	Max Stress (Pa)	R&D Costs (F89 M\$)	Manufacturing Cost (F89 M\$)	Support Investment Cost (F89 M\$)	Wing Level Maintenance Cost (F89 M\$)
	$\epsilon$	$\zeta$	$\eta$	$\epsilon$	$\alpha$	$\beta$	$\gamma$	$\delta$	$\theta$	$\kappa$	$\xi$	$\tau$
Baseline	3352.6	2360.0	54.850	0.390	2.355	0.044	0.461	1.E+08	2255.3	12632.1	1587.5	22686.3
Design 2	3290.3	2090.0	53.500	0.400	3.442	0.030	0.215	8.E+07	2679.8	12642.5	2025.2	22691.6
Design 3	3278.7	2038.0	53.240	0.402	6.740	0.027	0.178	7.E+07	2702.1	12962.4	2076.1	22691.6
Design 4	3270.9	2003.0	53.060	0.404	8.738	0.026	0.156	7.E+07	2752.0	13920.8	2203.7	22691.6
Design 5	3244.1	1882.0	52.460	0.408	9.153	0.100	0.187	4.E+07	2774.0	18113.3	2276.3	22691.6
	0.033	0.309	0.062	0.075	0.119	0.043	0.022	0.036	0.153	0.026	0.018	0.103

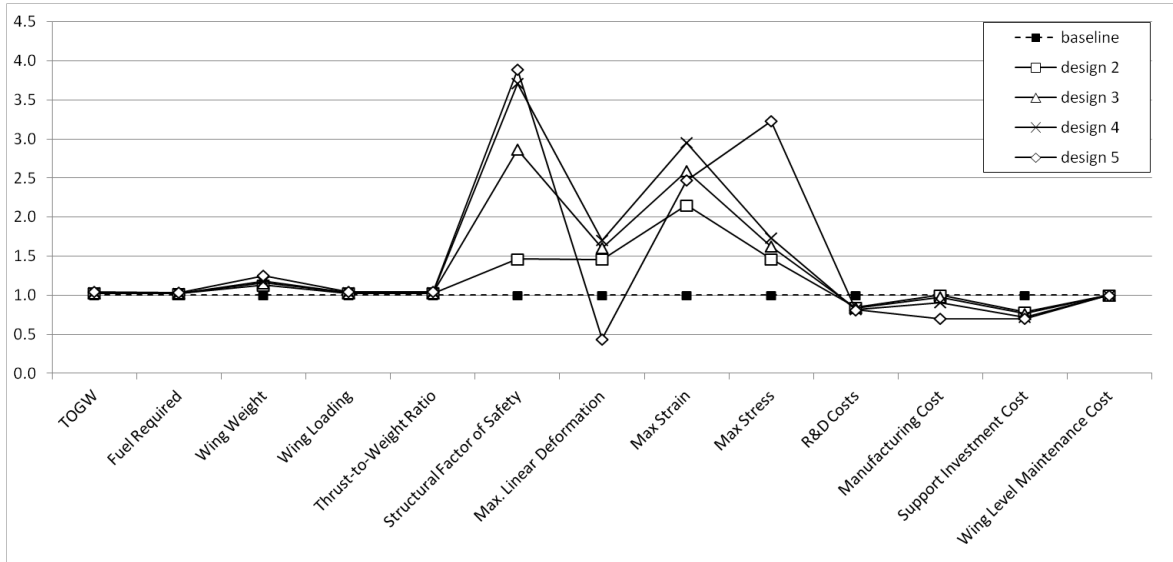


**Figure 75:** Comparison of Design Values of Feasible Alternatives as Function of Customers' Importances

deformation, stress and strain have the most dramatic proportional changes in their relative values over the design options. This, in turn, shows that the OEC value of the design is most sensitive to these metrics, provided that they are all weighted equally. As can be seen, Design 5 which has the most intensive and radical use of composite material possesses the highest structural strength with added benefit from lower weight, although with the expense of higher costs.

Since not all the metrics are treated equally, this is the direct result from QFD analyses and deployments that propagate customer desires into wing-level engineering characteristics with their corresponding weighted importance. Figure 77 show another depiction of the distribution of evaluation metrics with associated weighted importance. The characteristics are re-normalized with respect to their baseline counterparts. This plot shows two significant aspects of how the design options are evaluated. First, it can be seen that the significant of structural strength is reduced



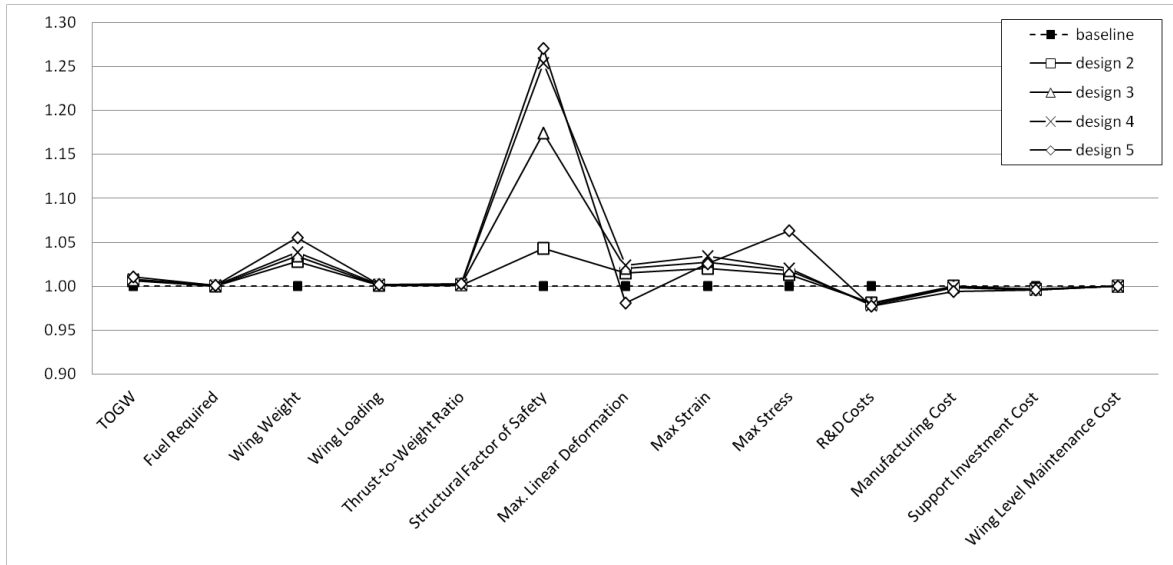


**Figure 76:** Distribution of Normalized Wing Characteristic Values

while wing weight and RDT&E costs exhibit greater importance. Still, strength is far more important as a result of greater emphasis on mission capability index, especially maneuverability as illustrated again in Figure 78 below.

By summing up all of the evaluation metrics for each design, the Overall Evaluation Criterion (OEC) value can be established as shown in Figure 79. The target OEC value set forth qualitatively at the beginning of the conceptual design phase is indicated by the red dotted line with the value of 1.198. It is used as a benchmark for a level of improvement expected for the new design as compared to the baseline. The result clearly shows that design 5, an all spar composite design is the best option available with 61% improvement in its value. Although, design option 2 is the least favorable design option, it is still a viable alternative since common sense tells us that this option is the most conservative alternative of all, i.e. minimum risk.

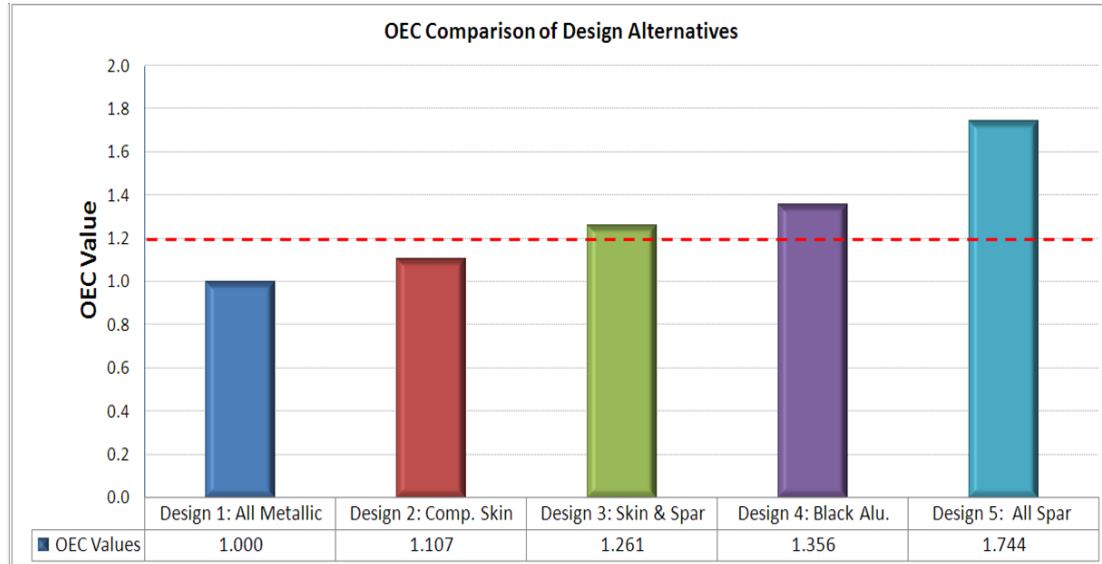
If the objective is to select the best design out of 5 alternatives using the specified customer requirements, the answer to this problem is clearly to pick option 5, the lowest weight option, since the performance gained outweighs the cost increase. It would be naive to assume that option 5 is the best just because the OEC value comes out



**Figure 77:** Renormalized Distribution Wing Characteristic Values with Associated Weighted Importances

		HOWs (Title)																
		Performance						Cost										
								RDT	Production		O&S							
F86 System Level		Customer Importance																
			Cl Max	Empty Weight	Turn Rate	L/D	Specific Fuel Consumption	T/W	Wing Loading	RDT&E Cost	Material Cost	Tooling Cost	Fabrication & Assembly Time	Maintenance Cost (Depot Level Maintenance)	Personnel Acquisition and Training Cost	Wing Manufacturing TRL		
		Direction of Improvement		↑	↓	↑	↑	↓	↑	↓	↓	↓	↓	↓	↓	↑		
		WHATs (Title)	Performance	Availability/Dependability	Reliability	6.0						○	○	○	△	●	○	
					Maintainability	4.0						●	○	△	△	○	●	
					Logistics Support	1.0				△				△	△	●	○	●
					Survivability	13.	△	△	●	△		△		●	△	△	△	○
			Performance	Capability	Endurance	11.		●		○	●	●	○	△		△	●	
					Payload	12.	○	●	△	○	△	○		●	△		○	●
					Maneuverability	15.	●	●	●	△		○	●	●	△		○	●
					Range	12.	△	●	△	●	○	○		●	△		△	●
					Speed	14.	△	●	△	○	●			●	△		△	●
					RDT&E	3.0	●	●	●	○	○	○		●	●	●	△	△
Cost		Acquisition Cost	7.0	○	●	△	○	△		△	●	●	●		●			
		Operations &	1.0		○	△		●		△	○	○	●	●	○			
		Disposal Cost	2.0		△						△	○	○	△	△			
Orgainzational Relative Importance																		

**Figure 78:** Difficulty Weighted Importance (DWI) of System Characteristics

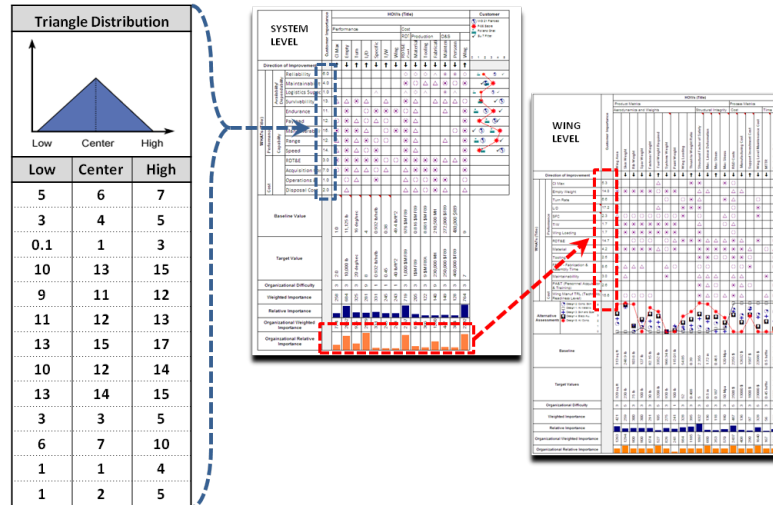


**Figure 79:** OEC Comparison of Design Alternatives

to be the highest. Two obvious problems related to practical use of this methodology is, first the customer requirements and any qualitative assessments performed during the concept exploration cannot be set in stone, thus engineering requirements that drive the evaluation can, and should, be altered as more knowledge about the design is accumulated. Secondly, performance analyses using low fidelity tools inherently contain uncertainties, or so called simulation errors, or prediction errors. To neglect these variabilities would be a mistake. To proof this point, the next case studies introduce these two aspects of uncertainties.

#### 7.3.4 Fuzzy Front End Evaluation

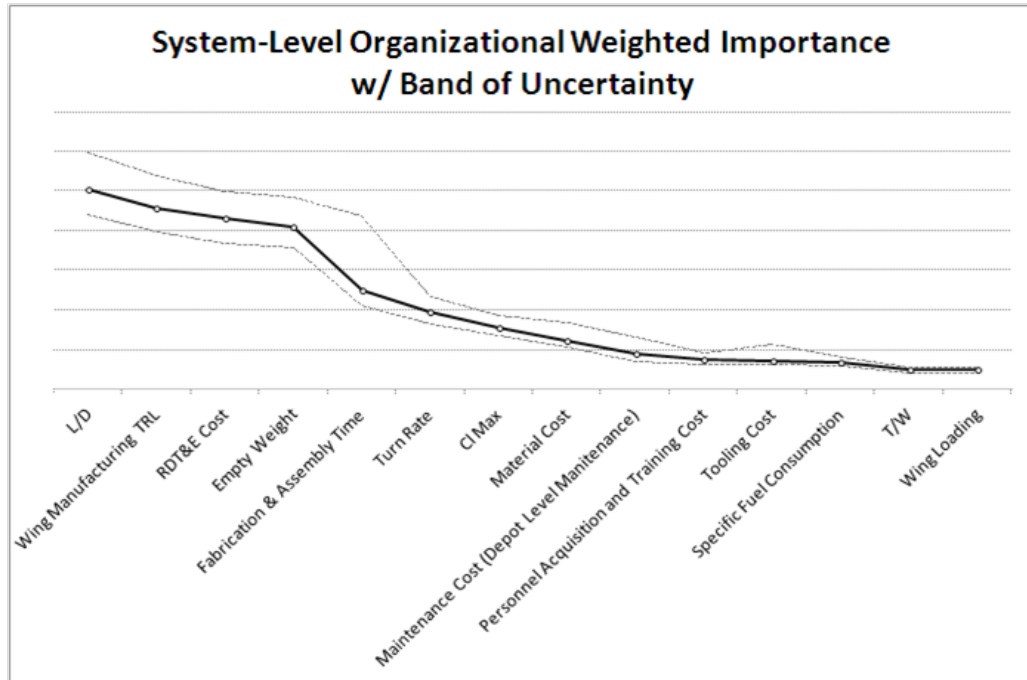
In this case study, we introduce variability with respect to customer requirement uncertainty and analytical tool fidelity. Rather than analyzing a point design as previously done in the last section, a range of possible design outcomes will be the subject of interest in this section. The requirements set forth by the customer are the accumulation of desires from all the relevant stakeholders, e.g. marketing, end-user, operation, logistic, maintenance, environment, and etc. To understand how decision to choose one design alternative over the others can be altered from variabilities in



**Figure 80:** Customer Requirements Uncertainties Integration to System-level QFD

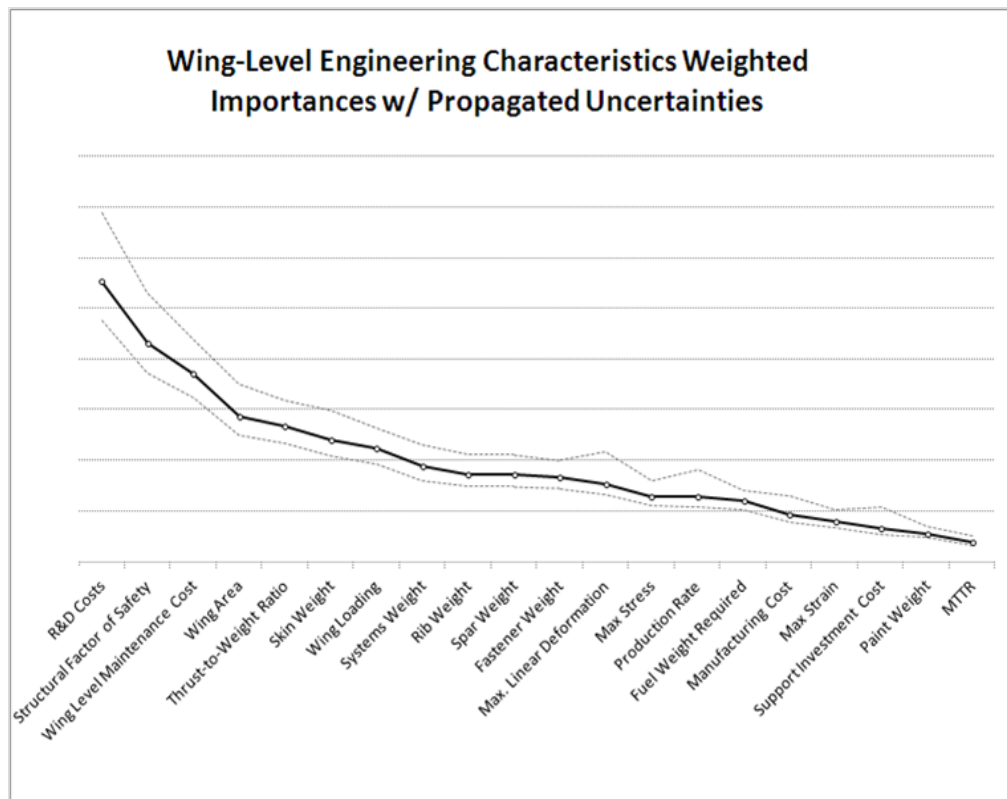
the requirements, uncertainties are introduced at the top level requirement to the QFD analysis as shown in Figure 80 below. The distributions of these noise variable may be beta, normal, triangular etc. If little knowledge is available about the shape of the distribution then a triangular shape distribution may be used. This triangle is centered around the most likely value with range endpoints unlikely to occur. The numbers in the table on the left of Figure 80 shows the possible variation for each requirement. The center value from each distribution is the weighted importance taken from Prioritization matrix. The low and high values are the associated possible variation from the center value based on the variation in the desires from various stakeholders. The uncertainties can be further propagated to the wing-level through the same mechanism as QFD deployment — system-level HOWs become wing-level WHATs.

Figure 81 and 82 below presents the resulting Organizational Weighted Importance at the system-level rearranged according to their importance ratings. The result is a Pareto-like plot showing the system-level characteristics arranged by their importance. A quick look at the plot tells us that the first four parameters are among the ones that should be focused on in the development cycle. However, upon a closer look at



**Figure 81:** System-level Organizational Weighted Importance with Integrated Uncertainty Interval

the band of uncertainties which shows the possible deviations from the norm, the fifth parameter on the list, *Fabrication and Assembly Time* could become important by virtue of the uncertainties from the customer requirements that have been identified previously. One might consider the fifth parameter to be worth mentioning. At the wing level, one conclusion that can be drawn from Figure 82 is the possible tradeoffs that can be done. For example, wing component weights and R&D costs appear to be the most important trades that must be further analyzed in detail. Also structural factor of safety (for the 7G loading condition) can be increased at the expense of higher wing weight but that may be offset by lower maintenance cost over the operating life of the aircraft.



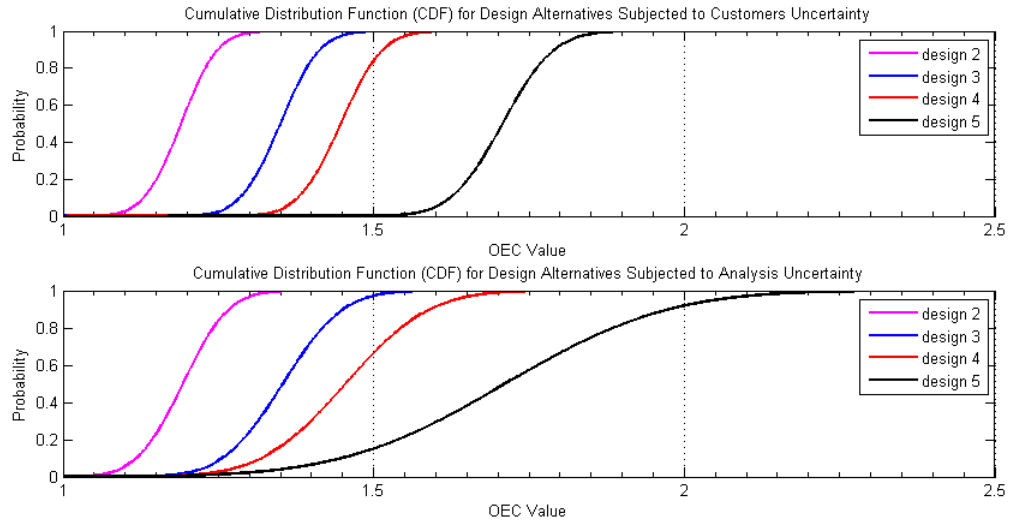
**Figure 82:** Wing-level Organizational Weighted Importance with Integrated Uncertainty Interval

### 7.3.5 Robust Design Simulation

Robust Design Simulation (RDS) is defined as the systematic approach to finding optimum values of design factors which result in economical design with low variability. To achieve this objective, many sources of uncertainties have to be quantified. In this study, two sources of uncertainties are identified, namely uncertainties associated with 1) customers requirements and 2) simulation and prediction Errors. The second step is to quantify how much variation from the norm in the form of variability distributions. Finally, propagating these uncertainties through the system design and analysis in order to understand and compare design outcomes in terms of their values, as well as variability of values as a result of system inherent random variables [18].

At the end of conceptual phase for highly complex aerospace system design, a fair amount of knowledge is gain about the system/sub-system characteristics and how they are related to the customer requirements to the point that particular design alternative and configuration can be chosen. Typical process for selecting a particular design is through the use of Multi-Attribute Decision Making (MADM) tools such as Pugh matrix, or Technique for Order Preference by Similarity to Ideal Solution (TOPSIS). These tools are essentially sophisticated ways of quantifying qualitative evaluation of alternatives. However, developing new and novel concepts and comparing them with traditional design can be difficult without engineering analyses to quantify certain characteristics before making decision. To use the decision making tools without any analysis to backup would be a miss opportunity. Robust design simulation and assessment enables moderate to high fidelity analysis tools to be integrated into the evaluation process and blurs the line between conceptual and preliminary design stages.

The success of a robust design approach hinges on the ability to integrate it into the design process and enhance the decision making capability of the designer and program manager. Robust design assessment differs from traditional point design in



**Figure 83:** Cumulative Distribution Functions (CDF) for Design Alternatives OEC.

that it accounts for both product and process contributions, under the presence of uncertainties. The uncertainty associated with the system analysis and customers requirements is provided in the form of a probability distribution when the statistics are known or by a fuzzy set when limited information as to the range and shape of the distribution is available [39].

The propagation of customers importances and simulation error distribution, as demonstrated in Figure 80 can be further analyzed for robust design assessment. The application of uncertainty to the system design is handled using a Monte Carlo simulation. Probabilistic Analysis Tool within Modelcenter environment is used. Its random number generator generates sets of random values based on the shaping function and calculates the OEC value yielding frequency and cumulative probability distribution.

Figure 83 shows CDFs as a result of customer uncertainty and analysis uncertainty introduced at the system and sub-system level, respectively. The customer uncertainty is an uncontrollable variable or noise. It can be seen that the inclusion of customers requirements' uncertainties uniformly increase the variability in the OEC distribution



over all design alternatives. The uncertainty with regard to analysis fidelity is related to the fact that the analysis tools used during the preliminary stage have difference degree of fidelities; hence difference level of confidence can be expected. Also the use of high fidelity analysis tool like finite element analysis tool to analyze advance composite structure for highly complex part designs presents a challenge in terms of accuracy of the result. Thus, higher variability is accounted for in the calculation of structural integrity index for advanced composite designs. The bottom part in Figure 83 provides the comparison between design values, and level of risk associated with it. The result from OEC distribution analysis reveals the fact that design 5 provides the best value that satisfy the customer requirements, but we also cautioned by common sense that it presents highest risk due to high usage of novel design and advance material, as well as possible prediction error from analysis tools and historical databases that may be utilized at their boundaries.

In conclusion, a Robust Design Simulation is employed in the IPPD environment. It assists the designer in creating the probabilistic environment needed to assess design viability and variability under the presence of uncertainty. A Monte Carlo Simulation is utilized to apply uncertainty analysis to the sub-system level response in terms of OEC distribution. This type of analysis can help the designer to minimize design variability from both controllable and uncontrollable sources.

## CHAPTER VIII

### CONCLUSION AND RECOMMENDATIONS

#### 8.1 *Conclusion*

The goal of this research is to study the possibility of introducing a new way to predict product lifecycle cost in such a way that it can be used throughout product development process and can play a more prominent role in influencing design decisions in this value-driven design era. The study involves identification of many estimating methodologies that are most relevant to various design phases. The relevancy of estimating methodology to a particular design phase depends on two important measures — the level of accuracy needed, and the amount of information available. The study also provide the understanding of the interactions among these estimating techniques and how they can be applied effectively such that the confidence in the outcome is improved.

The study lays the groundwork for shifting the responsibility of manufacturing and process engineers to the *left* of the product development timeline. It is achieved by integrating manufacturing knowledge in the form of production cycle time estimates into the lifecycle cost estimation, and taking advantage of the state-of-the-art virtual factory simulation to help provide the required knowledge. The consequence of this work is the creation of Hybrid Lifecycle Cost Estimating Tool (HLCET) which is the unification of weight-, process-, and activity-based estimating techniques. It is a modular and scalable estimating tool that can be used continuously throughout a product development process.

Additionally, the increased fidelity of HLCET demands higher degree of involvement from other disciplinary analyses. Thus, the validation process is done by integrating HLCET into a modeling and simulation environment as an experimental apparatus for design evaluation. The wing redesign problem is formulated. The redesign process follows Georgia Tech' Integrated Product and Process Development (IPPD) methodology where customer requirements dictate the design decision. The current study includes the following six disciplinary areas as part of the concept evaluation. However, the modularity of the analysis framework assures future additions.

- Brainstorming module using part of 7 Management and Planning tools (M&P)
- Vehicle sizing and synthesis module using FLOPS
- Product design module using Dassault Systemes' CATIA with parametric and relational design philosophies
- Structural stress analysis module using ANSYS
- Process design module using Dassault Systemes' DELMIA
- Lifecycle Cost estimation module using Hybrid Lifecycle Cost Estimating Tool (HLCET)

The lifecycle cost estimate resulting from the HLCET is shown to exhibit sensitivity to material and manufacturing process selection. The main contributor for this benefit is the direct usage of detail product-specific attributes — a direct contrast with existing cost estimating tools that rely on designer's subjective inputs, or complexity factors. Lastly, the ability to assess cost impacts from varying degrees of fidelity makes the tool accessible throughout the design process.

### 8.1.1 Fulfillment of Research Objectives

Three research objectives were stated in Chapter 1. All of these objectives were met with the work performed to complete this dissertation:

- *Create a design framework that revolves around and is driven by customers needs*

A design framework is created in this research study using a commercially available integration tool called Modelcenter. The integrated design and analysis architecture includes an Overall Evaluation Criteria (OEC) that was derived from figuring out the relationships between customers requirements and engineering characteristics through Quality Function Deployment (QFD). The OEC is then used to evaluate each design alternatives. As a result, the design evaluation is directly influenced by the customers needs.

- *Create a modular and scalable modeling and simulation environment—an analysis-oriented environment built from ground up*

The integration of analysis tools within Modelcenter environment was designed such that it can be configured to accommodate additional analysis tools to be integrated as necessary. The decision to use Modelcenter software suite makes it possible for the designer to configure the environment to analyze several discrete design alternatives without extensive modification to the system.

- *Bring in manufacturing-influenced decision support and high fidelity lifecycle cost analysis early in the product development cycle*

The main contribution of this dissertation is to develop a costing methodology that enable high fidelity cost-related analysis tools to be incorporated into low fidelity weight-based and complexity-based lifecycle cost analysis approaches used during the conceptual design phase. A Hybrid Lifecycle Cost Estimating Tool

(HLCET) was the result of the integration of three costing methodologies. The top level module, WbPL, is based on weight-based estimating technique that is then linked to the secondary process-based recurring manufacturing cost model (PbRM). PbRM contributes to the analysis by providing recurring manufacturing hours estimates that depend on several product and process characteristics. The third level is called AbTM module which help the design to construct new process alternative using a Time Measurement technique. The result is then modify the calculation in PbRM module. The overall framework for costing activity provided by HLCET allows high fidelity result to be integrated, not only during the early design phases, but also throughout the development cycle.

### 8.1.2 Research Questions Answered

The research questions posed in Chapter 1 will be answered with the evidence from the development of the tools in this thesis and the case studies that result in the following paragraphs;

- *How does the design decision influence the total product lifecycle cost?*

The importance of lifecycle cost of any product depends on the amount of dollars the customers are willing to spend for the return of products or services with expected performance. The cost incurred over the product life is typically considered as one of the major contributing factors involved in the aerospace systems design process. The issue of interest in the context of product design is the quantification of the level of importance of cost as compare to others competing metrics involved in making design decision. Additionally, the designer also interested in how much does a design decision affect the cost. To be able to quantify the effects of all the characteristics of a product on design value, a combination of tools is used in this thesis to map requirements to the

engineering characteristics such that the interactions among the involving entities can be understood. First, Prioritization Matrix can be used to rank the importance of the customer requirements. Next, Quality Function Deployment (QFD) is used to link the ranked customer requirements to all the engineering characteristics. Based on the degree of relationship, relative importance of engineering characteristics can be quantified. Lastly, the Overall Evaluation Criterion (OEC) is used to assign a value to the design — the higher the value, the better the design. Once the relationships are established, the effectiveness of design decisions can then be gauged through the change in the OEC value.

Section 7.3 steps through the process to convert the customers requirements to weighted engineering characteristics, and to define the OEC equation. The design options are then evaluated via the modeling and simulation environment. The result shown in Table 12 of Section 7.3.3 provides the relative performance benefit and the relative cost increase as compare to the baseline design. The decision to go from an all metallic design to a design with composite skin and metallic internal structure (Design 2) give a 17% increase in OEC value in terms of performance benefit. The reduction in OEC value due to cost increase is, however, only 9%. As a result, the overall OEC value is increased by 10% for the Design 2. The use of relative change in OEC value, instead of actual dollar amounts, makes it possible to quantify the effect of the decision since all the affected metrics are taken into account.

- *What are the limitations in today's cost analysis methodology as applicable to early design activity?*

As mentioned in the early chapters, most available cost estimating tools available in the conceptual design are limited to weight-based and complexity-based

parametric approaches. These cost estimating techniques only give good results when the design being estimated is similar to the previous design where the CERs are created. The similarity assumption of the cost tools severely limits the applicability of the tools to be applied to new design that does not conform to the same underlining design assumptions. The accuracy of the estimate is affected as a result.

For example, using weight-based approach to estimate the product cost means that lower weight design corresponds to lower cost. Although the complexity factors can be used as a work around to account for general effect of the fundamental differences in the design, such as, higher material cost, higher manufacturing complexity. This work around does not warrant the correct behavior if process specific parameters are to be considered. For example, the decision to reduce the overall weight by using cocuring process typically cost more than typical autoclave cure process. However, the weight-based estimating technique will predict lower cost, since the design weight is lower. To correct the result, new complexity factors need to be evaluated from higher fidelity analysis tool. In any case, the weight-based approach typically used during early design phases do not have enough sensitivity to do product and process trades.

- *How can these limitations be eliminated or reduced?*

The limitations described in the earlier question are in the two areas 1) accuracy of the estimates and 2) sensitivity to product and process parameters. First, the issue with accuracy of the estimate can be improved through acquiring new estimates through high fidelity analysis tools like process-based and activity-based approaches, then validate the results against actual data, and finally adjust the mathematical formulation, if necessary, to conform with the data. This research study does not provide any treatment on the validation process of the

results of new estimate since it is not possible to acquire actual data from the industry. The second issue is related to the lack of sensitivity of the tools to product and process parameters changes. In most situations, the accuracy of the prediction may not be as important as the relative effects the design change has on the cost. The weight-based cost estimating approaches are only sensitive to design weight changes. To be able to study the effect of difference design configurations and process alternatives, process-based approach as implemented in PbRM module in HLCET. It can be used to study how design features affect cost, since the independent variables required for the analysis are related to part information and features. It can also be used to perform trade studies on difference process alternatives that are defined within the tool. AbTM module in HLCET can also be used to populate new processes that do not exist in the existing PbRM module, thus providing the framework to expand the capability of the HLCET to follow the shift in the analysis fidelity needed for detailed design.

- *How can a cost analysis framework be developed that aid designers in high fidelity cost analysis?*

The HLCET is developed to aid the designers to perform detailed cost engineering at multiply level of fidelities depending on the availability of information about the design. Chapter 6 provides detailed treatment about the development of each module (WbPL, PbRM, and AbTM), as well as the integration work. One of the advantages of HLCET is that the designer can determine the level of fidelity he or she needs for the particular situation. Additinal fidelity can be added as the design knowledge accumulates throughout the design process. The flexibility that exist makes it more practical to be implemented than typical full-fledge bottom-up approaches that fail to provide the required result in a timely fashion.



- *How can producibility considerations and manufacturing knowledge be captured and used in the early design process?*

At the conceptual level, the producibility considerations such as feasible process alternatives, ease of production, production rate, manufacturing cost/time, and compatibility between process and raw material can be studied through PbRM module in HLCET. The knowledge database contained within the module can assist the designer in selecting appropriate process that is compatible with the design and material selection in terms of acceptable production rate and cost constraints. The level of confidence of the results, in terms of producibility considerations is also given. Low confidence level means that the knowledge database do not have enough data to infer appropriate result. The user may need to alter the selection that yield acceptable result with high level of confidence, or he or she can acquire more validated data to enhance the knowledge database.

### 8.1.3 Hypotheses Addressed

***Hypothesis 1:*** *If process characteristics of composite design are considered in lifecycle cost estimation, then certain design characteristics that yield cost and time benefits over traditional metallic design can be found – a task that cannot be easily achieved with weight- and complexity-based parametric approaches.*

The ability to tailor the design of composite parts not only enable weight saving benefit, but could potentially provide advantages in terms of cost savings. One of the advantages of composite part manufacturing is the ability to consolidate individual parts into a single assembly without the need for post-cure operation such as drilling, fastening and riveting. One example can be found in a NASA funded study on Advanced Subsonic Technology (AST) Composite Wing Program [42]. The study was

successfully designed and manufactured an aircraft wing lower cover panel in one piece. The lower cover panel part combines skin, stringer, spar cap, and intercostal sub-assembly using Stitched/Resin Film Infusion (S/RFI) process. The design achieved more than 30% weight savings, as well as cost savings at 20% below the cost of a comparable aluminum wing design. Similar conclusion has been found in this research study. It has been observed in Chapter ?? that if a process-based approach is used to predict composite part cost, it is possible to design the part such that the manufacturing labor is lower than a comparable metallic counterpart. Composite parts under about 35 pounds in weight tend to not be cost competitive with aluminum, owing to increase touch labor and quality assurance costs, and to the cost of tooling as shown in Figure 24 of Section 5.2. In conclusion, through a simple case study, the use of HLCET to estimate part manufacturing cost/time using process-based approach can give a conceptual viewpoint on how design characteristic (part size) can be determined such that cost/time benefits can be achieved by using composite design, thus verifying the hypothesis. One important note is that the example case study in this research only takes into account the direct impact on recurring manufacturing labor from reducing the need for post-cure operations, assuming that the combined part maintains the same level of manufacturing complexity.

***Hypothesis 2:*** *If the effects of material and process variations on product lifecycle cost are to be captured, the weight-based cost analysis approaches cannot be used since they do not provide enough sensitivity required. To achieve the added sensitivity, process- and activity-based cost estimating approaches must be used to be able to capture product and process-related impacts.*

The weight-based and complexity-based cost analysis approaches are

commonly used to predict product lifecycle cost during conceptual and preliminary design phase due to ease of use, and minimal information about the product is required. The major limitation of these approaches is the inherent assumption that the design characteristics are relatively unchanged from the previous design. The direct impact from this assumption is that the product cost is directly proportional to weight. In other word, lower weights result in lower cost. The impacts of product and process parameters on cost can only be thoroughly studied through the use of high fidelity analysis approaches, such as process- and activity-based estimating tools. When the knowledge and parameters pertaining to product and process design is captured at the right time in the development cycle, then a lifecycle cost estimate sensitivity to product and process characteristics can be increased. HLCET enables the designer to include product and process characteristics in the lifecycle cost analyses through the use of PbRM and AbTM module. CAD-CAM data can be used directly to provide necessary inputs for the detailed analyses within PbRM and AbTM modules. Figure 74 in Chapter 7 illustrates the limitation in the weight-based technique. The lower weight design corresponds to the lower cost design as shown in the weight-base production cost as well as weight-based LCC results. On the other hand, when specific materials and manufacturing processes are taken into considerations, the lower weight design does not always translate to lower cost as can be seen in all the design options that include composite material usage. The reason for higher cost result for composite uses is directly resulted from higher manufacturing labor requirement and initial investment on toolings and equipments. These factors cannot be easily represented if weight-based cost analysis approaches are used. The process- and activity-based cost

estimating techniques, thus, provide additional sensitivities related to material and process variations to the cost estimations.

## ***8.2 Recommendations for Future Works***

Although this study has laid out many ideas to advance the state of the art in design and analysis of complex aerospace systems, more work needs to be done in the following areas to improve their practicality and effectivity.

### **8.2.1 Integrated Design Framework**

In terms of integrated design framework, Phoenix Integration' ModelCenter 9.0, a commercially available software, is chosen in this study because of many beneficial features outlined in the thesis. However, there are other multidisciplinary design and optimization platforms available to general public, such as OpenMDAO that can potentially provide the same functionality at no cost. More disciplinary analyses can be included in the framework to explore other aspects of the product that can interplay and influence decision, such as dynamic analysis, vibration, noise, fatigue, and etc.

#### *8.2.1.1 Decouple when possible*

The design tradeoffs focused in the case study only address the issue of incorporating usage of advanced material such as carbon epoxy composite laminate to the wing structural components without changing much of the designs themselves. The purpose is to decouple the problem and be able to show that product and process trade is possible. The decoupling process is also recommended even with the expanded design space, e.g. full-fledged wing development, since the effectiveness of the framework may be reduced geometrically as more tools are integrated. Caution should be exercised when more analysis disciplines are necessary. Analysis time required for certain disciplines may be prohibitive in the early development phases when rapid

iteration is desired over accuracy. In such cases, response surface methodology and metamodeling may be desirable.

#### *8.2.1.2 Development for other complex systems*

The development of the tools in this framework only focuses on solving fixed-wing aircraft design problem, however, difference sets of tools can be used in the same manner outline in the proposed methodology to design and analyze other aerospace systems such as rotorcraft or spacecraft.

### **8.2.2 Hybrid Lifecycle Cost Estimating Tool (HLCET)**

Hybrid Lifecycle Cost Estimating Tool (HLCET) is developed by combining different cost estimating techniques into one framework. The proof of concept is demonstrated in Chapter IV. However, more validated data is needed to expand the analysis to include estimate relationships of difference types of aircrafts, materials, manufacturing processes, and etc. The current capability to include new manufacturing knowledge is through the use of response surface techniques to populate new estimate relationships. The tool also relies heavily on the availability of manufacturing knowledge in order to increase its fidelity beyond weight-based analysis, thus better integration with virtual manufacturing tool may be required.

### **8.2.3 Virtual Manufacturing**

There is still lack of research in the area of virtual manufacturing and process design activity compatible with early product development phases. Most of the usage of virtual manufacturing technology is geared toward process improvement rather than to influence product development. In terms of software development, manufacturing database should be developed such that many manufacturing rules of thumb are an integral part of virtual factory creation. At the same time, manufacturing enterprise

can adopt and propagate their proprietary knowledge into the system to enable effective knowledge acquisition and reuse. Parametric and relational design concepts used in product design should be expanded and applied to process design such that manufacturing processes become the building blocks of all product design. To demonstrate this idea, a machined part should be designed from a blank piece. Then material is removed to form machining features representing finished product. A composite part should be designed from flat sheet of laminate and later form a finished part through many folding and forming procedures typically found in the manufacturing environment. This way, part design will inherit manufacturing information right from the start, and many process attributes become an integral part of the product design.

## APPENDIX A

### FLOPS ANALYSIS OUTPUTS FOR ALL SPAR COMPOSITE DESIGN

#TITLE, BEGIN INPUT DATA ECHO

F-86F CLEAN

# NAMELIST \$OPTION

PROGRAM CONTROL, EXECUTION, ANALYSIS AND PLOT OPTION DATA

DESCRIPTION	NAME	VALUE	DIMENSIONS
TYPE OF PROBLEM	IOPT	1	
ANALYSIS OPTION	IANAL	3	
MAIN ENGINE DECK SWITCH	INENG	0	
DETAILED TAKEOFF SWITCH	ITAKOF	0	
DETAILED LANDING SWITCH	ILAND	0	
COST CALCULATION SWITCH	ICOST	1	
TRANSPORT/FIGHTER/GEN AV	IFITE	1	
TAKEOFF PROFILE FOR NOISE	NOPRO	0	
PROFILE OUTPUT FILE SWITCH	NPFILE	0	
NOISE CALCULATIONS SWITCH	NOISE	0	
MASTER PRINT CONTROL	MPRINT	1	
XFLOPS DATA PLOT SWITCH	IXFL	0	
AERO POLAR PLOT SWITCH	IPOLP	0	
THRUST DATA PLOT SWITCH	IPLTTH	0	
HISTORY DATA PLOT SWITCH	IPLTHS	0	

MANEUVER DATA PLOTS INPUT

EXCESS POWER PLOT SWITCH	IPLTPS	1	
EXCESS POWER DATA FILE	PSFILE		
PSPLOT			
MAX. MACH NO.	XMAX	0.9000	
MIN. MACH NO.	XMIN	0.3000	
MACH NO. INCREMENT	XINC	0.0500	
MAX. ALTITUDE	YMAX	25000.0	FT
MIN. ALTITUDE	YMIN	25000.0	FT
ALTITUDE INCREMENT	YINC	10000.0	FT
PLOT LOAD FACTOR	PLTNZ	-1.00	
ENGINE POWER SETTING	PLTPC	1.00	
FIXED WEIGHT FOR PLOT	PLTWT	0.	
FUEL FRACTION FOR WEIGHT	PLTFM	0.000	
DELTA WEIGHT	PLTWTA	0.	
MISSION SEGMENT FOR WEIGHT	IPLTSG	0	
STORE DRAG SCHEDULE	IPSTDG	0	

# NAMELIST \$WTIN

GEOMETRIC, WEIGHT, BALANCE AND INERTIA DATA

DESCRIPTION	NAME	VALUE	DIMENSIONS
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MAX OPER MACH NUMBER	VMMO	1.0000	
ULTIMATE LOAD FACTOR	ULF	7.0000	
REF WEIGHT NUMBER	NWREF	39	
CG REFERENCE LENGTH	CGREFL	540.0	IN
X FOR START OF CGREFL	CGREFX	0.0	IN
SWITCH TO COMPUTE WEIGHTS	MYWTS	0	
DESIGN GROSS WT. (RATIO)	DGW	1.000	
HYDRAULIC SYSTEM PRESSURE	HYDPR	3000.	

## WING DATA

DIHEDRAL(POSITIVE)	DIH	4.000	DEG
GLOVE AND BAT AREA	GLOV	0.00	SQ FT
SPAN	SPAN	36.99	FT
CONTROL SURFACE AREA RATIO	FLAPR	0.2700	
FRACTION OF COMPOSITES	FCOMP	0.0000	
AEROELASTIC TAILORING FACT	FAERT	0.0000	
STRUT BRACING FACTOR	FSTRT	0.0000	
VARIABLE SWEEP FACTOR	VARSWP	0.0000	

## HORIZONTAL TAIL DATA

AREA	SHT	26.80	SQ FT
1/4 CHORD SWEEP ANGLE	SWPHT	36.10	DEG
ASPECT RATIO	ARHT	2.21	
TAPER RATIO	TRHT	0.3400	
T/C	TCHT	0.0500	
LOCATION ON VERTICAL TAIL	HHT	0.0000	

## VERTICAL TAIL DATA

NUMBER OF VERTICAL TAILS	NVERT	1	
AREA	SVT	31.50	SQ FT
1/4 CHORD SWEEP ANGLE	SWPVT	33.30	DEG
ASPECT RATIO	ARVT	1.2700	
TAPER RATIO	TRVT	0.3400	
T/C	TCVT	0.0400	

## FUSELAGE DATA

NUMBER OF FUSELAGES	NFUSE	1	
TOTAL LENGTH	XL	45.00	FT
MAXIMUM WIDTH	WF	4.96	FT
MAXIMUM DEPTH	DF	5.18	FT
CARGO AIRCRAFT FACTOR	CARGF	0.0000	
PASSENGER COMPART LENGTH	XLP	0.00	FT

## LANDING GEAR DATA

LENGTH OF MAIN GEAR	XMLG	35.80	IN
LENGTH OF NOSE GEAR	XNLG	40.20	IN
DESIGN LANDING WEIGHT	WLDG	14471.9	LBF
SET WLDG TO END OF DESCENT	MLDWT	0	
DELTA WEIGHT FOR MLDWT=1	DLDWT	0.0	LBF
CARRIER BASED AIRCRAFT	CARBAS	0.00	

## PROPULSION SYSTEM DATA

NUMBER OF ENGINES ON WING	NEW	0	
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NUMBER OF ENGINES ON FUSE	NEF	1	
BASELINE ENGINE THRUST	THRSO	6090.0	LBF
BASELINE ENGINE WEIGHT	WENG	2950.0	LBF
WEIGHT SCALING PARAMETER	EEXP	0.00000	
BASELINE INLET WEIGHT	WINL	0.0	LBF
INLET WT SCALING EXPONENT	EINL	1.00000	
BASELINE NOZZLE WEIGHT	WNOZ	0.0	LBF
NOZZLE WT SCALING EXPONENT	ENOZ	1.00000	
BASELINE NACELLE LENGTH	XNAC	0.00	FT
BASELINE NACELLE DIAMETER	DNAC	0.00	FT
FUEL CAPACITY OF WING	FULWMX	3908.7	LBM
(FUEL CAPACITY FACTOR	FWMAX	23.000)	
FUEL CAPACITY OF FUSELAGE	FULFMX	0.0	LBM
ADJUST FUSE FUEL CAPACITY	IFUFU	0	
AUXIL TANK FUEL CAPACITY	FULAUX	0.0	LBM
NUMBER OF FUEL TANKS	NTANK	6	
ADDED MISC PROP SYSTEM WT	WPMISC	0.000	LBF

## CREW AND PAYLOAD DATA

FLIGHT CREW	NFLCR	-1	
EXTERNAL STORES - WING	CARGOW	0.0	LBF
EXT STORES - FUSELAGE	CARGOF	0.0	LBF

## OVERRIDE PARAMETERS FOR WEIGHTS

WING - TOTAL	FRWI	1.0000	
WING WEIGHT FIRST TERM	FRWI1	397.0835	
WING WEIGHT SECOND TERM	FRWI2	1.0000	
WING WEIGHT THIRD TERM	FRWI3	1.0000	
HORIZONTAL TAIL	FRHT	1.0000	
VERTICAL TAIL	FRVT	1.0000	
WING VERTICAL FIN	FRFIN	1.0000	
CANARD	FRCAN	1.0000	
FUSELAGE	FRFU	1.0000	
NOSE LANDING GEAR	FRLGN	1.0000	
MAIN LANDING GEAR	FRLGM	1.0000	
NACELLES - TOTAL OR	FRNA	1.0000	
AIR INDUCTION SYSTEM			
THRUST REVERSERS - TOTAL	WTHR	0.0000	
MISC PROPULSION SYSTEMS	WPMSC	1.0000	
FUEL SYSTEM	WFSYS	1.4000	
SURFACE CONTROLS	FRSC	1.0000	
AUXILIARY POWER UNIT	WAPU	0.0000	
INSTRUMENT GROUP	WIN	1.0000	
HYDRAULICS GROUP	WHYD	1.0000	
ELECTRICAL GROUP	WELEC	1.0000	
AVIONICS GROUP	WAVONC	1.0000	
ARMAMENT GROUP	WARM	0.0000	
FURNISHINGS GROUP	WFURN	1.0000	
AIR CONDITIONING GROUP	WAC	1.0000	
ANTI-ICING GROUP OR	WAI	1.0000	
AUXILIARY GEAR			
UNUSABLE FUEL	WUF	1.0000	
ENGINE OIL	WOIL	1.0000	

PASSENGER SERVICE OR AMMO AND NONFIXED WEAPONS	WSRV	594.0000
CARGO AND BAGGAGE CONTAIN. OR MISCELL. USEFUL LOAD	WCON	0.0000
AUXILIARY FUEL TANKS	WAUXT	0.0000
FLIGHT CREW AND BAGGAGE	WFLCRB	1.0000
CABIN CREW AND BAGGAGE	WSTUAB	1.0000

## HORIZONTAL CENTER OF GRAVITY DATA

WING	CGW	0.0	IN
HORIZONTAL TAIL	CGHT	0.0	IN
VERTICAL TAIL	CGVT	0.0	IN
WING VERTICAL FINNS	CGFIN	0.0	IN
CANARD	CGCAN	0.0	IN
FUSELAGE	CGF	0.0	IN
NOSE LANDING GEAR	CGLGN	0.0	IN
MAIN LANDING GEAR	CGLGM	0.0	IN
TWO FORWARD ENGINES	CGEF	0.0	IN
ONE OR TWO AFT ENGINES	CGEA	0.0	IN
AUXILIARY POWER UNIT	CGAP	0.0	IN
AVIONICS GROUP	CGAV	0.0	IN
ARMAMENT GROUP	CGARM	0.0	IN
FLIGHT CREW	CGCR	0.0	IN
PASSENGERS	CGP	0.0	IN
CARGO/EXT STORES IN WING	CGCW	0.0	IN
CARGO/EXT STORES IN FUSE	CGCF	0.0	IN
FUSELAGE FUEL	CGZWF	0.0	IN
WING FUEL	CGFWF	0.0	IN
AIR INDUCTION SYSTEM	CGN	0.0	IN
AIR CONDITIONING	CGAC	0.0	IN
AUXILIARY GEAR	CGAI	0.0	IN
AUXILIARY TANKS	CGAUT	0.0	IN
AMMO AND NONFIXED GUNS	CGAMMO	0.0	IN
MISCELLANEOUS USEFUL LOAD	CGMIS	0.0	IN

# NAMELIST \$CONFIN

GEOMETRIC RATIOS, OBJECTIVE FUNCTION FACTORS, AND DESIGN VARIABLES

DESCRIPTION	NAME	VALUE	DIMENSIONS
DESIGN RANGE	DESRNG	1100.0	N MI
WING LOADING REQUIRED	WSR	0.00	
THRUST/WEIGHT REQUIRED	TWR	0.00000	
GLOVE/WING AREA REQUIRED	PGLOV	0.00000	
HORIZ TAIL VOLUME COEF	HTVC	0.000000	
VERT TAIL VOLUME COEF	VTVC	0.000000	
COST CALCULATION SWITCH	ICOST	0	

FUNCTION TO BE OPTIMIZED - OBJ = 0.0000\*(RAMP WEIGHT) + 1.0000\*FUEL + 0.0000\*MACH\*(L/D) +  
0.0000\*RANGE + 0.0000\*COST + 0.0000\*(NOX EMISSIONS) +  
0.0000\*(SIDELINE NOISE) + 0.0000\*(FLYOVER NOISE) +

0.0000\*(NOISE FIGURE OF MERIT) + 0.0000\*(NOISE FOOTPRINT  
 AREA) +  
 0.0000\*(HOLD TIME FOR SEGMENT NHOLD)

## DESIGN VARIABLE DATA

VARIABLE	NAME	VALUE	ACTIVITY	LOWER BOUND	UPPER BOUND	SCALE FACTOR
- CONFIGURATION VARIABLES -						
RAMP WEIGHT, LBF	GW	15138.0	0.	0.0	0.0	0.00000
WING ASPECT RATIO	AR	4.8102	0.	0.0000	0.0000	0.00000
THRUST PER ENGINE, LBF	THRUST	6090.0	0.	0.000	0.000	0.00000
REF WING AREA, SQ FT	SW	284.5	0.	0.0	0.0	0.00000
WING TAPER RATIO	TR	0.50617	0.	0.00000	0.00000	0.00000
WING 1/4 CHORD SWEEP, DEG	SWEEP	40.00	0.	0.00	0.00	0.00000
WING T/C	TCA	0.10000	0.	0.00000	0.00000	0.00000
- MISSION VARIABLES -						
CRUISE MACH NUMBER	VCMN	0.82000	0.	0.00000	0.00000	0.00000
MAX CRUISE ALTITUDE, FT	CH	50000.0	0.	0.0	0.0	0.00000
- PROPULSION SYSTEM VARIABLES -						
TURBINE INLET TEMP (R)	ETIT	0.00	0.	0.00	0.00	0.00000
OVERALL PRESSURE RATIO	EOPR	0.000	0.	0.000	0.000	0.00000
FAN PRESSURE RATIO	EFPR	0.0000	0.	0.0000	0.0000	0.00000
BYPASS RATIO	EBPR	0.0000	0.	0.0000	0.0000	0.00000
THROTTLE RATIO	ETTR	0.00000	0.	0.00000	0.00000	0.00000
PROPELLER BLADE ANGLE	EBLA	0.00000	0.	0.00000	0.00000	0.00000
- NOISE ABATEMENT VARIABLES -						
TAKEOFF THRUST FACTOR	VARTH	0.00000	0.	0.00000	0.00000	0.00000
ROTATION VELOCITY	ROTVEL	0.00	0.	0.00	0.00	0.00
THRUST FRACTION AFTER PROGRAMMED LAPSE RATE	PLR	0.00000	0.	0.00000	0.00000	0.00000

## # NAMELIST \$AERIN

## AERODYNAMIC OPTIONS AND APPROXIMATE TAKEOFF AND LANDING DATA

DESCRIPTION	NAME	VALUE	DIMENSIONS
AERODYNAMIC INPUT METHOD	MYAERO	0	
WAVE DRAG INPUT SWITCH	IWAVE	0	
WAVE DRAG FACTOR	FWAVE	1.0000	
LINEAR/PARABOLIC INTERP	ITPAER	2	
AERO MATRIX FORMAT SWITCH	IBO	1	
MAX CAMBER AT 70 PERCENT SEMISPAN	CAM	1.00	PERCENT CHORD
AIRCRAFT BASE AREA	SBASE	0.0	SQ FT
WING TECHNOLOGY	AITEK	1.0	
MODIFY EDET DATA	MODARO	0	

FIXED DESIGN CL	FCLDES	-1.0000
FIXED DESIGN MACH NUMBER	FMDES	0.9000
TURBULENT/LAMINAR FLOW	XLLAM	0.0
AERO EFFICIENCY FACTOR	E	1.0000

## OVERRIDE PARAMETERS FOR WETTED AREAS

WING WETTED AREA	SWETW	1.0000
HOR. TAIL WETTED AREA	SWETH	1.0000
VERT. TAIL WETTED AREA	SWETV	1.0000
FUSELAGE WETTED AREA	SWETF	1.0000
NACELLE WETTED AREA	SWETN	1.0000
CANARD WETTED AREA	SWETC	1.0000

## TAKEOFF AND LANDING DATA

RATIO OF MAX. LANDING WT. TO MAX. TAKEOFF WT.	WRATIO	0.9560	
MAX. LANDING VELOCITY	VAPPR	150.0000	KTS
MAX. TAKEOFF FIELD LENGTH	FLTO	12000.0	FT
MAX. LANDING FIELD LENGTH	FLLDG	12000.0	FT
MAX. CL TAKEOFF CONFIG.	CLTOM	2.0000	
MAX. CL LANDING CONFIG.	CLLDM	3.0000	
APPROACH CL	CLAPP	0.0000	
AIR DENSITY RATIO	DRATIO	1.0000	
L/D RATIO 2ND SEG. CLIMB	ELODSS	0.0000	
L/D RATIO MISSED APPROACH	ELODMA	0.0000	
THRUST PER ENGINE TAKEOFF	THROFF	0.0000	
THRUST PER ENGINE 2ND SEG. CLIMB	THRSS	0.0	LBF
THRUST PER ENGINE MISSED APPROACH	THRMA	0.0	LBF

## # NAMELIST \$ENGDIN

## ENGINE DECK CONTROL, SCALING AND USAGE DATA

DESCRIPTION	NAME	VALUE	DIMENSIONS
ENGINE DECK PRINT CONTROL	NGPRT	1	
ENGINE DECK SOURCE SWITCH	IGENEN	1	
SLOPE FACTOR FOR EXTRAPOLATING FUEL FLOWS	EXTFAC	1.0000	
SUBSONIC FUEL FLOW FACTOR	FFFSUB	1.0000	
SUPERSONIC FUEL FLOW FACT	FFFSUP	1.0000	
FLIGHT IDLE SWITCH	IDLE	1	
IGNORE NEGATIVE THRUSTS	NONEG	0	
MIN IDLE FUEL FLOW FRACT	FIDMIN	0.0800	
MAX IDLE FUEL FLOW FRACT	FIDMAX	1.0000	
SFC EXTRAPOLATION SWITCH	IXTRAP	1	
PART POWER DATA SWITCH	IFILL	2	
MAX. CRUISE POWER SETTING	MAXCR	1	
BOOST ENGINE SWITCH	BOOST	0.0000	
FUEL FLOW SCALING			

CONSTANT TERM	DFFAC	0.0000
FUEL FLOW SCALING		
LINEAR TERM	FFFAC	0.0000
NITROGEN OXIDES SWITCH	NOX	0
INSTALLATION DRAG SWITCH	INSDRG	0

## # NAMELIST \$ENGINE

## ENGINE CYCLE ANALYSIS INPUT DATA

DESCRIPTION	NAME	VALUE	DIMENSIONS
TURBOJET	IENG	1	
ENGINE CYCLE DEF. FILE	IFILE		
TURJET			
COMPONENT MAP TABLES FILE	TFILE		
ENGTAB			
PRINT LEVEL INDICATOR	IPRINT	0	
PRINT VIB/ANOPP DATA	NPRINT	0	
PRINT LEVEL FOR WEIGHTS	IWTPRT	0	
PLOT ENGINE SCHEMATIC	IWTPLT	0	
CYCLE ANALYSIS OUTPUT FILE	OFFILE		
OUTPUT			
FLAG TO GENERATE A DECK	GENDEK	T	
ENGINE DECK OUTPUT FILE	EOFILE		
ENGDEK			
SWITCH FOR WEIGHT CALCS	NGINWT	0	
(0=NONE, 1=ENGINE, 2=1+INLET, 3=2+NACELLE, 4=3+NOZZLE)			
PART POWER DATA CONTROL	ITHROT	0	
NUMBER OF A/B POINTS	NPAB	0	
NUMBER OF DRY POINTS	NPDRY	15	
PART POWER THRUST CUTOFF	XIDLE	0.05000	
MAX ALLOWABLE ITERATIONS	NITMAX	50	

## DESIGN POINT DATA

DESIGN POINT NET THRUST	DESFN	6090.0	LBF
OVERALL PRESSURE RATIO	OPRDES	5.5000	
FAN PRESSURE RATIO	FPRDES	1.5000	
BYPASS RATIO	BPRDES	0.0000	
DESIGN TURBINE INLET TEMP	TETDES	2200.0	DEG R
DESIGN THROTTLE RATIO	TTRDES	1.1000	

## OTHER ENGINE CONFIGURATION DEFINITION DATA

FLAG FOR AFTERBURNER	ABURN	F	
FLAG FOR DUCT BURNER	DBURN	F	
AFTERBURNER EFFICIENCY	EFFAB	0.85000	
MAX AFTERBURNER TEMP	TABMAX	3500.0	DEG R
FLAG FOR VARIABLE NOZZLE	VEN	F	
CUSTOMER COMPRESSOR BLEED	COSTBL	0.0000	LB/SEC
FAN BLEED	FANBL	0.0000	LB/SEC
ADDITIONAL TAKEOFF BLEED	TKOFBL	0.0000	LB/SEC
TURBINE COOLING (FROM HPC)	WCOOL	0.0000	FRACTION (OR T41 R)

CUSTOMER POWER EXTRACTION	HPEXT	5.00	HP
FUEL HEATING VALUE	FHV	18500.0	BTU/LB
TECHNOLOGY AVAILABILITY	YEAR	1955.	YEAR
FLAG TO DO BOATTAIL DRAG	BOAT	F	
DELTA TEMPERATURE	DTCE	0.00	DEG C
DTCE VARIES TO ZERO AT	ATC	10000.	FT
FLAG TO DO SPILLAGE DRAG	SPILL	T	
FLAG TO DO LIP DRAG	LIP	T	

## USED FOR SPILLAGE INSTALLATION EFFECTS

INLET BLEED AT DESIGN	BLMAX	0.01366	
INLET DESIGN SPILLAGE	SPLDES	0.01000	
INLET DESIGN MACH NUMBER	AMINDS	0.9000	
INLET DESIGN ALTITUDE	ALINDS	50000.0	FT

## USED TO DEFINE MACH-ALTITUDE ARRAY POINTS

MAXIMUM MACH NUMBER	XMMAX	0.9000	
MAXIMUM ALTITUDE	AMAX	50000.0	FT
INCREMENT IN MACH NUMBER	XMINC	0.1000	
INCREMENT IN ALTITUDE	AINC	5000.0	FT
MINIMUM DYNAMIC PRESSURE	QMIN	25.00	PSF
MAXIMUM DYNAMIC PRESSURE	QMAX	2500.00	PSF

## ENGINE CYCLE OPTIMIZATION CRUISE CONDITION

MACH NUMBER	XMDDES	0.8000	
ALTITUDE	XADES	40000.0	FT

## ENGINE CYCLE BEHAVIORAL CONSTRAINTS

MAX COMPRESR DISCHARGE TMP	CDTMAX	99999.0000	R
MAX COMPRESR DISCHARGE PRS	CDPMAX	99999.0000	PSI
MAXIMUM JET VELOCITY	VJMAX	99999.0000	FT/SEC
MINIMUM SPECIFIC THRUST	STMIN	1.0000	LB/LB/SEC
MAXIMUM BYPASS/CORE AREA	ARMAX	99999.0000	

NO CONVERGENCE AND THRUST IS GOING UP FOR M = 0.200 ALTITUDE = 20000.0 FT., THROTTLE POINT = 14. SUM OF SQUARE OF ERRORS = 0.2981D-01.

NO CONVERGENCE AND THRUST IS GOING UP FOR M = 0.200 ALTITUDE = 5000.0 FT., THROTTLE POINT = 14. SUM OF SQUARE OF ERRORS = 0.1919D-01.

SEA LEVEL STATIC MAXIMUM THRUST	6090.0	LB
GENERATED PROPULSION SYSTEM WT.	2950.0	LB

(NEW BASELINE ENGINE THRUST - OVERRIDES THRSO)

## # ALL POINT ENGINE DECK SUMMARY

MACH = 0.900, ALTITUDE = 50000., THRUSTS/FUEL FLOWS/SFCS/NOX RATIOS FOLLOW

935.0	848.9	765.2	706.1	649.2	594.4	541.6	490.8	442.0	394.7	342.5
291.1	242.9	197.8	155.4	0.0						
1041.9	938.8	841.2	774.0	710.2	649.6	592.3	538.1	486.9	438.5	389.1
342.3	299.1	259.2	222.4	87.7						
1.114	1.106	1.099	1.096	1.094	1.093	1.094	1.096	1.102	1.111	1.136
1.176	1.231	1.310	1.431	0.000						

MACH = 0.900, ALTITUDE = 45000., THRUSTS/FUEL FLOWS/SFCS/NOX RATIOS FOLLOW

1186.5	1077.4	971.0	896.1	823.9	754.3	687.3	622.8	560.9	501.0	434.7
369.5	308.3	251.1	197.2	0.0						
1321.3	1190.6	1066.8	981.6	900.6	823.8	751.1	682.3	617.4	556.0	493.4
433.9	379.0	328.5	281.8	110.8						
1.114	1.105	1.099	1.095	1.093	1.092	1.093	1.095	1.101	1.110	1.135
1.174	1.229	1.308	1.429	0.000						

MACH = 0.900, ALTITUDE = 40000., THRUSTS/FUEL FLOWS/SFCS/NOX RATIOS FOLLOW

1506.1	1367.7	1232.7	1137.6	1045.9	957.6	872.5	790.7	712.0	636.1	552.0
469.1	391.5	318.8	250.4	0.0						
1676.4	1510.7	1353.6	1245.4	1142.6	1045.2	952.9	865.6	783.2	705.3	625.8
550.3	480.7	416.5	357.2	140.3						
1.113	1.105	1.098	1.095	1.092	1.092	1.092	1.095	1.100	1.109	1.134
1.173	1.228	1.307	1.427	0.000						

MACH = 0.900, ALTITUDE = 35000., THRUSTS/FUEL FLOWS/SFCS/NOX RATIOS FOLLOW

1915.6	1739.6	1567.9	1446.9	1330.3	1217.9	1109.8	1005.8	905.8	809.5	702.5
597.2	498.5	406.2	319.2	0.0						
2145.8	1933.5	1732.3	1593.7	1462.1	1337.3	1219.2	1107.4	1001.9	902.2	800.5
703.9	614.8	532.7	456.8	178.4						
1.120	1.111	1.105	1.101	1.099	1.098	1.099	1.101	1.106	1.115	1.139
1.179	1.233	1.312	1.431	0.000						

MACH = 0.900, ALTITUDE = 30000., THRUSTS/FUEL FLOWS/SFCS/NOX RATIOS FOLLOW

2433.0	2208.9	1991.6	1838.0	1689.8	1547.2	1410.0	1278.1	1151.4	1029.5	894.1
761.1	636.0	519.2	409.3	0.0						
2803.7	2524.7	2261.6	2080.3	1908.3	1745.2	1590.8	1444.7	1306.7	1176.5	1043.7
917.9	801.7	694.8	596.0	228.3						
1.152	1.143	1.136	1.132	1.129	1.128	1.128	1.130	1.135	1.143	1.167
1.206	1.260	1.338	1.456	0.000						

MACH = 0.900, ALTITUDE = 25000., THRUSTS/FUEL FLOWS/SFCS/NOX RATIOS FOLLOW

3059.0	2776.8	2504.3	2311.3	2125.0	1945.6	1773.0	1607.2	1447.9	1294.7	1124.4
957.8	800.8	654.1	516.5	0.0						
3623.4	3261.3	2920.6	2685.9	2463.2	2252.2	2052.5	1863.6	1685.1	1516.5	1344.6
1182.2	1032.3	894.3	767.1	289.9						
1.185	1.174	1.166	1.162	1.159	1.158	1.158	1.160	1.164	1.171	1.196
1.234	1.289	1.367	1.485	0.000						

MACH = 0.900, ALTITUDE = 20000., THRUSTS/FUEL FLOWS/SFCS/NOX RATIOS FOLLOW

3811.6	3460.0	3121.4	2880.6	2648.4	2424.7	2209.4	2002.5	1803.8	1612.5	1400.1
1192.8	997.2	814.3	643.0	0.0						
4637.8	4172.9	3736.2	3434.5	3148.7	2878.0	2621.9	2379.7	2151.1	1934.9	1714.4
1506.4	1314.4	1137.9	975.4	371.0						
1.217	1.206	1.197	1.192	1.189	1.187	1.187	1.188	1.193	1.200	1.224
1.263	1.318	1.397	1.517	0.000						

MACH = 0.900, ALTITUDE = 15000., THRUSTS/FUEL FLOWS/SFCS/NOX RATIOS FOLLOW

4698.8	4265.1	3849.3	3552.2	3265.8	2990.1	2724.8	2469.7	2224.5	1987.7	1725.8
1470.4	1229.3	1004.0	792.6	0.0						
5867.4	5277.7	4725.1	4342.5	3979.7	3636.6	3312.2	3005.6	2716.2	2442.1	2163.1
1899.8	1656.7	1433.6	1228.2	469.4						
1.249	1.237	1.228	1.222	1.219	1.216	1.216	1.217	1.221	1.229	1.253



1.292 1.348 1.428 1.550 0.000

MACH = 0.900, ALTITUDE = 10000., THRUSTS/FUEL FLOWS/SFCS/NOX RATIOS FOLLOW  
 5747.6 5215.9 4707.8 4346.4 3996.6 3659.8 3336.1 3024.7 2725.3 2435.2 2115.6  
 1803.9 1509.1 1234.0 975.6 0.0  
 7359.4 6617.5 5923.7 5444.6 4989.4 4558.6 4151.7 3767.4 3404.5 3060.6 2711.3  
 2381.6 2076.6 1796.8 1539.4 588.8  
 1.280 1.269 1.258 1.253 1.248 1.246 1.244 1.246 1.249 1.257 1.282  
 1.320 1.376 1.456 1.578 0.000

MACH = 0.900, ALTITUDE = 5000., THRUSTS/FUEL FLOWS/SFCS/NOX RATIOS FOLLOW  
 6661.4 6045.6 5453.9 5034.7 4630.4 4241.0 3866.5 3506.1 3159.2 2798.4 2429.9  
 2065.5 1725.5 1407.3 1104.1 0.0  
 8698.8 7827.5 7009.1 6445.2 5910.2 5403.4 4924.3 4471.6 4043.8 3622.2 3212.2  
 2822.2 2463.6 2133.7 1827.8 713.8  
 1.306 1.295 1.285 1.280 1.276 1.274 1.274 1.275 1.280 1.294 1.322  
 1.366 1.428 1.516 1.656 0.000

MACH = 0.900, ALTITUDE = 0., THRUSTS/FUEL FLOWS/SFCS/NOX RATIOS FOLLOW  
 7424.2 6741.6 6072.5 5605.7 5155.4 4721.6 4303.8 3901.3 3495.7 3065.2 2643.0  
 2240.9 1863.7 1509.1 1160.2 0.0  
 9855.7 8882.5 7956.6 7323.0 6721.4 6151.0 5610.8 5099.6 4604.0 4110.4 3641.9  
 3205.3 2802.1 2429.3 2078.0 909.4  
 1.328 1.318 1.310 1.306 1.304 1.303 1.304 1.307 1.317 1.341 1.378  
 1.430 1.503 1.610 1.791 0.000

MACH = 0.800, ALTITUDE = 50000., THRUSTS/FUEL FLOWS/SFCS/NOX RATIOS FOLLOW  
 845.7 768.2 692.7 639.4 588.0 538.5 490.8 445.0 400.9 358.0 310.7  
 264.1 220.4 179.5 140.8 0.0  
 916.8 826.4 740.6 681.3 625.0 571.6 521.1 473.3 428.3 385.4 341.9  
 300.5 262.4 227.3 194.8 76.7  
 1.084 1.076 1.069 1.066 1.063 1.062 1.062 1.064 1.068 1.077 1.100  
 1.138 1.190 1.266 1.384 0.000

MACH = 0.800, ALTITUDE = 45000., THRUSTS/FUEL FLOWS/SFCS/NOX RATIOS FOLLOW  
 1073.0 974.8 878.9 811.4 746.1 683.3 622.8 564.7 508.8 454.4 394.4  
 335.2 279.8 227.9 178.7 0.0  
 1162.5 1047.9 939.0 863.9 792.5 724.7 660.6 600.1 542.9 488.5 433.4  
 380.8 332.5 287.9 246.7 96.9  
 1.083 1.075 1.068 1.065 1.062 1.061 1.061 1.063 1.067 1.075 1.099  
 1.136 1.188 1.264 1.381 0.000

MACH = 0.800, ALTITUDE = 40000., THRUSTS/FUEL FLOWS/SFCS/NOX RATIOS FOLLOW  
 1361.9 1237.3 1115.7 1029.9 947.1 867.4 790.6 716.8 645.8 576.9 500.8  
 425.5 355.2 289.3 226.8 0.0  
 1474.6 1329.3 1191.3 1095.9 1005.3 919.3 838.0 761.1 688.5 619.6 549.6  
 482.9 421.5 365.0 312.7 122.6  
 1.083 1.074 1.068 1.064 1.061 1.060 1.060 1.062 1.066 1.074 1.097  
 1.135 1.187 1.262 1.378 0.000

MACH = 0.800, ALTITUDE = 35000., THRUSTS/FUEL FLOWS/SFCS/NOX RATIOS FOLLOW  
 1732.2 1573.8 1419.1 1310.0 1204.7 1103.3 1005.7 911.9 821.7 734.3 637.5  
 541.9 452.5 368.7 289.3 0.0

1887.4	1701.3	1524.5	1402.4	1286.4	1176.3	1072.1	973.7	880.7	792.7	703.0
617.7	539.1	466.8	399.8	155.7						
1.090	1.081	1.074	1.071	1.068	1.066	1.066	1.068	1.072	1.080	1.103
1.140	1.192	1.266	1.382	0.000						

MACH = 0.800, ALTITUDE = 30000., THRUSTS/FUEL FLOWS/SFCS/NOX RATIOS FOLLOW

2200.5	1998.9	1803.0	1664.2	1530.4	1401.7	1277.8	1158.8	1044.5	933.9	811.5
690.6	577.4	471.3	370.9	0.0						
2466.7	2222.2	1990.9	1831.0	1679.2	1535.3	1399.0	1270.2	1148.6	1033.5	916.5
805.3	702.9	608.5	521.2	198.8						
1.121	1.112	1.104	1.100	1.097	1.095	1.095	1.096	1.100	1.107	1.129
1.166	1.217	1.291	1.405	0.000						

MACH = 0.800, ALTITUDE = 25000., THRUSTS/FUEL FLOWS/SFCS/NOX RATIOS FOLLOW

2765.9	2511.9	2266.4	2092.2	1924.1	1762.3	1606.7	1457.1	1313.5	1174.8	1021.2
870.1	728.1	595.3	469.8	0.0						
3187.0	2869.5	2570.2	2363.4	2167.1	1981.1	1805.1	1638.5	1481.2	1332.4	1181.2
1038.0	905.9	784.4	672.0	255.0						
1.152	1.142	1.134	1.130	1.126	1.124	1.123	1.125	1.128	1.134	1.157
1.193	1.244	1.318	1.430	0.000						

MACH = 0.800, ALTITUDE = 20000., THRUSTS/FUEL FLOWS/SFCS/NOX RATIOS FOLLOW

3445.4	3128.6	2823.7	2606.7	2397.4	2195.8	2001.8	1815.5	1636.4	1463.4	1271.9
1084.2	907.5	742.2	586.7	0.0						
4077.8	3669.9	3286.2	3020.9	2769.4	2531.1	2305.5	2092.3	1890.9	1700.2	1506.4
1323.3	1154.4	999.1	855.9	326.2						
1.184	1.173	1.164	1.159	1.155	1.153	1.152	1.153	1.156	1.162	1.184
1.221	1.272	1.346	1.459	0.000						

MACH = 0.800, ALTITUDE = 15000., THRUSTS/FUEL FLOWS/SFCS/NOX RATIOS FOLLOW

4253.8	3862.7	3487.4	3219.1	2960.6	2711.7	2472.0	2241.7	2020.5	1806.3	1569.4
1337.7	1119.5	915.4	723.4	0.0						
5167.6	4649.3	4162.7	3825.1	3505.3	3202.7	2916.4	2645.8	2390.3	2148.3	1902.2
1669.9	1455.8	1259.1	1077.9	413.4						
1.215	1.204	1.194	1.188	1.184	1.181	1.180	1.180	1.183	1.189	1.212
1.248	1.300	1.376	1.490	0.000						

MACH = 0.800, ALTITUDE = 10000., THRUSTS/FUEL FLOWS/SFCS/NOX RATIOS FOLLOW

5202.5	4723.6	4266.3	3938.3	3622.2	3318.0	3025.4	2743.9	2473.4	2210.9	1921.2
1638.1	1371.3	1121.7	887.1	0.0						
6481.2	5829.4	5219.2	4795.1	4393.2	4013.0	3653.8	3314.4	2994.0	2690.0	2381.5
2090.3	1821.5	1575.0	1348.0	518.5						
1.246	1.234	1.223	1.218	1.213	1.209	1.208	1.208	1.210	1.217	1.240
1.276	1.328	1.404	1.520	0.000						

MACH = 0.800, ALTITUDE = 5000., THRUSTS/FUEL FLOWS/SFCS/NOX RATIOS FOLLOW

6316.6	5733.8	5178.2	4782.5	4399.3	4030.6	3676.2	3335.4	3007.7	2688.8	2338.1
1995.3	1671.2	1368.6	1084.2	0.0						
8063.4	7250.2	6489.6	5963.5	5463.3	4990.1	4543.1	4121.2	3722.9	3344.6	2961.5
2599.9	2265.5	1958.8	1676.8	645.1						
1.277	1.264	1.253	1.247	1.242	1.238	1.236	1.236	1.238	1.244	1.267
1.303	1.356	1.431	1.547	0.000						

MACH = 0.800, ALTITUDE = 0., THRUSTS/FUEL FLOWS/SFCS/NOX RATIOS FOLLOW  
 7185.8 6525.4 5889.0 5437.1 5001.5 4582.3 4179.1 3791.2 3417.5 3020.1 2620.0  
 2227.3 1860.2 1516.1 1184.5 0.0  
 9337.6 8404.2 7525.9 6918.4 6342.0 5796.3 5280.3 4792.8 4332.1 3873.0 3430.9  
 3012.4 2627.6 2273.4 1943.4 764.6  
 1.299 1.288 1.278 1.272 1.268 1.265 1.264 1.264 1.268 1.282 1.309  
 1.352 1.413 1.500 1.641 0.000

MACH = 0.700, ALTITUDE = 50000., THRUSTS/FUEL FLOWS/SFCS/NOX RATIOS FOLLOW  
 774.4 703.8 634.8 586.1 539.1 493.8 450.2 408.4 368.1 328.4 285.1  
 242.2 202.0 163.9 126.4 0.0  
 816.3 736.0 659.6 606.7 556.4 508.7 463.6 421.0 380.8 342.3 303.5  
 266.5 232.5 201.0 171.1 70.7  
 1.054 1.046 1.039 1.035 1.032 1.030 1.030 1.031 1.035 1.042 1.064  
 1.100 1.151 1.226 1.354 0.000

MACH = 0.700, ALTITUDE = 45000., THRUSTS/FUEL FLOWS/SFCS/NOX RATIOS FOLLOW  
 982.5 893.1 805.5 743.7 684.0 626.6 571.3 518.2 467.0 416.9 361.9  
 307.4 256.4 208.1 160.4 0.0  
 1034.7 933.0 836.2 769.1 705.3 644.8 587.6 533.6 482.5 433.8 384.6  
 337.6 294.5 254.6 216.7 89.2  
 1.053 1.045 1.038 1.034 1.031 1.029 1.029 1.030 1.033 1.041 1.063  
 1.099 1.149 1.223 1.351 0.000

MACH = 0.700, ALTITUDE = 40000., THRUSTS/FUEL FLOWS/SFCS/NOX RATIOS FOLLOW  
 1247.0 1133.6 1022.4 943.9 868.2 795.3 725.1 657.7 592.8 529.3 459.4  
 390.2 325.5 264.2 203.7 0.0  
 1312.4 1183.5 1060.6 975.5 894.5 817.8 745.2 676.7 611.9 550.2 487.6  
 428.0 373.3 322.6 274.5 112.8  
 1.052 1.044 1.037 1.033 1.030 1.028 1.028 1.029 1.032 1.039 1.061  
 1.097 1.147 1.221 1.348 0.000

MACH = 0.700, ALTITUDE = 35000., THRUSTS/FUEL FLOWS/SFCS/NOX RATIOS FOLLOW  
 1585.9 1441.7 1300.4 1200.6 1104.4 1011.7 922.5 836.8 754.3 673.8 584.9  
 497.0 414.8 336.9 260.0 0.0  
 1679.6 1514.5 1357.3 1248.2 1144.6 1046.4 953.4 865.6 782.7 703.8 623.7  
 547.5 477.5 412.6 351.0 143.0  
 1.059 1.051 1.044 1.040 1.036 1.034 1.034 1.034 1.038 1.045 1.066  
 1.102 1.151 1.224 1.350 0.000

MACH = 0.700, ALTITUDE = 30000., THRUSTS/FUEL FLOWS/SFCS/NOX RATIOS FOLLOW  
 2015.1 1831.5 1652.4 1525.6 1403.5 1285.8 1172.6 1063.8 959.4 857.7 745.4  
 634.1 530.1 431.5 334.7 0.0  
 2195.7 1978.9 1773.1 1630.3 1494.7 1366.2 1244.5 1129.5 1021.0 918.1 813.6  
 714.2 622.8 538.2 458.2 181.7  
 1.090 1.080 1.073 1.069 1.065 1.063 1.061 1.062 1.064 1.070 1.091  
 1.126 1.175 1.247 1.369 0.000

MACH = 0.700, ALTITUDE = 25000., THRUSTS/FUEL FLOWS/SFCS/NOX RATIOS FOLLOW  
 2533.0 2301.7 2077.4 1918.0 1764.4 1616.6 1474.3 1337.6 1206.4 1079.0 938.3  
 799.1 668.8 545.7 424.9 0.0  
 2837.2 2555.5 2289.3 2104.5 1929.2 1763.0 1605.7 1457.0 1316.6 1183.6 1048.8  
 920.7 802.9 693.9 591.0 229.0

1.120	1.110	1.102	1.097	1.093	1.091	1.089	1.089	1.091	1.097	1.118
1.152	1.200	1.272	1.391	0.000						

MACH = 0.700, ALTITUDE = 20000., THRUSTS/FUEL FLOWS/SFCS/NOX RATIOS FOLLOW

3154.0	2865.5	2587.0	2388.8	2197.6	2013.5	1836.5	1666.3	1502.8	1344.1	1169.1
996.5	834.5	681.8	532.5	0.0						
3628.6	3266.6	2925.6	2689.0	2464.5	2251.9	2050.7	1860.4	1680.7	1510.3	1337.8
1174.4	1023.9	885.0	754.0	290.3						
1.151	1.140	1.131	1.126	1.121	1.118	1.117	1.116	1.118	1.124	1.144
1.178	1.227	1.298	1.416	0.000						

MACH = 0.700, ALTITUDE = 15000., THRUSTS/FUEL FLOWS/SFCS/NOX RATIOS FOLLOW

3895.6	3539.0	3196.0	2951.2	2715.2	2487.9	2269.1	2058.9	1856.8	1660.5	1443.9
1231.2	1031.0	842.6	659.1	0.0						
4600.6	4140.0	3707.0	3406.1	3120.9	2850.9	2595.5	2354.1	2126.1	1909.8	1690.6
1483.5	1292.8	1116.9	951.5	368.0						
1.181	1.170	1.160	1.154	1.149	1.146	1.144	1.143	1.145	1.150	1.171
1.205	1.254	1.326	1.444	0.000						

MACH = 0.700, ALTITUDE = 10000., THRUSTS/FUEL FLOWS/SFCS/NOX RATIOS FOLLOW

4768.2	4331.5	3913.0	3613.0	3324.2	3046.1	2778.4	2521.0	2273.8	2032.9	1767.3
1506.8	1261.8	1031.1	806.4	0.0						
5775.4	5195.7	4651.8	4272.9	3913.9	3574.3	3253.3	2950.0	2663.6	2391.6	2116.2
1856.0	1616.5	1395.9	1188.4	462.0						
1.211	1.200	1.189	1.183	1.177	1.173	1.171	1.170	1.171	1.176	1.197
1.232	1.281	1.354	1.474	0.000						

MACH = 0.700, ALTITUDE = 5000., THRUSTS/FUEL FLOWS/SFCS/NOX RATIOS FOLLOW

5788.7	5257.3	4750.8	4387.4	4037.1	3700.1	3376.1	3064.3	2764.6	2472.3	2150.4
1834.7	1537.1	1257.4	985.0	0.0						
7184.9	6461.8	5785.3	5313.7	4866.7	4444.0	4044.8	3667.7	3311.7	2973.4	2631.0
2307.7	2009.6	1735.4	1477.8	574.8						
1.241	1.229	1.218	1.211	1.206	1.201	1.198	1.197	1.198	1.203	1.224
1.258	1.307	1.380	1.500	0.000						

MACH = 0.700, ALTITUDE = 0., THRUSTS/FUEL FLOWS/SFCS/NOX RATIOS FOLLOW

6979.1	6337.2	5725.3	5289.8	4867.9	4462.1	4072.2	3697.3	3336.7	2983.9	2597.1
2217.7	1858.8	1521.9	1194.2	0.0						
8870.7	7975.5	7138.3	6557.9	6005.8	5483.5	4990.3	4524.9	4085.7	3667.7	3245.9
2847.4	2479.3	2141.0	1823.5	709.7						
1.271	1.259	1.247	1.240	1.234	1.229	1.225	1.224	1.224	1.229	1.250
1.284	1.334	1.407	1.527	0.000						

MACH = 0.600, ALTITUDE = 50000., THRUSTS/FUEL FLOWS/SFCS/NOX RATIOS FOLLOW

719.7	654.5	590.5	545.0	501.3	459.2	418.8	379.9	342.5	305.3	264.8
224.7	186.0	148.3	111.1	0.0						
736.2	663.9	595.0	547.1	501.5	458.3	417.5	379.0	342.6	307.6	272.4
238.9	207.6	178.1	150.1	66.9						
1.023	1.014	1.008	1.004	1.000	0.998	0.997	0.998	1.000	1.007	1.028
1.063	1.116	1.200	1.352	0.000						

MACH = 0.600, ALTITUDE = 45000., THRUSTS/FUEL FLOWS/SFCS/NOX RATIOS FOLLOW

912.9	830.4	749.2	691.5	636.0	582.6	531.3	482.0	434.6	387.5	336.1
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285.2	236.1	188.3	141.0	0.0						
933.0	841.5	754.2	693.4	635.6	580.8	529.1	480.2	434.0	389.7	345.0
302.6	262.9	225.4	190.0	84.3						
1.022	1.013	1.007	1.003	0.999	0.997	0.996	0.996	0.999	1.006	1.027
1.061	1.113	1.197	1.347	0.000						

MACH = 0.600, ALTITUDE = 40000., THRUSTS/FUEL FLOWS/SFCS/NOX RATIOS FOLLOW

1158.6	1053.9	950.8	877.7	807.2	739.4	674.4	611.8	551.5	492.0	426.6
362.0	299.7	239.1	179.2	0.0						
1183.2	1067.3	956.5	879.3	806.0	736.5	670.9	608.8	550.2	494.1	437.3
383.5	333.1	285.6	240.7	106.4						
1.021	1.013	1.006	1.002	0.998	0.996	0.995	0.995	0.998	1.004	1.025
1.059	1.111	1.194	1.343	0.000						

MACH = 0.600, ALTITUDE = 35000., THRUSTS/FUEL FLOWS/SFCS/NOX RATIOS FOLLOW

1473.4	1340.3	1209.4	1116.4	1026.7	940.6	857.9	778.3	701.8	626.2	543.2
461.1	382.0	305.1	228.9	0.0						
1514.1	1365.7	1223.9	1125.1	1031.2	942.2	858.2	778.7	703.7	631.9	559.3
490.4	425.9	365.2	307.7	134.9						
1.028	1.019	1.012	1.008	1.004	1.002	1.000	1.000	1.003	1.009	1.030
1.064	1.115	1.197	1.344	0.000						

MACH = 0.600, ALTITUDE = 30000., THRUSTS/FUEL FLOWS/SFCS/NOX RATIOS FOLLOW

1872.1	1702.7	1536.9	1418.9	1305.2	1195.8	1090.8	990.0	893.0	797.8	692.9
589.0	489.3	392.0	296.2	0.0						
1979.6	1784.6	1599.2	1469.8	1347.0	1230.6	1120.4	1016.4	918.2	824.6	730.0
640.1	556.1	476.9	402.1	171.1						
1.057	1.048	1.041	1.036	1.032	1.029	1.027	1.027	1.028	1.034	1.054
1.087	1.137	1.217	1.358	0.000						

MACH = 0.600, ALTITUDE = 25000., THRUSTS/FUEL FLOWS/SFCS/NOX RATIOS FOLLOW

2353.7	2140.4	1932.5	1784.0	1641.1	1503.7	1371.6	1244.8	1123.1	1003.9	872.7
742.4	617.8	496.3	376.9	0.0						
2558.5	2305.3	2065.4	1897.8	1738.9	1588.3	1445.7	1311.1	1184.0	1063.1	941.1
825.1	717.0	615.0	518.8	215.4						
1.087	1.077	1.069	1.064	1.060	1.056	1.054	1.053	1.054	1.059	1.078
1.111	1.160	1.239	1.377	0.000						

MACH = 0.600, ALTITUDE = 20000., THRUSTS/FUEL FLOWS/SFCS/NOX RATIOS FOLLOW

2930.3	2664.1	2406.3	2221.7	2043.8	1872.8	1708.6	1550.7	1399.0	1250.8	1088.0
926.5	772.0	621.7	474.3	0.0						
3272.0	2946.4	2639.3	2424.8	2221.4	2028.7	1846.4	1674.1	1511.5	1356.8	1201.0
1053.0	915.1	785.2	662.9	269.2						
1.117	1.106	1.097	1.091	1.087	1.083	1.081	1.080	1.080	1.085	1.104
1.137	1.185	1.263	1.398	0.000						

MACH = 0.600, ALTITUDE = 15000., THRUSTS/FUEL FLOWS/SFCS/NOX RATIOS FOLLOW

3617.5	3288.5	2971.1	2743.4	2524.0	2313.0	2110.3	1915.5	1728.2	1544.8	1343.7
1144.9	954.6	769.5	588.7	0.0						
4146.3	3732.0	3342.1	3069.9	2811.8	2567.4	2336.3	2117.9	1911.7	1715.4	1517.7
1330.5	1156.1	991.8	837.5	334.9						
1.146	1.135	1.125	1.119	1.114	1.110	1.107	1.106	1.106	1.110	1.129
1.162	1.211	1.289	1.423	0.000						

MACH = 0.600, ALTITUDE = 10000., THRUSTS/FUEL FLOWS/SFCS/NOX RATIOS FOLLOW  
 4433.7 4030.0 3642.2 3363.0 3094.3 2835.9 2587.5 2348.8 2119.3 1894.6 1647.5  
 1404.1 1171.0 943.9 723.0 0.0  
 5212.9 4690.4 4199.6 3856.3 3531.2 3223.6 2932.6 2657.9 2398.5 2151.6 1902.6  
 1667.1 1448.1 1241.8 1048.3 417.0  
 1.176 1.164 1.153 1.147 1.141 1.137 1.133 1.132 1.132 1.136 1.155  
 1.187 1.237 1.316 1.450 0.000

MACH = 0.600, ALTITUDE = 5000., THRUSTS/FUEL FLOWS/SFCS/NOX RATIOS FOLLOW  
 5381.8 4891.3 4421.8 4082.9 3756.9 3443.7 3142.6 2853.1 2574.8 2301.6 2001.7  
 1706.2 1423.6 1147.5 878.7 0.0  
 6484.7 5833.3 5222.6 4794.7 4389.5 4006.3 3644.3 3302.4 2979.8 2672.2 2362.4  
 2069.5 1797.2 1540.6 1300.0 518.8  
 1.205 1.193 1.181 1.174 1.168 1.163 1.160 1.157 1.157 1.161 1.180  
 1.213 1.262 1.343 1.479 0.000

MACH = 0.600, ALTITUDE = 0., THRUSTS/FUEL FLOWS/SFCS/NOX RATIOS FOLLOW  
 6488.2 5895.4 5330.2 4922.9 4530.3 4153.3 3791.4 3443.3 3108.5 2779.4 2418.8  
 2063.6 1723.6 1390.8 1066.4 0.0  
 8006.1 7199.7 6445.4 5917.7 5417.1 4943.8 4496.9 4075.1 3677.1 3297.6 2915.6  
 2554.4 2218.8 1902.2 1605.2 640.5  
 1.234 1.221 1.209 1.202 1.196 1.190 1.186 1.183 1.183 1.186 1.205  
 1.238 1.287 1.368 1.505 0.000

MACH = 0.500, ALTITUDE = 50000., THRUSTS/FUEL FLOWS/SFCS/NOX RATIOS FOLLOW  
 679.9 618.8 558.6 515.6 474.1 434.3 396.0 359.1 323.7 288.1 249.3  
 209.3 170.1 132.3 94.3 0.0  
 673.4 607.4 544.4 500.2 458.2 418.5 381.0 345.6 312.1 279.7 247.3  
 215.6 185.6 157.6 130.9 64.5  
 0.990 0.982 0.974 0.970 0.966 0.964 0.962 0.962 0.964 0.971 0.992  
 1.030 1.091 1.191 1.388 0.000

MACH = 0.500, ALTITUDE = 45000., THRUSTS/FUEL FLOWS/SFCS/NOX RATIOS FOLLOW  
 862.4 785.1 708.7 654.1 601.5 550.9 502.3 455.6 410.7 365.6 316.3  
 265.6 215.9 168.0 120.1 0.0  
 853.3 769.7 689.8 633.8 580.6 530.3 482.7 437.8 395.3 354.3 313.1  
 272.9 234.9 199.5 165.7 81.1  
 0.989 0.980 0.973 0.969 0.965 0.963 0.961 0.961 0.963 0.969 0.990  
 1.028 1.088 1.187 1.380 0.000

MACH = 0.500, ALTITUDE = 40000., THRUSTS/FUEL FLOWS/SFCS/NOX RATIOS FOLLOW  
 1094.4 996.3 899.4 830.2 763.6 699.5 637.9 578.7 521.7 464.8 402.3  
 338.0 275.0 214.4 153.8 0.0  
 1081.9 976.0 874.7 803.7 736.4 672.6 612.3 555.4 501.5 449.7 397.4  
 346.5 298.3 253.4 210.6 102.1  
 0.989 0.980 0.973 0.968 0.964 0.962 0.960 0.960 0.961 0.968 0.988  
 1.025 1.085 1.182 1.369 0.000

MACH = 0.500, ALTITUDE = 35000., THRUSTS/FUEL FLOWS/SFCS/NOX RATIOS FOLLOW  
 1391.6 1266.9 1143.9 1055.8 971.1 889.6 811.3 736.0 663.6 591.4 512.0  
 430.3 350.4 273.5 196.6 0.0  
 1384.2 1248.7 1119.1 1028.2 941.9 860.2 783.0 710.0 641.1 574.8 507.9

442.8	381.2	323.7	269.1	129.3						
0.995	0.986	0.978	0.974	0.970	0.967	0.965	0.965	0.966	0.972	0.992
1.029	1.088	1.183	1.368	0.000						

MACH = 0.500, ALTITUDE = 30000., THRUSTS/FUEL FLOWS/SFCS/NOX RATIOS FOLLOW

1767.9	1609.4	1453.7	1342.0	1234.3	1130.7	1031.2	935.6	843.8	752.5	652.3
549.3	448.3	351.2	254.3	0.0						
1809.6	1631.8	1462.4	1343.2	1230.1	1122.9	1021.6	926.0	835.8	749.3	662.0
577.2	496.9	422.0	350.9	164.3						
1.024	1.014	1.006	1.001	0.997	0.993	0.991	0.990	0.991	0.996	1.015
1.051	1.108	1.201	1.380	0.000						

MACH = 0.500, ALTITUDE = 25000., THRUSTS/FUEL FLOWS/SFCS/NOX RATIOS FOLLOW

2222.7	2023.2	1828.0	1687.6	1552.3	1422.1	1297.0	1176.9	1061.7	947.5	822.4
693.6	567.6	446.3	325.9	0.0						
2339.3	2108.3	1889.1	1734.8	1588.5	1449.8	1318.7	1194.8	1078.1	966.4	854.0
744.7	641.4	544.9	453.5	206.4						
1.052	1.042	1.033	1.028	1.023	1.019	1.017	1.015	1.015	1.020	1.039
1.074	1.130	1.221	1.392	0.000						

MACH = 0.500, ALTITUDE = 20000., THRUSTS/FUEL FLOWS/SFCS/NOX RATIOS FOLLOW

2767.4	2518.4	2276.3	2101.5	1933.1	1771.2	1615.4	1465.8	1322.3	1180.6	1025.7
866.0	709.9	559.8	411.4	0.0						
2992.0	2695.1	2414.4	2216.8	2029.4	1852.0	1684.1	1525.6	1376.1	1233.3	1089.9
950.5	818.8	695.8	579.8	257.8						
1.081	1.070	1.061	1.055	1.050	1.046	1.043	1.041	1.041	1.045	1.063
1.098	1.153	1.243	1.409	0.000						

MACH = 0.500, ALTITUDE = 15000., THRUSTS/FUEL FLOWS/SFCS/NOX RATIOS FOLLOW

3415.5	3107.6	2809.8	2594.4	2386.8	2187.0	1995.1	1810.6	1633.3	1458.2	1267.8
1071.5	879.2	694.7	513.2	0.0						
3790.6	3412.7	3056.6	2806.0	2568.4	2343.5	2130.9	1930.0	1740.5	1559.4	1378.1
1202.0	1035.4	880.2	733.9	320.4						
1.110	1.098	1.088	1.082	1.076	1.072	1.068	1.066	1.066	1.069	1.087
1.122	1.178	1.267	1.430	0.000						

MACH = 0.500, ALTITUDE = 10000., THRUSTS/FUEL FLOWS/SFCS/NOX RATIOS FOLLOW

4183.8	3806.1	3442.2	3178.6	2924.6	2680.2	2445.2	2219.5	2002.4	1787.8	1554.3
1314.7	1079.0	853.0	631.7	0.0						
4763.2	4286.6	3838.4	3522.9	3224.0	2941.2	2673.8	2421.4	2183.2	1955.4	1727.4
1506.5	1297.4	1102.5	919.4	396.7						
1.138	1.126	1.115	1.108	1.102	1.097	1.094	1.091	1.090	1.094	1.111
1.146	1.202	1.293	1.456	0.000						

MACH = 0.500, ALTITUDE = 5000., THRUSTS/FUEL FLOWS/SFCS/NOX RATIOS FOLLOW

5085.2	4625.6	4184.5	3863.9	3555.4	3258.7	2973.3	2699.1	2435.7	2174.9	1890.7
1600.7	1313.8	1038.0	768.8	0.0						
5934.3	5339.0	4780.2	4386.0	4013.0	3660.2	3326.9	3012.2	2715.4	2431.5	2147.1
1872.6	1612.0	1369.0	1141.1	490.3						
1.167	1.154	1.142	1.135	1.129	1.123	1.119	1.116	1.115	1.118	1.136
1.170	1.227	1.319	1.484	0.000						

MACH = 0.500, ALTITUDE = 0., THRUSTS/FUEL FLOWS/SFCS/NOX RATIOS FOLLOW

6129.7	5574.7	5044.4	4658.0	4286.3	3929.3	3586.1	3256.1	2939.1	2624.8	2282.7
1934.8	1589.4	1255.4	929.3	0.0						
7326.3	6589.6	5899.7	5412.6	4951.3	4515.5	4104.0	3715.6	3349.3	2998.6	2647.7
2309.7	1988.3	1687.9	1406.2	603.5						
1.195	1.182	1.170	1.162	1.155	1.149	1.144	1.141	1.140	1.142	1.160
1.194	1.251	1.345	1.513	0.000						

MACH = 0.400, ALTITUDE = 50000., THRUSTS/FUEL FLOWS/SFCS/NOX RATIOS FOLLOW

654.0	595.9	538.4	496.9	457.0	418.6	381.6	346.1	311.9	276.7	236.5
194.8	154.2	115.0	41.5	0.0						
625.3	564.1	505.5	464.1	424.8	387.7	352.6	319.4	288.1	257.5	225.9
195.1	166.0	138.7	97.3	73.9						
0.956	0.947	0.939	0.934	0.930	0.926	0.924	0.923	0.924	0.931	0.956
1.001	1.076	1.207	2.342	0.000						

MACH = 0.400, ALTITUDE = 45000., THRUSTS/FUEL FLOWS/SFCS/NOX RATIOS FOLLOW

829.6	755.8	683.0	630.5	579.9	531.3	484.5	439.5	396.2	351.8	300.8
248.2	196.9	147.3	61.3	0.0						
792.2	714.6	640.5	588.0	538.4	491.3	446.9	405.0	365.3	326.7	286.6
247.6	210.8	176.3	127.5	92.8						
0.955	0.945	0.938	0.933	0.928	0.925	0.922	0.921	0.922	0.929	0.953
0.998	1.071	1.197	2.080	0.000						

MACH = 0.400, ALTITUDE = 40000., THRUSTS/FUEL FLOWS/SFCS/NOX RATIOS FOLLOW

1052.6	959.1	866.7	800.2	736.2	674.6	615.3	558.3	503.4	447.4	382.8
316.1	251.3	188.7	85.0	0.0						
1004.3	905.9	812.0	745.6	682.7	623.2	566.9	513.7	463.5	414.6	363.9
314.4	267.9	224.2	165.1	116.6						
0.954	0.945	0.937	0.932	0.927	0.924	0.921	0.920	0.921	0.927	0.951
0.995	1.066	1.189	1.943	0.000						

MACH = 0.400, ALTITUDE = 35000., THRUSTS/FUEL FLOWS/SFCS/NOX RATIOS FOLLOW

1338.2	1219.4	1102.2	1017.6	936.1	857.7	782.4	709.9	640.1	569.1	487.1
402.4	320.2	240.8	113.7	0.0						
1284.6	1158.8	1038.7	953.7	873.0	796.7	724.6	656.5	592.2	529.7	464.9
401.6	342.1	286.4	213.0	147.5						
0.960	0.950	0.942	0.937	0.933	0.929	0.926	0.925	0.925	0.931	0.954
0.998	1.068	1.189	1.874	0.000						

MACH = 0.400, ALTITUDE = 30000., THRUSTS/FUEL FLOWS/SFCS/NOX RATIOS FOLLOW

1699.5	1549.0	1400.6	1292.9	1189.0	1089.1	993.2	901.0	812.3	722.3	618.8
511.7	407.8	307.8	156.2	0.0						
1679.0	1514.3	1357.2	1245.4	1139.4	1039.0	944.3	854.9	770.5	688.8	604.2
521.6	444.1	371.6	280.6	186.9						
0.988	0.978	0.969	0.963	0.958	0.954	0.951	0.949	0.949	0.954	0.976
1.019	1.089	1.207	1.796	0.000						

MACH = 0.400, ALTITUDE = 25000., THRUSTS/FUEL FLOWS/SFCS/NOX RATIOS FOLLOW

2136.6	1947.1	1761.2	1626.0	1495.7	1370.1	1249.5	1133.7	1022.4	910.1	781.3
647.7	518.0	393.8	221.3	0.0						
2170.7	1956.8	1753.4	1608.8	1471.6	1341.8	1219.0	1103.2	994.1	888.9	780.1
673.8	573.9	480.9	371.7	231.7						
1.016	1.005	0.996	0.989	0.984	0.979	0.976	0.973	0.972	0.977	0.998



1.040	1.108	1.221	1.680	0.000							
MACH = 0.400, ALTITUDE = 20000., THRUSTS/FUEL FLOWS/SFCS/NOX RATIOS FOLLOW											
2660.3	2424.0	2193.2	2024.8	1862.6	1706.5	1556.2	1412.0	1273.4	1134.2	975.0	
809.2	648.8	495.4	296.1	0.0							
2776.9	2502.0	2241.6	2056.1	1880.5	1714.1	1556.9	1408.6	1268.9	1134.4	995.9	
860.2	732.9	614.5	482.0	285.1							
1.044	1.032	1.022	1.015	1.010	1.005	1.000	0.998	0.996	1.000	1.021	
1.063	1.130	1.240	1.628	0.000							
MACH = 0.400, ALTITUDE = 15000., THRUSTS/FUEL FLOWS/SFCS/NOX RATIOS FOLLOW											
3282.9	2990.5	2706.9	2499.4	2299.4	2107.0	1921.9	1743.9	1572.9	1401.3	1206.5	
1002.5	804.9	616.8	385.4	0.0							
3517.9	3167.9	2837.6	2602.6	2379.9	2169.2	1970.1	1782.1	1605.0	1434.6	1260.0	
1088.5	927.6	778.3	617.1	348.5							
1.072	1.059	1.048	1.041	1.035	1.030	1.025	1.022	1.020	1.024	1.044	
1.086	1.153	1.262	1.601	0.000							
MACH = 0.400, ALTITUDE = 10000., THRUSTS/FUEL FLOWS/SFCS/NOX RATIOS FOLLOW											
4019.9	3661.2	3314.7	3061.1	2816.5	2581.1	2354.9	2137.3	1927.9	1717.8	1480.9	
1231.1	988.9	758.7	485.4	0.0							
4419.1	3977.6	3562.1	3266.5	2986.6	2721.8	2471.7	2235.6	2012.9	1798.9	1580.3	
1365.1	1163.1	975.9	778.1	427.0							
1.099	1.086	1.075	1.067	1.060	1.055	1.050	1.046	1.044	1.047	1.067	
1.109	1.176	1.286	1.603	0.000							
MACH = 0.400, ALTITUDE = 5000., THRUSTS/FUEL FLOWS/SFCS/NOX RATIOS FOLLOW											
4889.1	4452.2	4031.8	3723.3	3426.4	3140.5	2865.5	2601.3	2347.0	2092.0	1805.8	
1502.2	1206.5	925.5	598.6	0.0							
5510.2	4958.1	4439.3	4069.9	3720.5	3390.1	3078.0	2783.6	2506.0	2239.1	1967.6	
1699.4	1447.2	1213.6	969.9	523.7							
1.127	1.114	1.101	1.093	1.086	1.079	1.074	1.070	1.068	1.070	1.090	
1.131	1.199	1.311	1.620	0.000							
MACH = 0.400, ALTITUDE = 0., THRUSTS/FUEL FLOWS/SFCS/NOX RATIOS FOLLOW											
5893.6	5366.3	4860.8	4488.6	4130.6	3786.5	3455.5	3137.2	2831.3	2523.5	2180.3	
1815.3	1458.0	1116.7	719.7	0.0							
6803.8	6120.5	5479.8	5022.7	4590.3	4182.0	3796.5	3432.9	3090.1	2760.2	2425.9	
2095.1	1783.5	1494.1	1192.4	645.3							
1.154	1.141	1.127	1.119	1.111	1.104	1.099	1.094	1.091	1.094	1.113	
1.154	1.223	1.338	1.657	0.000							
MACH = 0.300, ALTITUDE = 35000., THRUSTS/FUEL FLOWS/SFCS/NOX RATIOS FOLLOW											
1311.7	1196.7	1083.3	1000.4	920.6	843.8	769.9	698.8	630.2	554.7	467.4	
378.0	290.7	109.7	0.0	0.0							
1211.2	1092.6	979.4	898.3	821.5	748.9	680.3	615.5	554.2	492.2	427.8	
365.4	306.6	207.3	147.1	0.0							
0.923	0.913	0.904	0.898	0.892	0.887	0.884	0.881	0.879	0.887	0.915	
0.967	1.055	1.889	0.000	0.000							
MACH = 0.300, ALTITUDE = 30000., THRUSTS/FUEL FLOWS/SFCS/NOX RATIOS FOLLOW											
1665.1	1519.9	1376.2	1270.4	1168.4	1070.3	976.1	885.5	798.1	702.2	591.8	
478.6	368.2	173.9	0.0	0.0							

1582.6	1427.6	1279.4	1172.5	1071.3	975.5	885.2	800.0	719.6	638.4	554.3
472.8	396.2	285.5	186.5	0.0						
0.950	0.939	0.930	0.923	0.917	0.911	0.907	0.903	0.902	0.909	0.937
0.988	1.076	1.642	0.000	0.000						

MACH = 0.300, ALTITUDE = 25000., THRUSTS/FUEL FLOWS/SFCS/NOX RATIOS FOLLOW

2093.0	1910.2	1730.4	1597.7	1469.7	1346.4	1228.0	1114.2	1004.6	885.5	748.1
607.0	469.3	289.8	0.0	0.0						
2046.0	1844.8	1653.2	1514.9	1383.8	1259.8	1142.8	1032.5	928.5	824.1	716.0
611.2	512.6	400.2	218.7	0.0						
0.978	0.966	0.955	0.948	0.942	0.936	0.931	0.927	0.924	0.931	0.957
1.007	1.092	1.381	0.000	0.000						

MACH = 0.300, ALTITUDE = 20000., THRUSTS/FUEL FLOWS/SFCS/NOX RATIOS FOLLOW

2605.8	2377.9	2154.8	1989.5	1830.4	1677.0	1529.5	1387.8	1251.6	1104.5	934.7
759.8	589.6	399.9	0.0	0.0						
2617.8	2359.1	2113.7	1936.4	1768.5	1609.8	1459.8	1318.5	1185.4	1052.4	914.7
780.9	655.4	526.6	255.1	0.0						
1.005	0.992	0.981	0.973	0.966	0.960	0.954	0.950	0.947	0.953	0.979
1.028	1.112	1.317	0.000	0.000						

MACH = 0.300, ALTITUDE = 15000., THRUSTS/FUEL FLOWS/SFCS/NOX RATIOS FOLLOW

3215.4	2933.5	2659.2	2455.5	2259.2	2070.4	1888.6	1713.8	1545.8	1365.7	1157.5
942.1	732.9	523.2	0.0	0.0						
3316.6	2987.1	2675.9	2451.2	2238.4	2037.2	1847.2	1668.1	1499.4	1331.5	1157.8
988.7	830.1	677.8	297.7	0.0						
1.031	1.018	1.006	0.998	0.991	0.984	0.978	0.973	0.970	0.975	1.000
1.049	1.133	1.295	0.000	0.000						

MACH = 0.300, ALTITUDE = 10000., THRUSTS/FUEL FLOWS/SFCS/NOX RATIOS FOLLOW

3936.2	3590.3	3255.5	3006.6	2766.7	2535.8	2313.8	2100.1	1894.5	1675.5	1422.2
1158.4	902.3	656.9	0.0	0.0						
4165.5	3749.9	3358.5	3076.0	2808.7	2556.0	2317.5	2092.5	1880.6	1670.5	1453.1
1240.8	1041.9	855.9	357.7	0.0						
1.058	1.044	1.032	1.023	1.015	1.008	1.002	0.996	0.993	0.997	1.022
1.071	1.155	1.303	0.000	0.000						

MACH = 0.300, ALTITUDE = 5000., THRUSTS/FUEL FLOWS/SFCS/NOX RATIOS FOLLOW

4785.4	4364.0	3957.8	3655.6	3364.5	3084.2	2814.6	2555.4	2305.7	2041.5	1735.7
1414.7	1102.2	804.2	0.0	0.0						
5192.3	4672.5	4183.9	3831.3	3497.8	3182.8	2885.4	2605.1	2341.0	2080.0	1810.0
1545.4	1297.2	1065.8	441.4	0.0						
1.085	1.071	1.057	1.048	1.040	1.032	1.025	1.019	1.015	1.019	1.043
1.092	1.177	1.325	0.000	0.000						

MACH = 0.300, ALTITUDE = 0., THRUSTS/FUEL FLOWS/SFCS/NOX RATIOS FOLLOW

5773.1	5264.2	4775.2	4410.2	4059.1	3721.4	3396.5	3084.0	2783.5	2466.0	2099.2
1712.7	1333.9	972.7	0.0	0.0						
6417.6	5773.7	5169.4	4732.5	4319.6	3929.8	3562.0	3215.4	2888.9	2567.0	2234.1
1907.3	1600.0	1313.7	542.6	0.0						
1.112	1.097	1.083	1.073	1.064	1.056	1.049	1.043	1.038	1.041	1.064
1.114	1.199	1.351	0.000	0.000						

MACH = 0.200, ALTITUDE = 20000., THRUSTS/FUEL FLOWS/SFCS/NOX RATIOS FOLLOW  
 2602.5 2379.3 2160.2 1994.9 1835.7 1682.3 1534.8 1393.1 1254.0 1091.2 907.7  
 719.5 537.3 0.0 0.0 0.0  
 2508.4 2260.8 2025.7 1852.8 1689.2 1534.6 1388.7 1251.5 1120.9 984.9 846.1  
 712.1 586.4 215.8 0.0 0.0  
 0.964 0.950 0.938 0.929 0.920 0.912 0.905 0.898 0.894 0.903 0.932  
 0.990 1.092 0.000 0.000 0.000

MACH = 0.200, ALTITUDE = 15000., THRUSTS/FUEL FLOWS/SFCS/NOX RATIOS FOLLOW  
 3211.1 2935.0 2665.7 2461.9 2265.6 2076.7 1894.8 1719.9 1549.1 1349.9 1124.7  
 893.2 669.6 0.0 0.0 0.0  
 3178.3 2863.0 2564.9 2345.5 2138.0 1942.1 1757.3 1583.3 1418.0 1246.5 1071.4  
 902.0 743.4 268.5 0.0 0.0  
 0.990 0.975 0.962 0.953 0.944 0.935 0.927 0.921 0.915 0.923 0.953  
 1.010 1.110 0.000 0.000 0.000

MACH = 0.200, ALTITUDE = 10000., THRUSTS/FUEL FLOWS/SFCS/NOX RATIOS FOLLOW  
 3930.1 3591.3 3262.6 3013.8 2773.9 2543.1 2321.1 2107.4 1898.9 1657.6 1383.6  
 1100.2 827.0 0.0 0.0 0.0  
 3991.5 3593.7 3218.8 2943.3 2682.8 2436.8 2204.8 1986.3 1779.1 1564.8 1345.7  
 1133.2 934.5 333.1 0.0 0.0  
 1.016 1.001 0.987 0.977 0.967 0.958 0.950 0.943 0.937 0.944 0.973  
 1.030 1.130 0.000 0.000 0.000

MACH = 0.200, ALTITUDE = 5000., THRUSTS/FUEL FLOWS/SFCS/NOX RATIOS FOLLOW  
 4776.4 4363.6 3965.0 3663.0 3372.1 3092.0 2822.7 2563.6 2311.3 2020.8 1690.1  
 1345.4 1012.6 0.0 0.0 0.0  
 4974.3 4476.8 4008.8 3665.2 3340.4 3033.9 2744.9 2472.7 2214.9 1949.1 1677.1  
 1412.3 1164.7 411.5 0.0 0.0  
 1.041 1.026 1.011 1.001 0.991 0.981 0.972 0.965 0.958 0.965 0.992  
 1.050 1.150 0.000 0.000 0.000

MACH = 0.200, ALTITUDE = 0., THRUSTS/FUEL FLOWS/SFCS/NOX RATIOS FOLLOW  
 5764.8 5266.0 4785.8 4421.0 4070.1 3732.5 3407.8 3095.5 2792.1 2444.1 2047.6  
 1632.0 1228.7 0.0 0.0 0.0  
 6152.4 5535.5 4956.1 4530.1 4127.8 3748.4 3390.8 3054.1 2735.6 2408.0 2072.7  
 1745.3 1438.7 504.5 0.0 0.0  
 1.067 1.051 1.036 1.025 1.014 1.004 0.995 0.987 0.980 0.985 1.012  
 1.069 1.171 0.000 0.000 0.000

MACH = 0.100, ALTITUDE = 5000., THRUSTS/FUEL FLOWS/SFCS/NOX RATIOS FOLLOW  
 4861.9 4451.2 4054.0 3746.3 3449.9 3164.8 2890.7 2626.7 2364.0 2039.2 1678.7  
 1307.1 0.0 0.0 0.0 0.0  
 4847.1 4362.6 3906.7 3564.6 3241.7 2937.3 2650.7 2380.9 2122.7 1847.5 1570.5  
 1303.1 387.8 0.0 0.0 0.0  
 0.997 0.980 0.964 0.951 0.940 0.928 0.917 0.906 0.898 0.906 0.936  
 0.997 0.000 0.000 0.000 0.000

MACH = 0.100, ALTITUDE = 0., THRUSTS/FUEL FLOWS/SFCS/NOX RATIOS FOLLOW  
 5869.1 5372.4 4893.9 4522.1 4164.8 3821.0 3490.4 3172.6 2857.0 2468.8 2036.6  
 1588.0 0.0 0.0 0.0 0.0  
 5997.4 5396.2 4831.5 4407.4 4007.4 3630.5 3275.8 2942.2 2623.2 2284.3 1942.8  
 1612.0 479.8 0.0 0.0 0.0

1.022 1.004 0.987 0.975 0.962 0.950 0.938 0.927 0.918 0.925 0.954  
 1.015 0.000 0.000 0.000 0.000

MACH = 0.000, ALTITUDE = 5000., THRUSTS/FUEL FLOWS/SFCS/NOX RATIOS FOLLOW  
 5045.4 4630.1 4228.3 3908.7 3601.2 3305.5 3021.6 2746.9 2471.0 2109.1 1716.1  
 1315.5 0.0 0.0 0.0 0.0  
 4805.3 4325.1 3873.1 3525.4 3197.6 2889.1 2599.1 2325.9 2063.8 1776.9 1493.1  
 1221.7 384.4 0.0 0.0 0.0  
 0.952 0.934 0.916 0.902 0.888 0.874 0.860 0.847 0.835 0.843 0.870  
 0.929 0.000 0.000 0.000 0.000

MACH = 0.000, ALTITUDE = 0., THRUSTS/FUEL FLOWS/SFCS/NOX RATIOS FOLLOW  
 6090.0 5587.8 5103.6 4717.7 4346.9 3990.4 3648.0 3317.7 2986.2 2554.0 2083.1  
 1599.8 0.0 0.0 0.0 0.0  
 5946.4 5350.4 4790.6 4359.4 3953.4 3571.4 3212.5 2874.9 2551.0 2197.9 1848.0  
 1512.5 475.7 0.0 0.0 0.0  
 0.976 0.958 0.939 0.924 0.909 0.895 0.881 0.867 0.854 0.861 0.887  
 0.945 0.000 0.000 0.000 0.000

## # REVISED PROPULSION SYSTEM DATA

BASELINE ENGINE THRUST	THRSO	6090.0	LBF
BASELINE ENGINE WEIGHT	WENG	2950.0	LBF
BASELINE INLET WEIGHT	WINL	0.0	LBF
BASELINE NOZZLE WEIGHT	WNOZ	0.0	LBF
BASELINE NACELLE LENGTH	XNAC	0.00	FT
BASELINE NACELLE DIAMETER	DNAC	0.00	FT

## # NAMELIST \$MISSIN

## PERFORMANCE CONTROLS AND FACTORS AND MISSION SEGMENT DEFINITION

DESCRIPTION	NAME	VALUE	DIMENSIONS
ENDURANCE MISSION SWITCH	INDR	0	
OVERALL FUEL FLOW FACTOR	FACT	1.1436	
CDO FACTOR	FCDO	1.0000	
CDI FACTOR	FCDI	1.0000	
SUBSONIC CD FACTOR	FCDSUB	1.0000	
SUPERSONIC CD FACTOR	FCDSUP	1.0000	
ENGINE SCALING SWITCH	ISKAL	1	
OWE FACTOR	OWFACT	1.0000	
PRINT FLAG	IFLAG	2	
DETAILED MISSION PRINT	MSUMPT	0	
TEMPERATURE DEVIATION	DTC	0.0	DEG C
CALC RAMP WT OR RANGE	IRW	1	
RANGE TOLERANCE	RTOL	0.0010	N MI
ATA TRAFFIC ALLOWANCE	IATA	0	
TAIL WIND VELOCITY	TLWIND	0.00	KTS
WEIGHT INCREMENT	DWT	1.	LBF

## GROUND OPERATIONS AND TAKEOFF INPUT

TAKEOFF TIME TAKOTM 0.0 MIN  
 TAXI-OUT TIME TAXOTM 0.0 MIN  
 APPROACH TIME APPRTM 0.0 MIN  
 APPROACH FUEL FLOW FACTOR APPFFF 2.00  
 TAXI-IN TIME TAXITM 0.0 MIN

TAKEOFF POWER SETTING ITTFF 1  
 TAXI FUEL FLOWS WILL BE FROM THE ENGINE DECK

INPUT FOR 4 CLIMB SCHEDULES (1) (2) (3) (4)  
 (5) (6) (7) (8) (9) (10)

MINIMUM CLIMB MACH NUMBER	CLMMIN	0.6900	0.6900	0.6900	0.6900
0.3000	0.3000	0.3000	0.3000	0.3000	0.3000
MAXIMUM CLIMB MACH NUMBER	CLMMAX	0.7200	0.7500	0.7900	0.8200
0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
MINIMUM CLIMB ALTITUDE	CLAMIN	0.	0.	0.	0.
0.	0.	0.	0.	0.	0. FT
MAXIMUM CLIMB ALTITUDE	CLAMAX	10000.	20000.	30000.	40000.
0.	0.	0.	0.	0.	0. FT
NUMBER OF CLIMB STEPS	NINCL	31	31	31	31
31	31	31	31	31	31
CLIMB OPTIMIZATION FACTOR	FWF	-0.0010	-0.0010	-0.0010	-0.0010
-0.0010	-0.0010	-0.0010	-0.0010	-0.0010	-0.0010
FOLLOWING CRUISE SEGMENT	NCRCL	1	3	5	7
1	1	1	1	1	1
DRAG COEFFICIENT INCREMENT	CLDCD	0.00000	0.00000	0.00000	0.00000
0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
NO. OF POWER SETTINGS	IPPCL	1	1	1	1
1	1	1	1	1	1
STORE DRAG DURING CLIMB	ISTCL	0	0	0	0
0	0	0	0	0	0
MAX CLIMB POWER SETTING	MAXCL	1	1	1	1
1	1	1	1	1	1
FAA CLIMB ENFORCED	IFAACL	0			
FAA DESCENT ENFORCED	IFAADE	0			
MINIMUM CLIMB RATE SWITCH	NODIVE	1			
MINIMUM CLIMB RATE	DIVLIM	0.	FT/MIN		
Q LIMIT IN CLIMB	QLIM	0.0	PSF		
MAXIMUM RATE OF DESCENT	RDLIM	-99999.0	FT/MIN		

3 POINT CLIMB SCHEDULE FOR SEGMENT 1

ALTITUDE	CLIMB SPEED
FT	MACH NO
(ACTAB)	(VCTAB)
0.0	0.69
5000.0	0.71
10000.0	0.72

5 POINT CLIMB SCHEDULE FOR SEGMENT 2

ALTITUDE	CLIMB SPEED
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FT (ACTAB)	MACH NO (VCTAB)
0.0	0.69
5000.0	0.71
10000.0	0.72
15000.0	0.74
20000.0	0.75

4 POINT CLIMB SCHEDULE FOR SEGMENT 3

ALTITUDE		CLIMB SPEED	
FT (ACTAB)		MACH NO (VCTAB)	
0.0		0.69	
10000.0		0.72	
20000.0		0.75	
30000.0		0.79	

5 POINT CLIMB SCHEDULE FOR SEGMENT 4

ALTITUDE		CLIMB SPEED	
FT (ACTAB)		MACH NO (VCTAB)	
0.0		0.69	
10000.0		0.72	
20000.0		0.75	
30000.0		0.79	
40000.0		0.82	

INPUT FOR 8 CRUISE SCHEDULES				(1)	(2)	(3)	(4)
(5)	(6)	(7)	(8)	(9)	(10)		
CRUISE OPTION SWITCH		IOC		2	2	2	2
2	2	2	2	1	1		
CRUISE OPT FUEL FACTOR		FFUEL		1.000	1.000	1.000	1.000
1.000	1.000	1.000	1.000	1.000	1.000		
CRUISE OPT NOX FACTOR		FNOX		0.000	0.000	0.000	0.000
0.000	0.000	0.000	0.000	0.000	0.000		
MAXIMUM MACH NUMBER		CRMACH		0.7200	0.5600	0.7500	0.6300
0.7900	0.7200	0.8200	0.7900	0.0000	0.0000		
MAXIMUM ALTITUDE		CRALT		10000.	10000.	20000.	20000.
30000.	30000.	40000.	40000.	-1.	-1.	FT	
DRAG COEFFICIENT INCREMENT		CRDCD		0.00000	0.00000	0.00000	0.00000
0.00000	0.00000	0.00000	0.00000	0.00000			0.00000
STORE DRAG DURING CRUISE		ISTCR		0	0	0	0
0	0	0	0	0	0		
LONG RANGE CRUISE FACTOR		FLRCR		1.000	1.000	1.000	1.000
1.000	1.000	1.000	1.000	1.000	1.000		
MINIMUM MACH NUMBER		CRMMIN		0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000	0.0000	0.0000		
MAXIMUM LIFT COEFFICIENT		CRCLMX		2.0000	0.0000	0.0000	0.0000

0.0000	0.0000	0.0000	0.0000	0.0000	0.0000		
ENGINE FEATHERING ALLOWED	IFEATH			0	0	0	0
0	0	0	0	0	0		
ENGINE FRACTION REMAINING	FEATHF			0.5000	0.5000	0.5000	0.5000
0.5000	0.5000	0.5000	0.5000	0.5000	0.5000		
CD INCREASE FOR FEATHERING	CDFETH			0.00000	0.00000	0.00000	0.00000
0.00000	0.00000	0.00000	0.00000	0.00000			
MINIMUM CRUISE ALTITUDE	HPMIN			1000.	1000.	1000.	1000.
1000.	1000.	1000.	1000.	1000.	1000.	FT	
INCREMENT IN CRUISE WT.	DCWT			1.0	LBF		
RATE OF CLIMB CEILING	RCIN			100.0	FT/MIN		

## INPUT FOR DESCENT SCHEDULE

DESCENT OPTION SWITCH	IVS			0	
DESCENT LIFT COEFF.	DECL			0.8000	
MINIMUM DESCENT MACH NO.	DEMMIN			0.3000	
MAXIMUM DESCENT MACH NO.	DEMMAX			0.0000	
MINIMUM DESCENT ALTITUDE	DEAMIN			0.	FT
MAXIMUM DESCENT ALTITUDE	DEAMAX			0.	FT
NUMBER OF DESCENT STEPS	NINDE			31	
DRAG COEFFICIENT INCREMENT	DEDCD			0.00000	
STORE DRAG DURING DESCENT	ISTDE			0	

## RESERVE SEGMENT INPUT

RESERVE CALC. OR CONST	IRS			2	
RESERVE FUEL	RESRFU			1.000	LBM
FRACTION OF TRIP FUEL	RESTRP			0.000	
MISSED APPROACH TIME	TIMMAP			0.0	MIN
RANGE TO ALTERNATE AIRPORT	ALTRAN			0.0	N MI
RESERVE CLIMB SCHEDULE	NCLRES			1	
RESERVE CRUISE SCHEDULE	NCRRES			1	
START RESERVE MACH NUMBER	SREMCH			0.6900	
END RESERVE MACH NUMBER	EREMCH			0.3000	
START RESERVE ALTITUDE	SREALT			0.	FT
END RESERVE ALTITUDE	ERREALT			0.	FT
RESERVE HOLDING TIME	HOLDTM			0.0	MIN
HOLD CRUISE SCHEDULE	NCRHOL			1	
HOLD POSITION SWITCH	IHOPOS			1	
CRUISE ONLY SWITCH	ICRON			0	
2ND RES HOLD TIME OR FRAC	THOLD			0.000	MIN
THOLD CRUISE SCHEDULE	NCRTH			1	

## # MISSION SEQUENCE DEFINITION

START	MACH NUMBER = 0.6900	ALTITUDE =	0. FT
CLIMB	USE CLIMB SCHEDULE 4		
CRUISE	USE CRUISE SCHEDULE 7	SEGMENT DISTANCE =	2.0 N MI
CRUISE	USE CRUISE SCHEDULE 8	END CRUISE DISTANCE =	0.0 N MI
END	MACH NUMBER = 0.3000	ALTITUDE =	0. FT

#TITLE, BEGIN OUTPUT OF RESULTS

F-86F CLEAN

FINAL ANALYSIS

# AERODYNAMIC DATA

MACH NUMBER            ALTITUDE            REFERENCE AREA            TECHNOLOGY LEVEL  
 0.82                    50000. FT            284.46 SQ FT            1.00

COMPONENT	SWET SQ FT	LENGTH FT	FINENESS RATIO	FORM FACTOR	RN MILLIONS	CF	CDF
WING	477.92	7.69	0.1000	1.345	7.5	0.00293	0.00662
HORIZONTAL TAIL	40.70	3.48	0.0500	1.165	3.4	0.00336	0.00056
VERTICAL TAIL	63.49	4.98	0.0400	1.130	4.8	0.00316	0.00080
FUSELAGE	563.51	45.00	8.8731	1.138	43.8	0.00222	0.00501
NACELLE	0.00	0.00	1.0000	1.000	0.0	0.00000	0.00000
MISCELLANEOUS							0.00078
TOTAL	1145.62					0.00342	0.01376

CHANGE IN DRAG COEFFICIENT FROM CRUISE ALTITUDE

ALTITUDE	MACH NUMBER								
	0.200	0.300	0.400	0.500	0.600	0.700	0.800	0.850	0.875
	0.900	0.925	0.950						
0.	-0.00477	-0.00431	-0.00401	-0.00379	-0.00361	-0.00346	-0.00333	-0.00327	-0.00324
	-0.00321	-0.00318	-0.00316						
5000.	-0.00447	-0.00404	-0.00375	-0.00355	-0.00338	-0.00324	-0.00311	-0.00306	-0.00303
	-0.00300	-0.00298	-0.00295						
10000.	-0.00415	-0.00374	-0.00348	-0.00329	-0.00313	-0.00300	-0.00289	-0.00283	-0.00281
	-0.00278	-0.00276	-0.00274						
15000.	-0.00380	-0.00343	-0.00319	-0.00301	-0.00287	-0.00275	-0.00264	-0.00259	-0.00257
	-0.00255	-0.00253	-0.00250						
20000.	-0.00343	-0.00310	-0.00288	-0.00271	-0.00258	-0.00248	-0.00238	-0.00234	-0.00232
	-0.00230	-0.00228	-0.00226						
25000.	-0.00304	-0.00274	-0.00254	-0.00240	-0.00228	-0.00219	-0.00210	-0.00206	-0.00204
	-0.00203	-0.00201	-0.00199						
30000.	-0.00261	-0.00235	-0.00218	-0.00205	-0.00195	-0.00187	-0.00180	-0.00177	-0.00175
	-0.00173	-0.00172	-0.00170						
35000.	-0.00214	-0.00193	-0.00179	-0.00168	-0.00160	-0.00153	-0.00147	-0.00145	-0.00143
	-0.00142	-0.00141	-0.00139						
40000.	-0.00150	-0.00135	-0.00125	-0.00118	-0.00112	-0.00107	-0.00103	-0.00101	-0.00100
	-0.00099	-0.00098	-0.00097						
45000.	-0.00077	-0.00069	-0.00064	-0.00060	-0.00058	-0.00055	-0.00053	-0.00052	-0.00051
	-0.00051	-0.00050	-0.00050						
50000.	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
	0.00000	0.00000	0.00000						
55000.	0.00083	0.00074	0.00068	0.00064	0.00061	0.00058	0.00056	0.00055	0.00054
	0.00054	0.00053	0.00053						
60000.	0.00171	0.00152	0.00141	0.00132	0.00126	0.00120	0.00115	0.00113	0.00112
	0.00111	0.00110	0.00109						





MACH	DRAG POLARS					ALTITUDE = 50000. FT					
	CL										
	0.000	0.050	0.100	0.150	0.200	0.250	0.300	0.350	0.400	0.450	
	0.500	0.550	0.600	0.650	0.700						
0.200	0.01877	0.01880	0.01941	0.02060	0.02205	0.02385	0.02662	0.03025	0.03432	0.04035	0.04728
	0.05499	0.06619	0.07994	0.09520							
0.300	0.01742	0.01746	0.01807	0.01925	0.02068	0.02244	0.02526	0.02890	0.03297	0.03900	0.04594
	0.05365	0.06484	0.07859	0.09386							
0.400	0.01651	0.01654	0.01715	0.01834	0.01976	0.02151	0.02435	0.02799	0.03206	0.03809	0.04502
	0.05273	0.06393	0.07768	0.09294							
0.500	0.01580	0.01584	0.01645	0.01763	0.01906	0.02082	0.02365	0.02728	0.03135	0.03738	0.04432
	0.05203	0.06323	0.07697	0.09224							
0.600	0.01521	0.01525	0.01586	0.01705	0.01850	0.02029	0.02306	0.02669	0.03076	0.03680	0.04373
	0.05144	0.06264	0.07639	0.09165							
0.700	0.01487	0.01490	0.01551	0.01670	0.01818	0.02004	0.02273	0.02634	0.03042	0.03645	0.04338
	0.05109	0.06229	0.07604	0.09130							
0.800	0.01489	0.01490	0.01553	0.01676	0.01830	0.02024	0.02275	0.02634	0.03042	0.03645	0.04338
	0.05110	0.06229	0.07604	0.09130							
0.850	0.01508	0.01508	0.01572	0.01700	0.01859	0.02060	0.02300	0.02644	0.03092	0.03676	0.04359
	0.05125	0.06242	0.07626	0.09232							
0.875	0.01538	0.01536	0.01601	0.01735	0.01899	0.02105	0.02346	0.02710	0.03201	0.03778	0.04447
	0.05191	0.06283	0.07635	0.09214							
0.900	0.01604	0.01599	0.01667	0.01812	0.01984	0.02202	0.02470	0.02882	0.03416	0.04038	0.04717
	0.05459	0.06500	0.07760	0.09213							
0.925	0.01775	0.01770	0.01849	0.02011	0.02204	0.02437	0.02761	0.03261	0.03800	0.04498	0.05238
	0.06026	0.07008	0.08097	0.09205							
0.950	0.04040	0.04015	0.04101	0.04300	0.04547	0.04849	0.05273	0.05848	0.06500	0.07179	0.07973
	0.08921	0.09927	0.10947	0.12057							

DESIGN MACH NUMBER = 0.900, DESIGN CL = 0.352

MACH	CDF	CDC	BUFFET CL
0.200	0.01839	0.00000	0.895
0.300	0.01704	0.00000	0.877
0.400	0.01613	0.00000	0.836
0.500	0.01542	0.00000	0.773
0.600	0.01483	0.00000	0.697
0.700	0.01432	0.00017	0.628
0.800	0.01385	0.00063	0.548
0.850	0.01363	0.00103	0.497
0.875	0.01353	0.00141	0.469
0.900	0.01342	0.00215	0.439
0.925	0.01332	0.00391	0.402
0.950	0.01322	0.02640	0.360

CL	CDI
0.000	0.00000
0.050	0.00017
0.100	0.00066
0.150	0.00149
0.200	0.00265

0.250	0.00414
0.300	0.00596
0.350	0.00811
0.400	0.01059
0.450	0.01340
0.500	0.01654
0.550	0.02002
0.600	0.02382
0.650	0.02796
0.700	0.03243

PRESSURE DRAG COEFFICIENTS...CDP

MACH	CL										
	0.000	0.050	0.100	0.150	0.200	0.250	0.300	0.350	0.400	0.450	
	0.500	0.550	0.600	0.650	0.700						
0.200	0.00038	0.00025	0.00036	0.00073	0.00102	0.00132	0.00228	0.00376	0.00534	0.00856	0.01235
	0.01659	0.02398	0.03359	0.04439							
0.300	0.00038	0.00025	0.00037	0.00073	0.00100	0.00127	0.00227	0.00376	0.00534	0.00856	0.01235
	0.01659	0.02398	0.03359	0.04439							
0.400	0.00038	0.00025	0.00037	0.00073	0.00099	0.00125	0.00227	0.00376	0.00534	0.00856	0.01235
	0.01659	0.02398	0.03359	0.04439							
0.500	0.00038	0.00025	0.00037	0.00073	0.00100	0.00127	0.00227	0.00376	0.00534	0.00856	0.01235
	0.01659	0.02398	0.03359	0.04439							
0.600	0.00038	0.00025	0.00036	0.00073	0.00102	0.00132	0.00228	0.00376	0.00534	0.00856	0.01235
	0.01659	0.02398	0.03359	0.04439							
0.700	0.00038	0.00025	0.00036	0.00073	0.00105	0.00141	0.00229	0.00375	0.00534	0.00856	0.01235
	0.01659	0.02398	0.03359	0.04439							
0.800	0.00040	0.00025	0.00038	0.00079	0.00117	0.00162	0.00231	0.00375	0.00534	0.00856	0.01235
	0.01659	0.02398	0.03359	0.04439							
0.850	0.00041	0.00025	0.00039	0.00085	0.00128	0.00180	0.00239	0.00368	0.00567	0.00870	0.01239
	0.01657	0.02394	0.03364	0.04523							
0.875	0.00043	0.00025	0.00041	0.00092	0.00140	0.00197	0.00256	0.00405	0.00649	0.00944	0.01299
	0.01695	0.02407	0.03345	0.04477							
0.900	0.00047	0.00025	0.00044	0.00106	0.00162	0.00231	0.00317	0.00514	0.00800	0.01141	0.01505
	0.01900	0.02560	0.03407	0.04413							
0.925	0.00052	0.00031	0.00060	0.00139	0.00216	0.00300	0.00443	0.00727	0.01018	0.01435	0.01861
	0.02302	0.02902	0.03579	0.04240							
0.950	0.00079	0.00037	0.00073	0.00190	0.00321	0.00474	0.00716	0.01076	0.01480	0.01877	0.02357
	0.02958	0.03583	0.04190	0.04853							

# CRUISE OPTIMIZATION RESULTS

SUMMARY DATA FOR CRUISE SCHEDULE 1

WEIGHT	ALTITUDE	THRUST	FUEL	SFC	MACH	VELOCITY	SPECIFIC	RATE OF	
CL	L/D	ENGINES	NOX						
		AVAILABLE	REQUIRED	FLOW	NUMBER		RANGE		
		CLIMB		OPERATING	RATE				
11620.	10000.	4855.	1827.	2515.	1.3767	0.7200	459.6	0.18272	12128.4
0.0773	6.36	1.0	0.00						



11760.	10000.	4855.	1829.	2518.	1.3765	0.7200	459.6	0.18256	11976.8
0.0783	6.43	1.0	0.00						
11900.	10000.	4855.	1831.	2520.	1.3763	0.7200	459.6	0.18241	11828.8
0.0792	6.50	1.0	0.00						
12040.	10000.	4855.	1833.	2522.	1.3762	0.7200	459.6	0.18224	11684.0
0.0801	6.57	1.0	0.00						
12180.	10000.	4855.	1834.	2524.	1.3760	0.7200	459.6	0.18208	11542.5
0.0811	6.64	1.0	0.00						
12320.	10000.	4855.	1836.	2526.	1.3758	0.7200	459.6	0.18192	11404.0
0.0820	6.71	1.0	0.00						
12460.	10000.	4855.	1838.	2529.	1.3756	0.7200	459.6	0.18175	11268.6
0.0829	6.78	1.0	0.00						
12600.	10000.	4855.	1840.	2531.	1.3754	0.7200	459.6	0.18158	11136.0
0.0839	6.85	1.0	0.00						
12740.	10000.	4855.	1842.	2534.	1.3752	0.7200	459.6	0.18141	11006.3
0.0848	6.91	1.0	0.00						
12880.	10000.	4855.	1844.	2536.	1.3750	0.7200	459.6	0.18123	10879.3
0.0857	6.98	1.0	0.00						
13020.	10000.	4855.	1847.	2539.	1.3748	0.7200	459.6	0.18105	10754.9
0.0867	7.05	1.0	0.00						
13160.	10000.	4855.	1849.	2541.	1.3746	0.7200	459.6	0.18087	10633.0
0.0876	7.12	1.0	0.00						
13300.	10000.	4855.	1851.	2544.	1.3744	0.7200	459.6	0.18069	10513.6
0.0885	7.19	1.0	0.00						
13440.	10000.	4855.	1853.	2546.	1.3741	0.7200	459.6	0.18051	10396.6
0.0894	7.25	1.0	0.00						
13580.	10000.	4855.	1855.	2549.	1.3739	0.7200	459.6	0.18032	10281.9
0.0904	7.32	1.0	0.00						
13720.	10000.	4855.	1857.	2551.	1.3737	0.7200	459.6	0.18014	10169.4
0.0913	7.39	1.0	0.00						
13860.	10000.	4855.	1860.	2554.	1.3735	0.7200	459.6	0.17995	10059.1
0.0922	7.45	1.0	0.00						
14000.	10000.	4855.	1862.	2557.	1.3733	0.7200	459.6	0.17975	9950.9
0.0932	7.52	1.0	0.00						
14140.	10000.	4855.	1864.	2560.	1.3730	0.7200	459.6	0.17956	9844.7
0.0941	7.59	1.0	0.00						
14280.	10000.	4855.	1867.	2562.	1.3728	0.7200	459.6	0.17936	9740.5
0.0950	7.65	1.0	0.00						
14420.	10000.	4855.	1869.	2565.	1.3726	0.7200	459.6	0.17917	9638.3
0.0960	7.72	1.0	0.00						
14560.	10000.	4855.	1871.	2568.	1.3724	0.7200	459.6	0.17897	9537.9
0.0969	7.78	1.0	0.00						
14700.	10000.	4855.	1874.	2571.	1.3721	0.7200	459.6	0.17876	9439.4
0.0978	7.85	1.0	0.00						
14840.	10000.	4855.	1876.	2574.	1.3719	0.7200	459.6	0.17856	9342.6
0.0988	7.91	1.0	0.00						
14980.	10000.	4855.	1879.	2577.	1.3716	0.7200	459.6	0.17835	9247.5
0.0997	7.97	1.0	0.00						
15120.	10000.	4855.	1881.	2580.	1.3714	0.7200	459.6	0.17814	9154.1
0.1006	8.04	1.0	0.00						
15260.	10000.	4855.	1884.	2583.	1.3712	0.7200	459.6	0.17793	9062.2
0.1016	8.10	1.0	0.00						

## SUMMARY DATA FOR CRUISE SCHEDULE 2

WEIGHT CL	ALTITUDE		THRUST		FUEL FLOW	SFC	MACH	VELOCITY	SPECIFIC RANGE	RATE OF
	L/D	ENGINES	AVAILABLE CLIMB	REQUIRED NOX						
11620.	10000.	4334.	1225.	1683.	1.3731	0.5600	357.5	0.21246	9683.8	
0.1278	9.48	1.0	0.00							
11760.	10000.	4334.	1229.	1686.	1.3722	0.5600	357.5	0.21200	9557.9	
0.1294	9.57	1.0	0.00							
11900.	10000.	4334.	1232.	1690.	1.3713	0.5600	357.5	0.21154	9434.8	
0.1309	9.66	1.0	0.00							
12040.	10000.	4334.	1236.	1694.	1.3704	0.5600	357.5	0.21107	9314.5	
0.1325	9.74	1.0	0.00							
12180.	10000.	4334.	1239.	1697.	1.3695	0.5600	357.5	0.21060	9196.7	
0.1340	9.83	1.0	0.00							
12320.	10000.	4334.	1243.	1701.	1.3685	0.5600	357.5	0.21013	9081.5	
0.1355	9.91	1.0	0.00							
12460.	10000.	4334.	1247.	1705.	1.3676	0.5600	357.5	0.20965	8968.7	
0.1371	9.99	1.0	0.00							
12600.	10000.	4334.	1251.	1709.	1.3666	0.5600	357.5	0.20917	8858.3	
0.1386	10.08	1.0	0.00							
12740.	10000.	4334.	1254.	1713.	1.3657	0.5600	357.5	0.20868	8750.2	
0.1402	10.16	1.0	0.00							
12880.	10000.	4334.	1258.	1717.	1.3647	0.5600	357.5	0.20819	8644.3	
0.1417	10.24	1.0	0.00							
13020.	10000.	4334.	1262.	1721.	1.3638	0.5600	357.5	0.20770	8540.6	
0.1432	10.32	1.0	0.00							
13160.	10000.	4334.	1266.	1725.	1.3628	0.5600	357.5	0.20720	8438.9	
0.1448	10.40	1.0	0.00							
13300.	10000.	4334.	1270.	1729.	1.3618	0.5600	357.5	0.20670	8339.2	
0.1463	10.47	1.0	0.00							
13440.	10000.	4334.	1274.	1734.	1.3608	0.5600	357.5	0.20619	8241.4	
0.1479	10.55	1.0	0.00							
13580.	10000.	4334.	1278.	1738.	1.3598	0.5600	357.5	0.20568	8145.6	
0.1494	10.63	1.0	0.00							
13720.	10000.	4334.	1282.	1742.	1.3589	0.5600	357.5	0.20520	8052.3	
0.1509	10.70	1.0	0.00							
13860.	10000.	4334.	1286.	1746.	1.3580	0.5600	357.5	0.20474	7961.3	
0.1525	10.78	1.0	0.00							
14000.	10000.	4334.	1289.	1750.	1.3572	0.5600	357.5	0.20428	7872.0	
0.1540	10.86	1.0	0.00							
14140.	10000.	4334.	1293.	1754.	1.3563	0.5600	357.5	0.20383	7784.5	
0.1556	10.93	1.0	0.00							
14280.	10000.	4334.	1297.	1758.	1.3554	0.5600	357.5	0.20337	7698.6	
0.1571	11.01	1.0	0.00							
14420.	10000.	4334.	1301.	1762.	1.3545	0.5600	357.5	0.20291	7614.4	
0.1586	11.09	1.0	0.00							
14560.	10000.	4334.	1304.	1766.	1.3536	0.5600	357.5	0.20245	7531.7	
0.1602	11.16	1.0	0.00							
14700.	10000.	4334.	1308.	1770.	1.3527	0.5600	357.5	0.20198	7450.5	

0.1617	11.24	1.0	0.00						
14840.	10000.	4334.	1312.	1774.	1.3518	0.5600	357.5	0.20152	7370.8
0.1633	11.31	1.0	0.00						
14980.	10000.	4334.	1316.	1778.	1.3510	0.5600	357.5	0.20106	7292.5
0.1648	11.38	1.0	0.00						
15120.	10000.	4334.	1320.	1782.	1.3501	0.5600	357.5	0.20060	7215.7
0.1663	11.45	1.0	0.00						
15260.	10000.	4334.	1324.	1786.	1.3492	0.5600	357.5	0.20013	7140.2
0.1679	11.53	1.0	0.00						

## SUMMARY DATA FOR CRUISE SCHEDULE 3

WEIGHT CL	ALTITUDE		THRUST		FUEL FLOW	SFC	MACH	VELOCITY	SPECIFIC RANGE	RATE OF
	L/D	ENGINES	AVAILABLE CLIMB	REQUIRED NOX						
11620.	20000.	3300.	1436.	1876.	1.3064	0.7500	460.8	0.24563	7483.9	
0.1066	8.09	1.0	0.00							
11760.	20000.	3300.	1439.	1879.	1.3062	0.7500	460.8	0.24517	7383.8	
0.1079	8.17	1.0	0.00							
11900.	20000.	3300.	1442.	1883.	1.3061	0.7500	460.8	0.24471	7285.8	
0.1092	8.25	1.0	0.00							
12040.	20000.	3300.	1444.	1886.	1.3060	0.7500	460.8	0.24425	7190.0	
0.1104	8.34	1.0	0.00							
12180.	20000.	3300.	1447.	1890.	1.3059	0.7500	460.8	0.24378	7096.1	
0.1117	8.42	1.0	0.00							
12320.	20000.	3300.	1450.	1894.	1.3058	0.7500	460.8	0.24331	7004.3	
0.1130	8.49	1.0	0.00							
12460.	20000.	3300.	1453.	1898.	1.3056	0.7500	460.8	0.24283	6914.3	
0.1143	8.57	1.0	0.00							
12600.	20000.	3300.	1456.	1901.	1.3055	0.7500	460.8	0.24234	6826.3	
0.1156	8.65	1.0	0.00							
12740.	20000.	3300.	1459.	1905.	1.3054	0.7500	460.8	0.24185	6739.9	
0.1169	8.73	1.0	0.00							
12880.	20000.	3300.	1463.	1909.	1.3053	0.7500	460.8	0.24136	6655.3	
0.1182	8.81	1.0	0.00							
13020.	20000.	3300.	1466.	1913.	1.3051	0.7500	460.8	0.24086	6572.4	
0.1194	8.88	1.0	0.00							
13160.	20000.	3300.	1469.	1917.	1.3050	0.7500	460.8	0.24036	6491.1	
0.1207	8.96	1.0	0.00							
13300.	20000.	3300.	1472.	1921.	1.3049	0.7500	460.8	0.23985	6411.3	
0.1220	9.03	1.0	0.00							
13440.	20000.	3300.	1476.	1925.	1.3047	0.7500	460.8	0.23934	6333.1	
0.1233	9.11	1.0	0.00							
13580.	20000.	3300.	1479.	1929.	1.3046	0.7500	460.8	0.23882	6256.3	
0.1246	9.18	1.0	0.00							
13720.	20000.	3300.	1482.	1934.	1.3045	0.7500	460.8	0.23830	6181.0	
0.1259	9.26	1.0	0.00							
13860.	20000.	3300.	1486.	1938.	1.3043	0.7500	460.8	0.23778	6107.0	
0.1271	9.33	1.0	0.00							
14000.	20000.	3300.	1489.	1942.	1.3042	0.7500	460.8	0.23725	6034.4	

0.1284	9.40	1.0	0.00						
14140.	20000.	3300.	1493.	1947.	1.3040	0.7500	460.8	0.23672	5963.0
0.1297	9.47	1.0	0.00						
14280.	20000.	3300.	1496.	1951.	1.3039	0.7500	460.8	0.23618	5893.0
0.1310	9.54	1.0	0.00						
14420.	20000.	3300.	1500.	1955.	1.3038	0.7500	460.8	0.23564	5824.1
0.1323	9.61	1.0	0.00						
14560.	20000.	3300.	1503.	1960.	1.3036	0.7500	460.8	0.23509	5756.5
0.1336	9.68	1.0	0.00						
14700.	20000.	3300.	1507.	1965.	1.3035	0.7500	460.8	0.23455	5690.0
0.1348	9.75	1.0	0.00						
14840.	20000.	3300.	1511.	1969.	1.3033	0.7500	460.8	0.23399	5624.6
0.1361	9.82	1.0	0.00						
14980.	20000.	3300.	1515.	1974.	1.3032	0.7500	460.8	0.23344	5560.3
0.1374	9.89	1.0	0.00						
15120.	20000.	3300.	1518.	1979.	1.3030	0.7500	460.8	0.23288	5497.0
0.1387	9.96	1.0	0.00						
15260.	20000.	3300.	1522.	1983.	1.3029	0.7500	460.8	0.23232	5434.8
0.1400	10.02	1.0	0.00						

## SUMMARY DATA FOR CRUISE SCHEDULE 4

WEIGHT CL	ALTITUDE L/D	THRUST ENGINES AVAILABLE CLIMB	THRUST NOX REQUIRED	FUEL FLOW OPERATING	SFC	MACH NUMBER RATE	VELOCITY	SPECIFIC RANGE	RATE OF
11620.	20000.	2997.	1107.	1415.	1.2779	0.6300	387.0	0.27352	6375.4
0.1511	10.49	1.0	0.00						
11760.	20000.	2997.	1111.	1419.	1.2772	0.6300	387.0	0.27276	6287.1
0.1529	10.58	1.0	0.00						
11900.	20000.	2997.	1115.	1423.	1.2765	0.6300	387.0	0.27197	6200.7
0.1547	10.67	1.0	0.00						
12040.	20000.	2997.	1119.	1427.	1.2760	0.6300	387.0	0.27117	6116.3
0.1565	10.76	1.0	0.00						
12180.	20000.	2997.	1122.	1432.	1.2754	0.6300	387.0	0.27037	6033.7
0.1583	10.85	1.0	0.00						
12320.	20000.	2997.	1126.	1436.	1.2748	0.6300	387.0	0.26957	5952.9
0.1602	10.94	1.0	0.00						
12460.	20000.	2997.	1130.	1440.	1.2742	0.6300	387.0	0.26877	5873.8
0.1620	11.03	1.0	0.00						
12600.	20000.	2997.	1134.	1444.	1.2736	0.6300	387.0	0.26797	5796.4
0.1638	11.11	1.0	0.00						
12740.	20000.	2997.	1138.	1449.	1.2731	0.6300	387.0	0.26717	5720.6
0.1656	11.20	1.0	0.00						
12880.	20000.	2997.	1142.	1453.	1.2725	0.6300	387.0	0.26636	5646.4
0.1674	11.28	1.0	0.00						
13020.	20000.	2997.	1146.	1457.	1.2719	0.6300	387.0	0.26556	5573.7
0.1693	11.36	1.0	0.00						
13160.	20000.	2997.	1150.	1462.	1.2713	0.6300	387.0	0.26475	5502.5
0.1711	11.44	1.0	0.00						
13300.	20000.	2997.	1154.	1466.	1.2707	0.6300	387.0	0.26395	5432.7

0.1729	11.53	1.0	0.00						
13440.	20000.	2997.	1158.	1471.	1.2702	0.6300	387.0	0.26314	5364.2
0.1747	11.61	1.0	0.00						
13580.	20000.	2997.	1162.	1475.	1.2696	0.6300	387.0	0.26234	5297.1
0.1765	11.69	1.0	0.00						
13720.	20000.	2997.	1166.	1480.	1.2690	0.6300	387.0	0.26153	5231.3
0.1784	11.76	1.0	0.00						
13860.	20000.	2997.	1170.	1485.	1.2684	0.6300	387.0	0.26072	5166.7
0.1802	11.84	1.0	0.00						
14000.	20000.	2997.	1175.	1489.	1.2678	0.6300	387.0	0.25991	5103.3
0.1820	11.92	1.0	0.00						
14140.	20000.	2997.	1179.	1494.	1.2673	0.6300	387.0	0.25910	5041.2
0.1838	12.00	1.0	0.00						
14280.	20000.	2997.	1183.	1498.	1.2667	0.6300	387.0	0.25830	4980.1
0.1856	12.07	1.0	0.00						
14420.	20000.	2997.	1187.	1503.	1.2661	0.6300	387.0	0.25749	4920.2
0.1875	12.15	1.0	0.00						
14560.	20000.	2997.	1192.	1508.	1.2655	0.6300	387.0	0.25668	4861.4
0.1893	12.22	1.0	0.00						
14700.	20000.	2997.	1196.	1513.	1.2649	0.6300	387.0	0.25587	4803.6
0.1911	12.29	1.0	0.00						
14840.	20000.	2997.	1200.	1517.	1.2644	0.6300	387.0	0.25506	4746.8
0.1929	12.36	1.0	0.00						
14980.	20000.	2997.	1205.	1522.	1.2638	0.6300	387.0	0.25425	4691.0
0.1948	12.44	1.0	0.00						
15120.	20000.	2997.	1209.	1527.	1.2632	0.6300	387.0	0.25344	4636.2
0.1966	12.51	1.0	0.00						
15260.	20000.	2997.	1213.	1532.	1.2626	0.6300	387.0	0.25263	4582.3
0.1984	12.58	1.0	0.00						

## SUMMARY DATA FOR CRUISE SCHEDULE 5

WEIGHT CL	ALTITUDE L/D	THRUST		FUEL FLOW	SFC	MACH	VELOCITY	SPECIFIC RANGE	RATE OF
		AVAILABLE CLIMB	REQUIRED NOX						
11620.	30000.	2182.	1165.	1456.	1.2497	0.7900	465.7	0.31988	4127.7
0.1485	9.98	1.0	0.00						
11760.	30000.	2182.	1169.	1461.	1.2496	0.7900	465.7	0.31874	4061.7
0.1503	10.06	1.0	0.00						
11900.	30000.	2182.	1173.	1466.	1.2496	0.7900	465.7	0.31770	3998.6
0.1521	10.15	1.0	0.00						
12040.	30000.	2182.	1177.	1471.	1.2495	0.7900	465.7	0.31665	3936.7
0.1539	10.23	1.0	0.00						
12180.	30000.	2182.	1181.	1475.	1.2495	0.7900	465.7	0.31561	3876.2
0.1557	10.31	1.0	0.00						
12320.	30000.	2182.	1185.	1480.	1.2494	0.7900	465.7	0.31456	3816.9
0.1574	10.40	1.0	0.00						
12460.	30000.	2182.	1189.	1485.	1.2494	0.7900	465.7	0.31351	3758.8
0.1592	10.48	1.0	0.00						
12600.	30000.	2182.	1193.	1490.	1.2494	0.7900	465.7	0.31246	3702.0

0.1610	10.56	1.0	0.00						
12740.	30000.	2182.	1197.	1495.	1.2493	0.7900	465.7	0.31141	3646.2
0.1628	10.64	1.0	0.00						
12880.	30000.	2182.	1201.	1500.	1.2493	0.7900	465.7	0.31036	3591.6
0.1646	10.72	1.0	0.00						
13020.	30000.	2182.	1205.	1505.	1.2492	0.7900	465.7	0.30930	3538.0
0.1664	10.80	1.0	0.00						
13160.	30000.	2182.	1209.	1511.	1.2492	0.7900	465.7	0.30825	3485.4
0.1682	10.88	1.0	0.00						
13300.	30000.	2182.	1214.	1516.	1.2491	0.7900	465.7	0.30720	3433.9
0.1700	10.96	1.0	0.00						
13440.	30000.	2182.	1218.	1521.	1.2491	0.7900	465.7	0.30614	3383.3
0.1718	11.04	1.0	0.00						
13580.	30000.	2182.	1222.	1526.	1.2490	0.7900	465.7	0.30509	3333.6
0.1735	11.11	1.0	0.00						
13720.	30000.	2182.	1226.	1532.	1.2490	0.7900	465.7	0.30403	3284.9
0.1753	11.19	1.0	0.00						
13860.	30000.	2182.	1231.	1537.	1.2489	0.7900	465.7	0.30298	3237.0
0.1771	11.26	1.0	0.00						
14000.	30000.	2182.	1235.	1542.	1.2489	0.7900	465.7	0.30193	3190.0
0.1789	11.34	1.0	0.00						
14140.	30000.	2182.	1239.	1548.	1.2488	0.7900	465.7	0.30087	3143.8
0.1807	11.41	1.0	0.00						
14280.	30000.	2182.	1244.	1553.	1.2488	0.7900	465.7	0.29982	3098.4
0.1825	11.48	1.0	0.00						
14420.	30000.	2182.	1248.	1559.	1.2487	0.7900	465.7	0.29876	3053.8
0.1843	11.55	1.0	0.00						
14560.	30000.	2182.	1253.	1564.	1.2487	0.7900	465.7	0.29771	3010.0
0.1861	11.62	1.0	0.00						
14700.	30000.	2182.	1257.	1570.	1.2486	0.7900	465.7	0.29665	2966.9
0.1879	11.69	1.0	0.00						
14840.	30000.	2182.	1262.	1575.	1.2486	0.7900	465.7	0.29560	2924.5
0.1896	11.76	1.0	0.00						
14980.	30000.	2182.	1266.	1581.	1.2485	0.7900	465.7	0.29454	2882.8
0.1914	11.83	1.0	0.00						
15120.	30000.	2182.	1271.	1587.	1.2485	0.7900	465.7	0.29348	2841.8
0.1932	11.90	1.0	0.00						
15260.	30000.	2182.	1275.	1592.	1.2486	0.7900	465.7	0.29241	2801.4
0.1950	11.96	1.0	0.00						

## SUMMARY DATA FOR CRUISE SCHEDULE 6

WEIGHT CL	ALTITUDE		THRUST		FUEL FLOW	SFC OPERATING	MACH NUMBER	VELOCITY	SPECIFIC RANGE	RATE OF
	L/D	ENGINES	AVAILABLE CLIMB	REQUIRED						
11620.	30000.		2052.	1017.	1245.	1.2245	0.7200	424.4	0.34082	3829.0
0.1788	11.43	1.0	0.00							
11760.	30000.		2052.	1021.	1250.	1.2243	0.7200	424.4	0.33943	3767.9
0.1809	11.52	1.0	0.00							
11900.	30000.		2052.	1025.	1255.	1.2242	0.7200	424.4	0.33805	3708.0



0.1831	11.60	1.0	0.00						
12040.	30000.	2052.	1030.	1261.	1.2241	0.7200	424.4	0.33666	3649.5
0.1852	11.69	1.0	0.00						
12180.	30000.	2052.	1034.	1266.	1.2240	0.7200	424.4	0.33527	3592.1
0.1874	11.78	1.0	0.00						
12320.	30000.	2052.	1039.	1271.	1.2238	0.7200	424.4	0.33389	3536.0
0.1895	11.86	1.0	0.00						
12460.	30000.	2052.	1043.	1276.	1.2237	0.7200	424.4	0.33250	3480.9
0.1917	11.95	1.0	0.00						
12600.	30000.	2052.	1047.	1282.	1.2236	0.7200	424.4	0.33112	3427.0
0.1939	12.03	1.0	0.00						
12740.	30000.	2052.	1052.	1287.	1.2235	0.7200	424.4	0.32973	3374.1
0.1960	12.11	1.0	0.00						
12880.	30000.	2052.	1057.	1293.	1.2233	0.7200	424.4	0.32835	3322.3
0.1982	12.19	1.0	0.00						
13020.	30000.	2052.	1061.	1298.	1.2232	0.7200	424.4	0.32696	3271.4
0.2003	12.27	1.0	0.00						
13160.	30000.	2052.	1066.	1304.	1.2231	0.7200	424.4	0.32554	3221.1
0.2025	12.35	1.0	0.00						
13300.	30000.	2052.	1071.	1309.	1.2229	0.7200	424.4	0.32412	3171.8
0.2046	12.42	1.0	0.00						
13440.	30000.	2052.	1075.	1315.	1.2228	0.7200	424.4	0.32270	3123.3
0.2068	12.50	1.0	0.00						
13580.	30000.	2052.	1080.	1321.	1.2227	0.7200	424.4	0.32128	3075.7
0.2089	12.57	1.0	0.00						
13720.	30000.	2052.	1085.	1327.	1.2226	0.7200	424.4	0.31985	3028.9
0.2111	12.64	1.0	0.00						
13860.	30000.	2052.	1090.	1333.	1.2226	0.7200	424.4	0.31840	2982.9
0.2132	12.71	1.0	0.00						
14000.	30000.	2052.	1095.	1339.	1.2225	0.7200	424.4	0.31696	2937.7
0.2154	12.78	1.0	0.00						
14140.	30000.	2052.	1100.	1345.	1.2225	0.7200	424.4	0.31551	2893.3
0.2175	12.85	1.0	0.00						
14280.	30000.	2052.	1105.	1351.	1.2225	0.7200	424.4	0.31406	2849.6
0.2197	12.92	1.0	0.00						
14420.	30000.	2052.	1111.	1358.	1.2224	0.7200	424.4	0.31262	2806.6
0.2219	12.98	1.0	0.00						
14560.	30000.	2052.	1116.	1364.	1.2224	0.7200	424.4	0.31117	2764.3
0.2240	13.05	1.0	0.00						
14700.	30000.	2052.	1121.	1370.	1.2224	0.7200	424.4	0.30973	2722.7
0.2262	13.11	1.0	0.00						
14840.	30000.	2052.	1126.	1377.	1.2223	0.7200	424.4	0.30828	2681.7
0.2283	13.18	1.0	0.00						
14980.	30000.	2052.	1132.	1383.	1.2223	0.7200	424.4	0.30684	2641.4
0.2305	13.24	1.0	0.00						
15120.	30000.	2052.	1137.	1390.	1.2223	0.7200	424.4	0.30540	2601.6
0.2326	13.30	1.0	0.00						
15260.	30000.	2052.	1142.	1396.	1.2222	0.7200	424.4	0.30396	2562.5
0.2348	13.36	1.0	0.00						

SUMMARY DATA FOR CRUISE SCHEDULE 7

WEIGHT CL	ALTITUDE L/D	THRUST ENGINES AVAILABLE CLIMB	THRUST NOX REQUIRED	FUEL FLOW OPERATING	SFC	MACH	VELOCITY	SPECIFIC RANGE	RATE OF
11620.	40000.	1391.	955.	1167.	1.2213	0.8200	470.3	0.40317	1785.3
0.2208	12.17	1.0	0.00						
11760.	40000.	1391.	961.	1173.	1.2214	0.8200	470.3	0.40086	1742.0
0.2234	12.24	1.0	0.00						
11900.	40000.	1391.	966.	1180.	1.2215	0.8200	470.3	0.39854	1699.5
0.2261	12.32	1.0	0.00						
12040.	40000.	1391.	972.	1187.	1.2217	0.8200	470.3	0.39620	1657.7
0.2287	12.39	1.0	0.00						
12180.	40000.	1391.	977.	1194.	1.2219	0.8200	470.3	0.39385	1616.7
0.2314	12.46	1.0	0.00						
12320.	40000.	1391.	983.	1201.	1.2221	0.8200	470.3	0.39151	1576.3
0.2341	12.53	1.0	0.00						
12460.	40000.	1391.	989.	1209.	1.2223	0.8200	470.3	0.38917	1536.7
0.2367	12.60	1.0	0.00						
12600.	40000.	1391.	995.	1216.	1.2225	0.8200	470.3	0.38683	1497.7
0.2394	12.67	1.0	0.00						
12740.	40000.	1391.	1000.	1223.	1.2227	0.8200	470.3	0.38450	1459.3
0.2420	12.73	1.0	0.00						
12880.	40000.	1391.	1006.	1231.	1.2229	0.8200	470.3	0.38217	1421.5
0.2447	12.80	1.0	0.00						
13020.	40000.	1391.	1012.	1238.	1.2231	0.8200	470.3	0.37984	1384.3
0.2474	12.86	1.0	0.00						
13160.	40000.	1391.	1018.	1246.	1.2234	0.8200	470.3	0.37752	1347.7
0.2500	12.92	1.0	0.00						
13300.	40000.	1391.	1025.	1254.	1.2236	0.8200	470.3	0.37516	1311.2
0.2527	12.98	1.0	0.00						
13440.	40000.	1391.	1031.	1262.	1.2238	0.8200	470.3	0.37279	1275.1
0.2553	13.04	1.0	0.00						
13580.	40000.	1391.	1037.	1270.	1.2240	0.8200	470.3	0.37043	1239.6
0.2580	13.09	1.0	0.00						
13720.	40000.	1391.	1044.	1278.	1.2242	0.8200	470.3	0.36808	1204.5
0.2607	13.14	1.0	0.00						
13860.	40000.	1391.	1050.	1286.	1.2244	0.8200	470.3	0.36572	1169.8
0.2633	13.20	1.0	0.00						
14000.	40000.	1391.	1057.	1294.	1.2247	0.8200	470.3	0.36334	1135.6
0.2660	13.25	1.0	0.00						
14140.	40000.	1391.	1064.	1303.	1.2251	0.8200	470.3	0.36096	1101.9
0.2686	13.29	1.0	0.00						
14280.	40000.	1391.	1070.	1312.	1.2254	0.8200	470.3	0.35858	1068.5
0.2713	13.34	1.0	0.00						
14420.	40000.	1391.	1077.	1320.	1.2257	0.8200	470.3	0.35621	1035.6
0.2740	13.39	1.0	0.00						
14560.	40000.	1391.	1084.	1329.	1.2261	0.8200	470.3	0.35384	1003.0
0.2766	13.43	1.0	0.00						
14700.	40000.	1391.	1091.	1338.	1.2264	0.8200	470.3	0.35148	970.8
0.2793	13.47	1.0	0.00						
14840.	40000.	1391.	1098.	1347.	1.2267	0.8200	470.3	0.34913	939.0
0.2819	13.51	1.0	0.00						

14980.	40000.	1391.	1105.	1356.	1.2270	0.8200	470.3	0.34678	907.5
0.2846	13.55	1.0	0.00						
15120.	40000.	1391.	1113.	1365.	1.2274	0.8200	470.3	0.34444	876.4
0.2873	13.59	1.0	0.00						
15260.	40000.	1391.	1120.	1375.	1.2277	0.8200	470.3	0.34211	845.7
0.2899	13.63	1.0	0.00						

## SUMMARY DATA FOR CRUISE SCHEDULE 8

WEIGHT	ALTITUDE	THRUST	FUEL	SFC	MACH	VELOCITY	SPECIFIC	RATE OF	
CL	L/D	ENGINES	NOX						
		AVAILABLE	REQUIRED	FLOW	NUMBER		RANGE		
		CLIMB		OPERATING	RATE				
11620.	40000.	1350.	912.	1103.	1.2100	0.7900	453.1	0.41068	1731.7
0.2378	12.74	1.0	0.00						
11760.	40000.	1350.	918.	1110.	1.2101	0.7900	453.1	0.40808	1688.8
0.2407	12.82	1.0	0.00						
11900.	40000.	1350.	923.	1117.	1.2102	0.7900	453.1	0.40548	1646.6
0.2436	12.89	1.0	0.00						
12040.	40000.	1350.	929.	1125.	1.2103	0.7900	453.1	0.40289	1605.2
0.2464	12.96	1.0	0.00						
12180.	40000.	1350.	935.	1132.	1.2104	0.7900	453.1	0.40030	1564.4
0.2493	13.02	1.0	0.00						
12320.	40000.	1350.	941.	1140.	1.2106	0.7900	453.1	0.39761	1523.5
0.2522	13.09	1.0	0.00						
12460.	40000.	1350.	948.	1148.	1.2109	0.7900	453.1	0.39486	1483.0
0.2550	13.15	1.0	0.00						
12600.	40000.	1350.	954.	1156.	1.2111	0.7900	453.1	0.39210	1443.0
0.2579	13.21	1.0	0.00						
12740.	40000.	1350.	961.	1164.	1.2114	0.7900	453.1	0.38934	1403.5
0.2608	13.26	1.0	0.00						
12880.	40000.	1350.	967.	1172.	1.2116	0.7900	453.1	0.38658	1364.6
0.2636	13.31	1.0	0.00						
13020.	40000.	1350.	974.	1181.	1.2119	0.7900	453.1	0.38382	1326.1
0.2665	13.37	1.0	0.00						
13160.	40000.	1350.	981.	1189.	1.2122	0.7900	453.1	0.38107	1288.2
0.2694	13.42	1.0	0.00						
13300.	40000.	1350.	988.	1198.	1.2124	0.7900	453.1	0.37831	1250.7
0.2722	13.46	1.0	0.00						
13440.	40000.	1350.	995.	1207.	1.2127	0.7900	453.1	0.37555	1213.6
0.2751	13.51	1.0	0.00						
13580.	40000.	1350.	1002.	1215.	1.2129	0.7900	453.1	0.37280	1177.0
0.2780	13.55	1.0	0.00						
13720.	40000.	1350.	1009.	1224.	1.2132	0.7900	453.1	0.37005	1140.8
0.2808	13.59	1.0	0.00						
13860.	40000.	1350.	1017.	1234.	1.2134	0.7900	453.1	0.36731	1105.1
0.2837	13.63	1.0	0.00						
14000.	40000.	1350.	1024.	1243.	1.2138	0.7900	453.1	0.36456	1069.7
0.2866	13.67	1.0	0.00						
14140.	40000.	1350.	1032.	1252.	1.2142	0.7900	453.1	0.36178	1034.7
0.2894	13.71	1.0	0.00						

14280.	40000.	1350.	1039.	1262.	1.2146	0.7900	453.1	0.35902	1000.1
0.2923	13.74	1.0	0.00						
14420.	40000.	1350.	1047.	1272.	1.2149	0.7900	453.1	0.35626	965.9
0.2952	13.77	1.0	0.00						
14560.	40000.	1350.	1055.	1282.	1.2153	0.7900	453.1	0.35351	932.0
0.2980	13.81	1.0	0.00						
14700.	40000.	1350.	1063.	1292.	1.2158	0.7900	453.1	0.35069	897.9
0.3009	13.83	1.0	0.00						
14840.	40000.	1350.	1071.	1303.	1.2162	0.7900	453.1	0.34772	862.5
0.3038	13.85	1.0	0.00						
14980.	40000.	1350.	1080.	1314.	1.2166	0.7900	453.1	0.34474	827.2
0.3066	13.87	1.0	0.00						
15120.	40000.	1350.	1089.	1326.	1.2170	0.7900	453.1	0.34175	792.0
0.3095	13.88	1.0	0.00						
15260.	40000.	1350.	1099.	1338.	1.2175	0.7900	453.1	0.33876	757.0
0.3124	13.89	1.0	0.00						

## CRUISE SCHEDULE RANGE AND TIME SUMMARY

WEIGHT	RANGE -1-	TIME	RANGE -2-	TIME	RANGE -3-	TIME	RANGE -4-	TIME
RANGE -5-	TIME	RANGE -6-	TIME	RANGE -7-	TIME	RANGE -8-	TIME	
(POUNDS)	(N.MI.)	(HR)	(N.MI.)	(HR)	(N.MI.)	(HR)	(N.MI.)	(HR)
(N.MI.)	(HR)	(N.MI.)	(HR)	(N.MI.)	(HR)	(N.MI.)	(HR)	
15260.	0.0	0.00	0.0	0.00	0.0	0.00	0.0	
0.00	0.0	0.00	0.0	0.00	0.0	0.00	0.0	0.00
15190.	12.5	0.03	14.0	0.04	16.3	0.04	17.7	
0.05	20.5	0.04	21.3	0.05	24.0	0.05	23.8	0.05
15120.	24.9	0.05	28.1	0.08	32.6	0.07	35.4	
0.09	41.0	0.09	42.7	0.10	48.1	0.10	47.6	0.11
15050.	37.4	0.08	42.1	0.12	48.9	0.11	53.2	
0.14	61.6	0.13	64.1	0.15	72.2	0.15	71.6	0.16
14980.	49.9	0.11	56.2	0.16	65.2	0.14	71.0	
0.18	82.2	0.18	85.5	0.20	96.4	0.21	95.7	0.21
14910.	62.4	0.14	70.2	0.20	81.6	0.18	88.8	0.23
102.8	0.22	107.0	0.25	120.8	0.26	119.9	0.26	
14840.	74.9	0.16	84.3	0.24	97.9	0.21	106.6	0.28
123.5	0.27	128.6	0.30	145.2	0.31	144.2	0.32	
14770.	87.4	0.19	98.5	0.28	114.3	0.25	124.5	0.32
144.2	0.31	150.2	0.35	169.6	0.36	168.6	0.37	
14700.	99.9	0.22	112.6	0.31	130.7	0.28	142.4	0.37
164.9	0.35	171.8	0.40	194.2	0.41	193.0	0.43	
14630.	112.4	0.24	126.7	0.35	147.2	0.32	160.3	0.41
185.7	0.40	193.5	0.46	218.8	0.47	217.6	0.48	
14560.	124.9	0.27	140.9	0.39	163.6	0.36	178.3	0.46
206.5	0.44	215.3	0.51	243.6	0.52	242.3	0.53	
14490.	137.4	0.30	155.1	0.43	180.1	0.39	196.2	0.51
227.4	0.49	237.1	0.56	268.4	0.57	267.1	0.59	
14420.	150.0	0.33	169.3	0.47	196.5	0.43	214.3	0.55
248.3	0.53	259.0	0.61	293.3	0.62	292.0	0.64	
14350.	162.5	0.35	183.5	0.51	213.1	0.46	232.3	0.60
269.2	0.58	280.9	0.66	318.3	0.68	317.0	0.70	
14280.	175.1	0.38	197.7	0.55	229.6	0.50	250.4	0.65

290.2	0.62	302.8	0.71	343.3	0.73	342.1	0.75	
14210.	187.6	0.41	212.0	0.59	246.1	0.53	268.4	0.69
311.2	0.67	324.8	0.77	368.5	0.78	367.3	0.81	
14140.	200.2	0.44	226.2	0.63	262.7	0.57	286.6	0.74
332.2	0.71	346.9	0.82	393.7	0.84	392.5	0.87	
14070.	212.8	0.46	240.5	0.67	279.3	0.61	304.7	0.79
353.3	0.76	369.0	0.87	419.0	0.89	417.9	0.92	
14000.	225.4	0.49	254.8	0.71	295.9	0.64	322.9	0.83
374.4	0.80	391.2	0.92	444.4	0.94	443.4	0.98	
13930.	237.9	0.52	269.1	0.75	312.5	0.68	341.1	0.88
395.6	0.85	413.4	0.97	469.9	1.00	469.0	1.03	
13860.	250.5	0.55	283.4	0.79	329.1	0.71	359.3	0.93
416.8	0.90	435.6	1.03	495.4	1.05	494.6	1.09	
13790.	263.1	0.57	297.8	0.83	345.8	0.75	377.6	0.98
438.0	0.94	458.0	1.08	521.1	1.11	520.4	1.15	
13720.	275.7	0.60	312.1	0.87	362.4	0.79	395.9	1.02
459.3	0.99	480.3	1.13	546.8	1.16	546.2	1.21	
13650.	288.4	0.63	326.5	0.91	379.1	0.82	414.2	1.07
480.6	1.03	502.7	1.18	572.6	1.22	572.2	1.26	
13580.	301.0	0.65	340.9	0.95	395.8	0.86	432.6	1.12
501.9	1.08	525.2	1.24	598.5	1.27	598.2	1.32	
13510.	313.6	0.68	355.3	0.99	412.6	0.90	451.0	1.17
523.3	1.12	547.7	1.29	624.4	1.33	624.4	1.38	
13440.	326.2	0.71	369.7	1.03	429.3	0.93	469.4	1.21
544.7	1.17	570.3	1.34	650.5	1.38	650.6	1.44	
13370.	338.9	0.74	384.2	1.07	446.1	0.97	487.8	1.26
566.1	1.22	592.9	1.40	676.6	1.44	677.0	1.49	
13300.	351.5	0.76	398.6	1.12	462.8	1.00	506.3	1.31
587.6	1.26	615.6	1.45	702.9	1.49	703.4	1.55	
13230.	364.2	0.79	413.1	1.16	479.6	1.04	524.7	1.36
609.2	1.31	638.3	1.50	729.2	1.55	729.9	1.61	
13160.	376.8	0.82	427.6	1.20	496.5	1.08	543.3	1.40
630.7	1.35	661.0	1.56	755.5	1.61	756.5	1.67	
13090.	389.5	0.85	442.1	1.24	513.3	1.11	561.8	1.45
652.3	1.40	683.8	1.61	782.0	1.66	783.3	1.73	
13020.	402.2	0.88	456.6	1.28	530.1	1.15	580.4	1.50
673.9	1.45	706.7	1.67	808.6	1.72	810.1	1.79	
12950.	414.8	0.90	471.2	1.32	547.0	1.19	599.0	1.55
695.6	1.49	729.6	1.72	835.2	1.78	837.0	1.85	
12880.	427.5	0.93	485.7	1.36	563.9	1.22	617.6	1.60
717.3	1.54	752.6	1.77	861.9	1.83	864.0	1.91	
12810.	440.2	0.96	500.3	1.40	580.8	1.26	636.3	1.64
739.1	1.59	775.6	1.83	888.7	1.89	891.1	1.97	
12740.	452.9	0.99	514.9	1.44	597.7	1.30	655.0	1.69
760.8	1.63	798.6	1.88	915.6	1.95	918.3	2.03	
12670.	465.6	1.01	529.5	1.48	614.7	1.33	673.7	1.74
782.7	1.68	821.7	1.94	942.5	2.00	945.6	2.09	
12600.	478.3	1.04	544.2	1.52	631.6	1.37	692.4	1.79
804.5	1.73	844.9	1.99	969.6	2.06	973.0	2.15	
12530.	491.0	1.07	558.8	1.56	648.6	1.41	711.2	1.84
826.4	1.77	868.1	2.05	996.7	2.12	1000.5	2.21	
12460.	503.8	1.10	573.5	1.60	665.6	1.44	730.0	1.89
848.3	1.82	891.4	2.10	1023.9	2.18	1028.1	2.27	

12390.	516.5	1.12	588.2	1.65	682.6	1.48	748.8	1.93
870.3	1.87	914.7	2.16	1051.2	2.23	1055.8	2.33	
12320.	529.2	1.15	602.9	1.69	699.6	1.52	767.7	1.98
892.3	1.92	938.0	2.21	1078.5	2.29	1083.6	2.39	
12250.	541.9	1.18	617.6	1.73	716.7	1.56	786.6	2.03
914.3	1.96	961.4	2.27	1106.0	2.35	1111.5	2.45	
12180.	554.7	1.21	632.3	1.77	733.7	1.59	805.5	2.08
936.4	2.01	984.8	2.32	1133.5	2.41	1139.4	2.51	
12110.	567.4	1.23	647.1	1.81	750.8	1.63	824.4	2.13
958.5	2.06	1008.3	2.38	1161.1	2.47	1167.5	2.58	
12040.	580.2	1.26	661.8	1.85	767.9	1.67	843.4	2.18
980.7	2.11	1031.9	2.43	1188.8	2.53	1195.7	2.64	
11970.	592.9	1.29	676.6	1.89	785.0	1.70	862.4	2.23
1002.9	2.15	1055.5	2.49	1216.6	2.59	1223.9	2.70	
11900.	605.7	1.32	691.4	1.93	802.1	1.74	881.4	2.28
1025.1	2.20	1079.1	2.54	1244.4	2.65	1252.3	2.76	
11830.	618.5	1.35	706.2	1.98	819.2	1.78	900.5	2.33
1047.3	2.25	1102.8	2.60	1272.4	2.71	1280.7	2.83	
11760.	631.3	1.37	721.1	2.02	836.4	1.82	919.5	2.38
1069.6	2.30	1126.5	2.65	1300.4	2.76	1309.2	2.89	
11690.	644.0	1.40	735.9	2.06	853.6	1.85	938.6	2.43
1092.0	2.34	1150.3	2.71	1328.5	2.82	1337.8	2.95	
11620.	656.8	1.43	750.8	2.10	870.7	1.89	957.8	2.47
1114.3	2.39	1174.1	2.77	1356.7	2.88	1366.5	3.02	

\* ITERATION 1 -- RANGE = 1158.980 FOR GROSS WEIGHT = 15138.00

\* ITERATION 2 -- RANGE = 1111.371 FOR GROSS WEIGHT = 14963.83

\* ITERATION 3 -- RANGE = 1099.939 FOR GROSS WEIGHT = 14922.23

\* ITERATION 4 -- RANGE = 1100.000 FOR GROSS WEIGHT = 14922.46

#### # OUTPUT FROM THE WEIGHTS MODULE

DESCRIPTION	VALUE	DIMENSIONS
WING BENDING FACTOR	11.1905	
ENGINE INERTIA RELIEF FACTOR	1.000000	
WING WEIGHT BREAKDOWN		
TERM 1	397.1	LB
TERM 2	780.7	LB
TERM 3	704.6	LB
WING SPAN	36.99	FT
WING GLOVE AREA	0.00	SQ FT
HORIZONTAL TAIL AREA	26.80	SQ FT
MODIFIED VOLUME COEFFICIENT	0.551314	
VERTICAL TAIL AREA	31.50	SQ FT
MODIFIED VOLUME COEFFICIENT	0.134714	

NACELLE LENGTH	0.00	FT
NACELLE DIAMETER	0.00	FT
LENGTH OF MAIN GEAR	35.80	IN
LENGTH OF NOSE GEAR	40.20	IN
MAXIMUM LANDING WEIGHT	14265.9	LB
WING FUEL CAPACITY	3908.7	LB
FUSELAGE FUEL CAPACITY	0.0	LB
AUXILIARY TANK CAPACITY	0.0	LB
TOTAL FUEL CAPACITY	3908.7	LB
EXCESS FUEL CAPACITY	664.5	LB

MASS AND BALANCE SUMMARY	PERCENT WREF	POUNDS	PERCENT LREF	HORI
CG-INCHES				
WING	12.61	1882.		
0.0 0.0				
HORIZONTAL TAIL	0.48	72.		
0.0 0.0				
VERTICAL TAIL	0.81	120.		
0.0 0.0				
VERTICAL FIN	0.00	0.		
0.0 0.0				
CANARD	0.00	0.		
0.0 0.0				
FUSELAGE	14.13	2108.		
0.0 0.0				
LANDING GEAR	3.69	551.		
0.0 0.0				
NACELLE (AIR INDUCTION)	1.35	202.		
0.0 0.0				
STRUCTURE TOTAL	( 33.08)	( 4936.)	( 0.0)	
( 0.0)				
ENGINES	19.77	2950.		
0.0 0.0				
THRUST REVERSERS	0.00	0.		
0.0 0.0				
MISCELLANEOUS SYSTEMS	0.38	57.		
0.0 0.0				
FUEL SYSTEM-TANKS AND PLUMBING	4.33	646.		
0.0 0.0				
PROPULSION TOTAL	( 24.47)	( 3652.)	( 0.0)	
( 0.0)				
SURFACE CONTROLS	4.44	662.		
0.0 0.0				
AUXILIARY POWER	0.00	0.		
0.0 0.0				
INSTRUMENTS	0.51	77.		
0.0 0.0				
HYDRAULICS	1.16	173.		
0.0 0.0				





14922.	9222.	0.	0.690	456.4	14209.	1	0.00	0.0	0.0	705.3	0.00
0.0	0.0	0.074	6.37	6930.	1.000						
14907.	10575.	1335.	0.694	456.8	13528.	1	0.10	0.7	15.9	679.4	0.10
0.7	15.9	0.077	6.56	6632.	1.000						
14891.	11927.	2670.	0.698	457.3	12833.	1	0.10	0.8	16.0	654.2	0.20
1.5	31.9	0.080	6.75	6333.	1.000						
14875.	13279.	4005.	0.702	457.7	12126.	1	0.11	0.8	16.0	629.8	0.31
2.3	47.9	0.083	6.94	6033.	1.000						
14859.	14632.	5340.	0.706	458.1	11457.	1	0.11	0.8	16.0	606.0	0.42
3.1	63.9	0.086	7.15	5749.	1.000						
14842.	15984.	6675.	0.710	458.6	10876.	1	0.12	0.9	16.1	582.9	0.54
4.0	80.0	0.090	7.35	5495.	1.000						
14826.	17336.	8011.	0.714	459.0	10281.	1	0.13	1.0	16.1	560.4	0.67
5.0	96.1	0.093	7.57	5239.	1.000						
14802.	19352.	10000.	0.720	459.6	9369.	1	0.21	1.5	24.2	528.2	0.88
6.5	120.3	0.099	7.89	4855.	1.000						
14786.	20675.	11317.	0.724	459.8	8868.	1	0.15	1.1	16.0	507.0	1.02
7.6	136.3	0.103	8.12	4637.	1.000						
14770.	21999.	12635.	0.728	459.9	8356.	1	0.15	1.2	16.0	486.5	1.18
8.7	152.3	0.107	8.36	4417.	1.000						
14754.	23322.	13952.	0.731	460.1	7832.	1	0.16	1.2	16.2	466.7	1.34
10.0	168.5	0.111	8.60	4196.	1.000						
14738.	24646.	15269.	0.735	460.2	7319.	1	0.17	1.3	16.3	447.4	1.51
11.3	184.7	0.116	8.84	3981.	1.000						
14721.	25969.	16586.	0.739	460.4	6883.	1	0.19	1.4	16.4	428.8	1.70
12.7	201.2	0.121	9.09	3793.	1.000						
14705.	27293.	17904.	0.743	460.5	6436.	1	0.20	1.5	16.6	410.7	1.90
14.2	217.7	0.126	9.34	3604.	1.000						
14688.	28616.	19221.	0.748	460.7	5977.	1	0.21	1.6	16.8	393.3	2.11
15.8	234.5	0.131	9.59	3413.	1.000						
14678.	29399.	20000.	0.750	460.8	5700.	1	0.13	1.0	10.0	383.2	2.25
16.9	244.6	0.135	9.74	3300.	1.000						
14660.	30759.	21333.	0.755	461.4	5329.	1	0.25	1.9	17.6	367.3	2.49
18.7	262.2	0.140	9.98	3140.	1.000						
14642.	32118.	22666.	0.760	462.1	4945.	1	0.26	2.0	17.9	351.8	2.76
20.8	280.1	0.146	10.22	2980.	1.000						
14624.	33478.	23999.	0.765	462.7	4552.	1	0.29	2.2	18.2	336.8	3.04
23.0	298.3	0.153	10.47	2817.	1.000						
14605.	34837.	25332.	0.771	463.4	4174.	1	0.31	2.4	18.6	322.3	3.36
25.4	317.0	0.159	10.72	2661.	1.000						
14586.	36197.	26665.	0.776	464.0	3856.	1	0.34	2.6	19.1	308.3	3.69
28.0	336.0	0.166	10.98	2526.	1.000						
14567.	37557.	27998.	0.782	464.7	3529.	1	0.37	2.8	19.5	294.7	4.06
30.8	355.6	0.174	11.23	2389.	1.000						
14547.	38916.	29330.	0.787	465.3	3191.	1	0.40	3.1	20.2	281.5	4.47
33.9	375.7	0.182	11.48	2252.	1.000						
14536.	39599.	30000.	0.790	465.7	3017.	1	0.22	1.7	10.4	275.1	4.69
35.6	386.1	0.186	11.61	2182.	1.000						
14513.	41055.	31429.	0.796	466.3	2727.	1	0.51	3.9	22.9	261.7	5.19
39.6	409.0	0.195	11.88	2060.	1.000						
14490.	42512.	32857.	0.802	467.0	2428.	1	0.56	4.4	23.9	248.8	5.76
44.0	432.9	0.205	12.14	1937.	1.000						

14464.	43968.	34286.	0.809	467.7	2119.	1	0.64	5.0	25.2	236.3	6.40
48.9	458.1	0.215	12.38	1815.	1.000						
14437.	45424.	35714.	0.815	468.3	1842.	1	0.74	5.7	27.0	224.4	7.14
54.7	485.1	0.226	12.61	1706.	1.000						
14408.	46880.	37143.	0.818	469.0	1596.	1	0.85	6.6	29.2	211.0	7.98
61.3	514.3	0.240	12.88	1603.	1.000						
14376.	48337.	38571.	0.819	469.7	1334.	1	0.99	7.8	32.1	197.6	8.98
69.1	546.4	0.256	13.14	1497.	1.000						
14339.	49793.	40000.	0.820	470.3	1054.	1	1.22	9.5	36.6	185.0	10.20
78.6	583.0	0.272	13.36	1391.	1.000						

\* ITERATION 5 -- RANGE = 1100.000 FOR GROSS WEIGHT = 14922.46

# SIZING AND PERFORMANCE RESULTS

CONFIGURATION DATA AFTER RESIZING (IF ANY)

OPERATING WEIGHT EMPTY	11678.3 LB
PAYLOAD	0.0 LB
MAXIMUM FUEL	3244.1 LB
GROSS WEIGHT	14922.5 LB
REFERENCE WING AREA	284.46 SQ FT
WING LOADING	52.46 LB/SQ FT
THRUST PER ENGINE	6090.0 LB
ENGINE SCALE FACTOR	1.0000
THRUST-WEIGHT RATIO	0.4081

\* \* \* M I S S I O N S U M M A R Y \* \* \*

SEGMENT	INITIAL ALTITUDE (FT)		FUEL (LB)		TIME (MIN)		DISTANCE (N MI)		MACH NUMBER	
	WEIGHT (LB)	SEGMENT	NOX	EMISS (LB)	SEGMENT	TOTAL	SEGMENT	TOTAL	START	END
START	END	SEGMENT	TOTAL							
TAXI OUT	14922.	0.	0.	0.0	0.0	0.0				
TAKE OFF	14922.	0.	0.	0.0	0.0	0.0				
0.690		0.								
CLIMB	14922.	583.	583.	10.2	10.2	78.6	78.6	0.690		
0.820	0.	40000.	0.00	0.00						
CRUISE	14339.	6.	589.	0.3	10.5	2.0	80.6	0.820	0.820	
40000.	40000.	0.00	0.00							
CRUISE	14334.	2655.	3243.	135.0	145.4	1019.4	1100.0	0.790	0.790	
40000.	40000.	0.00	0.00							
RESERVES	11679.	1.	3244.							
TAXI IN		0.		0.0	145.4					
ZERO FUEL	11678.									

DESIGN RANGE 1100.0  
 FLIGHT TIME 145.4

BLOCK TIME = 2.42 HOURS  
 BLOCK FUEL = 3243.1 POUNDS  
 TOTAL NITROGEN OXIDES EMISSIONS = 0.00 POUNDS

ATA TRAFFIC ALLOWANCE = 84.7 NAUTICAL MILES  
 AIR MANEUVER = 45.3  
 AIRPORT TRAFFIC ALLOWANCE = 17.4  
 AIRWAY DISTANCE FACTOR = 22.0

ATA RANGE = 1100.0 NAUTICAL MILES

## #OBJ/VAR/CONSTR SUMMARY

FUEL SWEEP	RANGE TCA	VAPP VCMN	FAROFF CH	FARLDG W/S	AMFOR T/W	SSFOR	GW	AR	THRUST	SW	TR
3244.1	1100.0	92.0	3292.	4281.	2605.	3583.	14922.5	4.810	6090.0	284.5	0.506
40.00	0.1000	0.820	50000.	52.4591	0.408110						
DESIGN - THRUST	TIT SFC	OPR OVEFF	FPR CDT	BPR CDP	TTR	BLA	(SLS)ST	VJET	(CRUISE)	MACH	ALT
2200.0	5.500	1.5000	0.000	1.1000	20.00	75.0	2366.0			1.00	50000.
1.1449	0.2115	806.6	17.56								1045.

DFAROFF = 3292.  
 DFARLDG = 4281.  
 FUEL WT = 3244.1  
 TOGW = 14922.5  
 RANGE FLAG = 1100.0  
 DTHRUST = 6090.0  
 DVAPP = 92.0  
 DRPM = 0.000000  
 Approx MAP = 2605.0  
 Approx SSC = 3582.9  
 DFO NOISE = 0.0  
 DSL NOISE = 0.0

FO= 0.324412D+04, OBJ= 0.324412D+04, PEN= 0.154385D+02, G= -1.000000 -0.386618 -0.725651  
 -0.643280 -0.427747 -0.588332 -0.204840

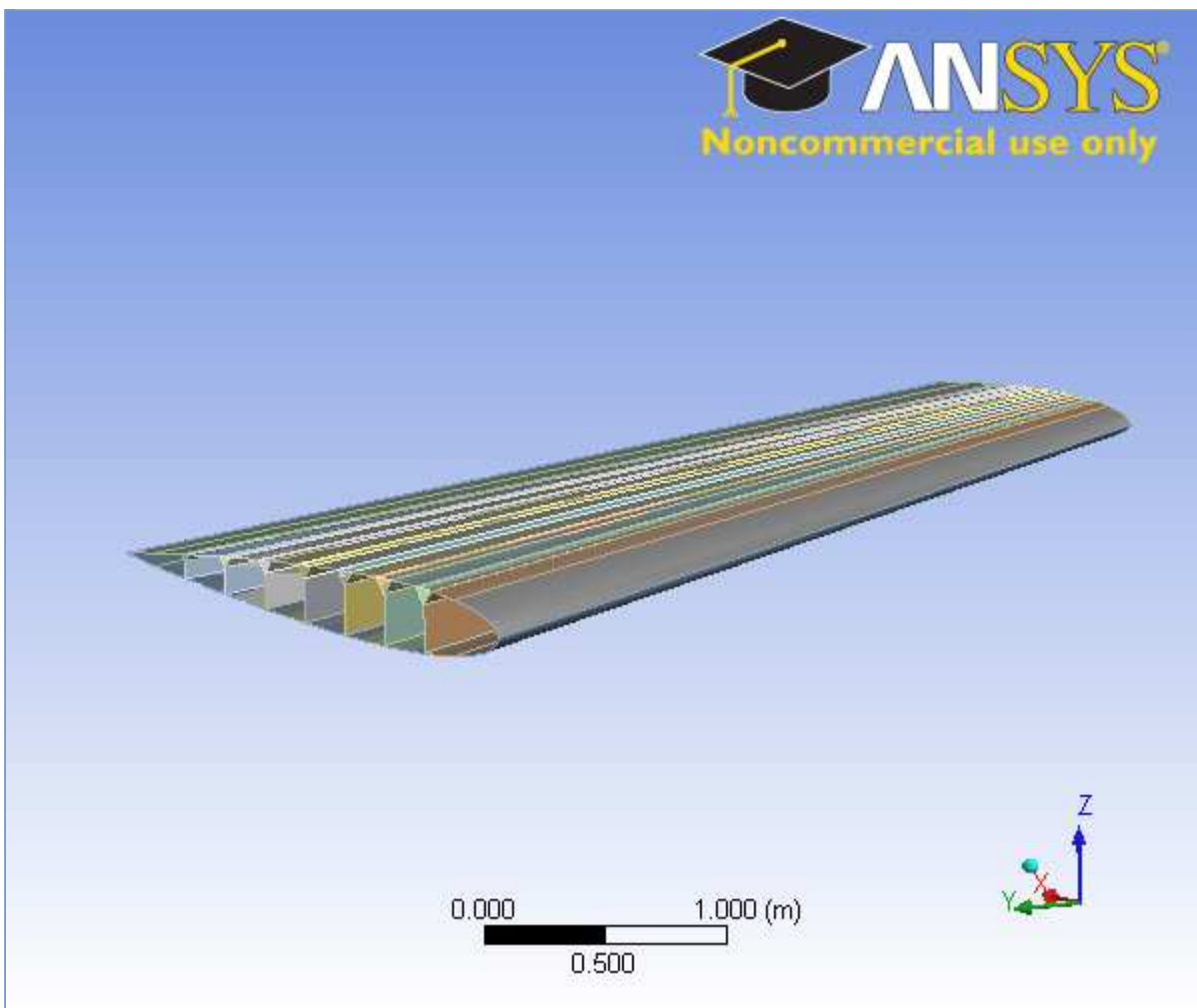
## APPENDIX B

### ANSYS ANALYSIS REPORT FOR ALL SPAR COMPOSITE DESIGN



# Project

First Saved	Wednesday, August 24, 2011
Last Saved	Thursday, August 25, 2011
Product Version	13.0 Release



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- [Material Data](#)
  - [Carbon/Epoxy Composite Sheet \(Smear\)](#)
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## Units

**TABLE 1**

Unit System	Metric (m, kg, N, s, V, A) Degrees rad/s Celsius
Angle	Degrees
Rotational Velocity	rad/s
Temperature	Celsius

## Model (B4)

### Geometry

**TABLE 2**  
**Model (B4) > Geometry**

Object Name	<i>Geometry</i>
State	Fully Defined
<b>Definition</b>	
Source	C:\TempDoc\Research\F86 All Spar Design\F86 Wing All Spar [SURFACE].CATPart
Type	Catia5
Length Unit	Millimeters

Element Control	Program Controlled
Display Style	Part Color
<b>Bounding Box</b>	
Length X	5.6713 m
Length Y	5.3 m
Length Z	0.54407 m
<b>Properties</b>	
Volume	0.11021 m <sup>3</sup>
Mass	176.34 kg
Surface Area(approx.)	65.689 m <sup>2</sup>
Scale Factor Value	1.
<b>Statistics</b>	
Bodies	18
Active Bodies	17
Nodes	9141
Elements	8688
Mesh Metric	None
<b>Preferences</b>	
Import Solid Bodies	Yes
Import Surface Bodies	Yes
Import Line Bodies	No
Parameter Processing	Yes
Personal Parameter Key	DS
CAD Attribute Transfer	No
Named Selection Processing	No
Material Properties Transfer	No
CAD Associativity	Yes
Import Coordinate Systems	No
Reader Save Part File	No
Import Using Instances	Yes
Do Smart Update	No
Attach File Via Temp File	Yes
Temporary Directory	C:\Users\Nate\AppData\Local\Temp
Analysis Type	3-D
Mixed Import Resolution	None
Enclosure and Symmetry Processing	Yes

**TABLE 3**  
**Model (B4) > Geometry > Parts**

Object Name	<i>Reference Surfaces\Geometrical Set.1 [skinIMLTopSurface]</i>	<i>Reference Surfaces\Geometrical Set.1 [skinIMLBottomSurface]</i>	<i>Reference Surfaces\Spar Tube Surfaces [Trailing Edge Spar Surface]</i>	<i>Reference Surfaces\Spar Tube Surfaces [Leading Edge Spar Surface]</i>	<i>Reference Surfaces\Spar Tube Surfaces[Spar 1 Surface]</i>
State	Meshed				
<b>Graphics Properties</b>					
Visible	Yes				
Transparency	1				
<b>Definition</b>					
Suppressed	No				

Stiffness Behavior	Flexible				
Coordinate System	Default Coordinate System				
Reference Temperature	By Environment				
Thickness	2.e-003 m			1.5e-003 m	
Thickness Mode	Manual				
Offset Type	Middle(Membrane)				
<b>Material</b>					
Assignment	Carbon/Epoxy Composite Sheet (Smear)				
Nonlinear Effects	Yes				
Thermal Strain Effects	Yes				
<b>Bounding Box</b>					
Length X	5.6713 m		2.808 m	4.038 m	3.9164 m
Length Y	5.3 m				
Length Z	0.14039 m		9.8169e-002 m	0.26548 m	0.28073 m
<b>Properties</b>					
Volume	2.5268e-002 m <sup>3</sup>	2.5273e-002 m <sup>3</sup>	6.2447e-003 m <sup>3</sup>	6.3137e-003 m <sup>3</sup>	7.1751e-003 m <sup>3</sup>
Mass	40.428 kg	40.437 kg	9.9915 kg	10.102 kg	11.48 kg
Centroid X	4.5429 m	4.5427 m	5.5257 m	3.7695 m	3.913 m
Centroid Y	-2.3601 m	-2.3602 m	-2.6429 m	-2.3659 m	-2.3053 m
Centroid Z	0.17404 m	2.5934e-002 m	9.8271e-002 m	9.3176e-002 m	9.1471e-002 m
Moment of Inertia Ip1	134.22 kg·m <sup>2</sup>	134.24 kg·m <sup>2</sup>	28.867 kg·m <sup>2</sup>	34.822 kg·m <sup>2</sup>	37.96 kg·m <sup>2</sup>
Moment of Inertia Ip2	14.343 kg·m <sup>2</sup>	14.352 kg·m <sup>2</sup>	6.381e-002 kg·m <sup>2</sup>	0.10121 kg·m <sup>2</sup>	0.16166 kg·m <sup>2</sup>
Moment of Inertia Ip3	148.51 kg·m <sup>2</sup>	148.54 kg·m <sup>2</sup>	28.906 kg·m <sup>2</sup>	34.777 kg·m <sup>2</sup>	37.952 kg·m <sup>2</sup>
Surface Area (approx.)	12.634 m <sup>2</sup>	12.636 m <sup>2</sup>	3.1223 m <sup>2</sup>	3.1569 m <sup>2</sup>	4.7834 m <sup>2</sup>
<b>Statistics</b>					
Nodes	2383	2473	343	348	455
Elements	2234	2316	290	295	449
Mesh Metric	None				

**TABLE 4**  
**Model (B4) > Geometry > Parts**

Object Name	<i>Reference Surfaces\Spar Tube Surfaces [Spar 2 Surface]</i>	<i>Reference Surfaces\Spar Tube Surfaces [Spar 3 Surface]</i>	<i>Reference Surfaces\Spar Tube Surfaces [Spar 4 Surface]</i>	<i>Reference Surfaces\Spar Tube Surfaces [Spar 5 Surface]</i>	<i>Reference Surfaces\Spar Tube Surfaces [Spar 6 Surface]</i>
State	Meshed				
<b>Graphics Properties</b>					
Visible	Yes				
Transparency	1				
<b>Definition</b>					
Suppressed	No				



Stiffness Behavior	Flexible				
Coordinate System	Default Coordinate System				
Reference Temperature	By Environment				
Thickness	1.5e-003 m				
Thickness Mode	Manual				
Offset Type	Middle(Membrane)				
<b>Material</b>					
Assignment	Carbon/Epoxy Composite Sheet (Smear)				
Nonlinear Effects	Yes				
Thermal Strain Effects	Yes				
<b>Bounding Box</b>					
Length X	3.7114 m	3.5064 m	3.3014 m	3.0965 m	2.8915 m
Length Y	5.3 m				
Length Z	0.28038 m	0.26678 m	0.23839 m	0.19909 m	0.15193 m
<b>Properties</b>					
Volume	7.1315e-003 m <sup>3</sup>	6.8644e-003 m <sup>3</sup>	6.4405e-003 m <sup>3</sup>	5.928e-003 m <sup>3</sup>	5.3766e-003 m <sup>3</sup>
Mass	11.41 kg	10.983 kg	10.305 kg	9.4848 kg	8.6025 kg
Centroid X	4.1561 m	4.4013 m	4.6486 m	4.8985 m	5.1482 m
Centroid Y	-2.3063 m	-2.3105 m	-2.3185 m	-2.3309 m	-2.3454 m
Centroid Z	9.1555e-002 m	9.2184e-002 m	9.2931e-002 m	9.4106e-002 m	9.5872e-002 m
Moment of Inertia Ip1	36.427 kg·m <sup>2</sup>	33.9 kg·m <sup>2</sup>	30.81 kg·m <sup>2</sup>	27.526 kg·m <sup>2</sup>	24.272 kg·m <sup>2</sup>
Moment of Inertia Ip2	0.16409 kg·m <sup>2</sup>	0.15077 kg·m <sup>2</sup>	0.12784 kg·m <sup>2</sup>	0.10161 kg·m <sup>2</sup>	7.6625e-002 kg·m <sup>2</sup>
Moment of Inertia Ip3	36.421 kg·m <sup>2</sup>	33.904 kg·m <sup>2</sup>	30.826 kg·m <sup>2</sup>	27.553 kg·m <sup>2</sup>	24.306 kg·m <sup>2</sup>
Surface Area (approx.)	4.7543 m <sup>2</sup>	4.5763 m <sup>2</sup>	4.2937 m <sup>2</sup>	3.952 m <sup>2</sup>	3.5844 m <sup>2</sup>
<b>Statistics</b>					
Nodes	445	434	412	380	
Elements	441	430	407	375	
Mesh Metric	None				

**TABLE 5**  
**Model (B4) > Geometry > Parts**

Object Name	<i>Reference Surfaces\Spar Tube Surfaces [Delta Spar 0 Surface]</i>	<i>Reference Surfaces\Spar Tube Surfaces [Delta Spar 1 Surface]</i>	<i>Reference Surfaces\Spar Tube Surfaces [Delta Spar 2 Surface]</i>	<i>Reference Surfaces\Spar Tube Surfaces [Delta Spar 3 Surface]</i>	<i>Reference Surfaces\Spar Tube Surfaces [Delta Spar 4 Surface]</i>
State	Meshed				
<b>Graphics Properties</b>					
Visible	Yes				
Transparency	1				
<b>Definition</b>					
Suppressed	No				
Stiffness Behavior	Flexible				

Coordinate System	Default Coordinate System				
Reference Temperature	By Environment				
Thickness	1.e-003 m				
Thickness Mode	Manual				
Offset Type	Middle(Membrane)				
<b>Material</b>					
Assignment	Carbon/Epoxy Composite Sheet (Smear)				
Nonlinear Effects	Yes				
Thermal Strain Effects	Yes				
<b>Bounding Box</b>					
Length X	3.8877 m	3.685 m	3.4747 m	3.2648 m	3.0557 m
Length Y	5.3 m				
Length Z	0.10374 m	0.10643 m	0.10306 m	9.392e-002 m	7.8995e-002 m
<b>Properties</b>					
Volume	1.3682e-003 m <sup>3</sup>	1.3883e-003 m <sup>3</sup>	1.3083e-003 m <sup>3</sup>	1.2342e-003 m <sup>3</sup>	1.1742e-003 m <sup>3</sup>
Mass	2.1891 kg	2.2213 kg	2.0933 kg	1.9747 kg	1.8787 kg
Centroid X	3.8458 m	4.1017 m	4.3645 m	4.6254 m	4.8586 m
Centroid Y	-2.3824 m	-2.4046 m	-2.4401 m	-2.4768 m	-2.469 m
Centroid Z	0.18851 m	0.19276 m	0.18968 m	0.18114 m	0.16891 m
Moment of Inertia Ip1	7.5064 kg·m <sup>2</sup>	7.3831 kg·m <sup>2</sup>	6.7629 kg·m <sup>2</sup>	6.2003 kg·m <sup>2</sup>	5.6973 kg·m <sup>2</sup>
Moment of Inertia Ip2	1.9774e-003 kg·m <sup>2</sup>	2.1128e-003 kg·m <sup>2</sup>	1.7982e-003 kg·m <sup>2</sup>	1.538e-003 kg·m <sup>2</sup>	1.3761e-003 kg·m <sup>2</sup>
Moment of Inertia Ip3	7.507 kg·m <sup>2</sup>	7.3839 kg·m <sup>2</sup>	6.7636 kg·m <sup>2</sup>	6.2009 kg·m <sup>2</sup>	5.6979 kg·m <sup>2</sup>
Surface Area (approx.)	1.3682 m <sup>2</sup>	1.3883 m <sup>2</sup>	1.3083 m <sup>2</sup>	1.2342 m <sup>2</sup>	1.1742 m <sup>2</sup>
<b>Statistics</b>					
Nodes	163	161	158	156	153
Elements	162	160	157	154	151
Mesh Metric	None				

**TABLE 6**  
**Model (B4) > Geometry > Parts**

Object Name	<i>Reference Surfaces\Spar Tube Surfaces[Delta Spar 5 Surface]</i>	<i>Reference Surfaces\Spar Tube Surfaces[Delta Spar 6 Surface]</i>	<i>Reference Surfaces\External References[wingTipPlane]</i>
State	Meshed		Suppressed
<b>Graphics Properties</b>			
Visible	Yes		No
Transparency	1		
<b>Definition</b>			
Suppressed	No		Yes
Stiffness Behavior	Flexible		
Coordinate System	Default Coordinate System		
Reference Temperature	By Environment		

Thickness	1.e-003 m		0. m
Thickness Mode	Manual		Refresh on Update
Offset Type	Middle(Membrane)		
<b>Material</b>			
Assignment	Carbon/Epoxy Composite Sheet (Smear)		Aluminum Alloy
Nonlinear Effects	Yes		
Thermal Strain Effects	Yes		
<b>Bounding Box</b>			
Length X	2.8378 m	2.6128 m	1.e-003 m
Length Y	5.3 m		0. m
Length Z	5.7704e-002 m	3.3293e-002 m	1.e-003 m
<b>Properties</b>			
Volume	9.9564e-004 m <sup>3</sup>	7.265e-004 m <sup>3</sup>	0. m <sup>3</sup>
Mass	1.593 kg	1.1624 kg	
Centroid X	5.0987 m	5.3831 m	6.4904 m
Centroid Y	-2.4731 m	-2.5696 m	-5.3 m
Centroid Z	0.15493 m	0.13942 m	0.50318 m
Moment of Inertia Ip1	4.6797 kg·m <sup>2</sup>	3.3458 kg·m <sup>2</sup>	0. kg·m <sup>2</sup>
Moment of Inertia Ip2	8.6598e-004 kg·m <sup>2</sup>	3.3682e-004 kg·m <sup>2</sup>	0. kg·m <sup>2</sup>
Moment of Inertia Ip3	4.6801 kg·m <sup>2</sup>	3.346 kg·m <sup>2</sup>	0. kg·m <sup>2</sup>
Surface Area (approx.)	0.99564 m <sup>2</sup>	0.7265 m <sup>2</sup>	1.e-006 m <sup>2</sup>
<b>Statistics</b>			
Nodes	150	147	0
Elements	148	144	0
Mesh Metric	None		

## Coordinate Systems

**TABLE 7**  
**Model (B4) > Coordinate Systems > Coordinate System**

Object Name	<i>Global Coordinate System</i>
State	Fully Defined
<b>Definition</b>	
Type	Cartesian
Coordinate System ID	0.
<b>Origin</b>	
Origin X	0. m
Origin Y	0. m
Origin Z	0. m
<b>Directional Vectors</b>	
X Axis Data	[ 1. 0. 0. ]
Y Axis Data	[ 0. 1. 0. ]
Z Axis Data	[ 0. 0. 1. ]

## Connections

**TABLE 8**  
**Model (B4) > Connections**

Object Name	<i>Connections</i>
State	Fully Defined
<b>Auto Detection</b>	
Generate Automatic Connection On Refresh	Yes
<b>Transparency</b>	
Enabled	Yes

**TABLE 9**  
**Model (B4) > Connections > Contacts**

Object Name	<i>Contacts</i>
State	Fully Defined
<b>Definition</b>	
Connection Type	Contact
<b>Scope</b>	
Scoping Method	Geometry Selection
Geometry	All Bodies
<b>Auto Detection</b>	
Tolerance Type	Slider
Tolerance Slider	0.
Tolerance Value	1.9453e-002 m
Face/Face	Yes
Face/Edge	No
Edge/Edge	No
Priority	Include All
Group By	Bodies
Search Across	Bodies

**TABLE 10**  
**Model (B4) > Connections > Contacts > Contact Regions**

Object Name	<i>Contact Region</i>	<i>Contact Region</i> 2	<i>Contact Region</i> 3	<i>Contact Region</i> 4	<i>Contact Region</i> 5
State	Fully Defined				
<b>Scope</b>					
Scoping Method	Geometry Selection				
Contact	1 Face				
Target	1 Face	2 Faces		1 Face	
Contact Bodies	Reference Surfaces\Geometrical Set.1[skinIMLTopSurface]				
Target Bodies	Reference Surfaces\Geometrical Set.1 [skinIMLBottomSurface]	Reference Surfaces\Spar Tube Surfaces [Trailing Edge Spar Surface]	Reference Surfaces\Spar Tube Surfaces [Leading Edge Spar Surface]	Reference Surfaces\Spar Tube Surfaces [Spar 1 Surface]	Reference Surfaces\Spar Tube Surfaces [Spar 2 Surface]
Contact Shell Face	Program Controlled				
Target Shell Face	Program Controlled				
<b>Definition</b>					
Type	Bonded				
Scope Mode	Automatic				

Behavior	Symmetric
Suppressed	No
<b>Advanced</b>	
Formulation	Pure Penalty
Normal Stiffness	Program Controlled
Update Stiffness	Never
Pinball Region	Program Controlled

**TABLE 11**  
**Model (B4) > Connections > Contacts > Contact Regions**

Object Name	Contact Region 6	Contact Region 7	Contact Region 8	Contact Region 9	Contact Region 10
State	Fully Defined				
<b>Scope</b>					
Scoping Method	Geometry Selection				
Contact	1 Face				
Target	1 Face				
Contact Bodies	Reference Surfaces\Geometrical Set.1[skinIMLTopSurface]				
Target Bodies	Reference Surfaces\Spar Tube Surfaces [Spar 3 Surface]	Reference Surfaces\Spar Tube Surfaces [Spar 4 Surface]	Reference Surfaces\Spar Tube Surfaces [Spar 5 Surface]	Reference Surfaces\Spar Tube Surfaces [Spar 6 Surface]	Reference Surfaces\Spar Tube Surfaces [Delta Spar 0 Surface]
Contact Shell Face	Program Controlled				
Target Shell Face	Program Controlled				
<b>Definition</b>					
Type	Bonded				
Scope Mode	Automatic				
Behavior	Symmetric				
Suppressed	No				
<b>Advanced</b>					
Formulation	Pure Penalty				
Normal Stiffness	Program Controlled				
Update Stiffness	Never				
Pinball Region	Program Controlled				

**TABLE 12**  
**Model (B4) > Connections > Contacts > Contact Regions**

Object Name	Contact Region 11	Contact Region 12	Contact Region 13	Contact Region 14	Contact Region 15
State	Fully Defined				
<b>Scope</b>					
Scoping Method	Geometry Selection				

Contact	1 Face				
Target	1 Face				
Contact Bodies	Reference Surfaces\Geometrical Set.1[skinIMLTopSurface]				
Target Bodies	Reference Surfaces\Spar Tube Surfaces [Delta Spar 1 Surface]	Reference Surfaces\Spar Tube Surfaces [Delta Spar 2 Surface]	Reference Surfaces\Spar Tube Surfaces [Delta Spar 3 Surface]	Reference Surfaces\Spar Tube Surfaces [Delta Spar 4 Surface]	Reference Surfaces\Spar Tube Surfaces [Delta Spar 5 Surface]
Contact Shell Face	Program Controlled				
Target Shell Face	Program Controlled				
<b>Definition</b>					
Type	Bonded				
Scope Mode	Automatic				
Behavior	Symmetric				
Suppressed	No				
<b>Advanced</b>					
Formulation	Pure Penalty				
Normal Stiffness	Program Controlled				
Update Stiffness	Never				
Pinball Region	Program Controlled				

**TABLE 13**  
**Model (B4) > Connections > Contacts > Contact Regions**

Object Name	<i>Contact Region 16</i>	<i>Contact Region 17</i>	<i>Contact Region 18</i>	<i>Contact Region 19</i>	<i>Contact Region 20</i>
State	Fully Defined				
<b>Scope</b>					
Scoping Method	Geometry Selection				
Contact	1 Face				
Target	1 Face				
Contact Bodies	Reference Surfaces\Geometrical Set.1 [skinIMLTopSurface]	Reference Surfaces\Geometrical Set.1[skinIMLBottomSurface]			
Target Bodies	Reference Surfaces\Spar Tube Surfaces[Delta Spar 6 Surface]	Reference Surfaces\Spar Tube Surfaces [Trailing Edge Spar Surface]	Reference Surfaces\Spar Tube Surfaces [Leading Edge Spar Surface]	Reference Surfaces\Spar Tube Surfaces [Spar 1 Surface]	Reference Surfaces\Spar Tube Surfaces [Spar 2 Surface]
Contact Shell Face	Program Controlled				
Target Shell Face	Program Controlled				
<b>Definition</b>					
Type	Bonded				
Scope Mode	Automatic				

Behavior	Symmetric
Suppressed	No
<b>Advanced</b>	
Formulation	Pure Penalty
Normal Stiffness	Program Controlled
Update Stiffness	Never
Pinball Region	Program Controlled

**TABLE 14**  
**Model (B4) > Connections > Contacts > Contact Regions**

Object Name	Contact Region 21	Contact Region 22	Contact Region 23	Contact Region 24	Contact Region 25
State	Fully Defined				
<b>Scope</b>					
Scoping Method	Geometry Selection				
Contact	1 Face				
Target	1 Face				
Contact Bodies	Reference Surfaces\Geometrical Set.1[skinIMLBottomSurface]				Reference Surfaces\Spar Tube Surfaces[Trailing Edge Spar Surface]
Target Bodies	Reference Surfaces\Spar Tube Surfaces [Spar 3 Surface]	Reference Surfaces\Spar Tube Surfaces [Spar 4 Surface]	Reference Surfaces\Spar Tube Surfaces [Spar 5 Surface]	Reference Surfaces\Spar Tube Surfaces[Spar 6 Surface]	
Contact Shell Face	Program Controlled				
Target Shell Face	Program Controlled				
<b>Definition</b>					
Type	Bonded				
Scope Mode	Automatic				
Behavior	Symmetric				
Suppressed	No				
<b>Advanced</b>					
Formulation	Pure Penalty				
Normal Stiffness	Program Controlled				
Update Stiffness	Never				
Pinball Region	Program Controlled				

**TABLE 15**  
**Model (B4) > Connections > Contacts > Contact Regions**

Object Name	Contact Region 26	Contact Region 27	Contact Region 28	Contact Region 29	Contact Region 30
State	Fully Defined				
<b>Scope</b>					
	Geometry Selection				

Scoping Method					
Contact	2 Faces	1 Face	2 Faces	1 Face	
Target	2 Faces	1 Face	2 Faces	1 Face	
Contact Bodies	Reference Surfaces\Spar Tube Surfaces [Trailing Edge Spar Surface]	Reference Surfaces\Spar Tube Surfaces[Leading Edge Spar Surface]		Reference Surfaces\Spar Tube Surfaces[Spar 1 Surface]	
Target Bodies	Reference Surfaces\Spar Tube Surfaces [Delta Spar 6 Surface]	Reference Surfaces\Spar Tube Surfaces [Spar 1 Surface]	Reference Surfaces\Spar Tube Surfaces [Delta Spar 0 Surface]	Reference Surfaces\Spar Tube Surfaces [Spar 2 Surface]	Reference Surfaces\Spar Tube Surfaces [Delta Spar 0 Surface]
Contact Shell Face	Program Controlled				
Target Shell Face	Program Controlled				
<b>Definition</b>					
Type	Bonded				
Scope Mode	Automatic				
Behavior	Symmetric				
Suppressed	No				
<b>Advanced</b>					
Formulation	Pure Penalty				
Normal Stiffness	Program Controlled				
Update Stiffness	Never				
Pinball Region	Program Controlled				

**TABLE 16**  
**Model (B4) > Connections > Contacts > Contact Regions**

Object Name	Contact Region 31	Contact Region 32	Contact Region 33	Contact Region 34	Contact Region 35
State	Fully Defined				
<b>Scope</b>					
Scoping Method	Geometry Selection				
Contact	2 Faces	1 Face	2 Faces		1 Face
Target	2 Faces	1 Face	2 Faces		1 Face
Contact Bodies	Reference Surfaces\Spar Tube Surfaces [Spar 1 Surface]	Reference Surfaces\Spar Tube Surfaces[Spar 2 Surface]			Reference Surfaces\Spar Tube Surfaces [Spar 3 Surface]
Target Bodies	Reference Surfaces\Spar Tube Surfaces [Delta Spar 1 Surface]	Reference Surfaces\Spar Tube Surfaces [Spar 3 Surface]	Reference Surfaces\Spar Tube Surfaces [Delta Spar 1 Surface]	Reference Surfaces\Spar Tube Surfaces [Delta Spar 2 Surface]	Reference Surfaces\Spar Tube Surfaces [Spar 4 Surface]
Contact Shell Face	Program Controlled				
	Program Controlled				



Target Shell Face	
<b>Definition</b>	
Type	Bonded
Scope Mode	Automatic
Behavior	Symmetric
Suppressed	No
<b>Advanced</b>	
Formulation	Pure Penalty
Normal Stiffness	Program Controlled
Update Stiffness	Never
Pinball Region	Program Controlled

**TABLE 17**  
**Model (B4) > Connections > Contacts > Contact Regions**

Object Name	<i>Contact Region</i> 36	<i>Contact Region</i> 37	<i>Contact Region</i> 38	<i>Contact Region</i> 39	<i>Contact Region</i> 40
State	Fully Defined				
<b>Scope</b>					
Scoping Method	Geometry Selection				
Contact	2 Faces		1 Face	2 Faces	
Target	2 Faces		1 Face	2 Faces	
Contact Bodies	Reference Surfaces\Spar Tube Surfaces[Spar 3 Surface]		Reference Surfaces\Spar Tube Surfaces[Spar 4 Surface]		
Target Bodies	Reference Surfaces\Spar Tube Surfaces [Delta Spar 2 Surface]	Reference Surfaces\Spar Tube Surfaces [Delta Spar 3 Surface]	Reference Surfaces\Spar Tube Surfaces [Spar 5 Surface]	Reference Surfaces\Spar Tube Surfaces [Delta Spar 3 Surface]	Reference Surfaces\Spar Tube Surfaces [Delta Spar 4 Surface]
Contact Shell Face	Program Controlled				
Target Shell Face	Program Controlled				
<b>Definition</b>					
Type	Bonded				
Scope Mode	Automatic				
Behavior	Symmetric				
Suppressed	No				
<b>Advanced</b>					
Formulation	Pure Penalty				
Normal Stiffness	Program Controlled				
Update Stiffness	Never				
Pinball Region	Program Controlled				

**TABLE 18**  
**Model (B4) > Connections > Contacts > Contact Regions**

Object Name	Contact Region 41	Contact Region 42	Contact Region 43	Contact Region 44	Contact Region 45
State	Fully Defined				
<b>Scope</b>					
Scoping Method	Geometry Selection				
Contact	1 Face			2 Faces	
Target	1 Face			2 Faces	
Contact Bodies	Reference Surfaces\Spar Tube Surfaces[Spar 5 Surface]			Reference Surfaces\Spar Tube Surfaces[Spar 6 Surface]	
Target Bodies	Reference Surfaces\Spar Tube Surfaces[Spar 6 Surface]	Reference Surfaces\Spar Tube Surfaces[Delta Spar 4 Surface]	Reference Surfaces\Spar Tube Surfaces[Delta Spar 5 Surface]	Reference Surfaces\Spar Tube Surfaces[Delta Spar 6 Surface]	
Contact Shell Face	Program Controlled				
Target Shell Face	Program Controlled				
<b>Definition</b>					
Type	Bonded				
Scope Mode	Automatic				
Behavior	Symmetric				
Suppressed	No				
<b>Advanced</b>					
Formulation	Pure Penalty				
Normal Stiffness	Program Controlled				
Update Stiffness	Never				
Pinball Region	Program Controlled				

## Mesh

**TABLE 19**  
**Model (B4) > Mesh**

Object Name	Mesh
State	Solved
<b>Defaults</b>	
Physics Preference	Mechanical
Relevance	0
<b>Sizing</b>	
Use Advanced Size Function	On: Curvature
Relevance Center	Coarse
Initial Size Seed	Active Assembly
Smoothing	Low
Span Angle Center	Coarse
Curvature Normal Angle	Default (30.0 °)
Min Size	Default (2.4393e-002 m)
Max Face Size	Default (0.121960 m)
Growth Rate	Default
Minimum Edge Length	1.e-003 m
<b>Inflation</b>	

Use Automatic Inflation	None
Inflation Option	Smooth Transition
Transition Ratio	0.272
Maximum Layers	2
Growth Rate	1.2
Inflation Algorithm	Pre
View Advanced Options	No
<b>Advanced</b>	
Shape Checking	Standard Mechanical
Element Midside Nodes	Program Controlled
Number of Retries	Default (4)
Extra Retries For Assembly	Yes
Rigid Body Behavior	Dimensionally Reduced
Mesh Morphing	Disabled
<b>Defeaturing</b>	
Use Sheet Thickness for Pinch	No
Pinch Tolerance	Default (2.1954e-002 m)
Generate Pinch on Refresh	No
Sheet Loop Removal	No
Automatic Mesh Based Defeaturing	On
Defeaturing Tolerance	Default (1.8295e-002 m)
<b>Statistics</b>	
Nodes	9141
Elements	8688
Mesh Metric	None

## Static Structural (B5)

**TABLE 20**  
**Model (B4) > Analysis**

Object Name	<i>Static Structural (B5)</i>
State	Solved
<b>Definition</b>	
Physics Type	Structural
Analysis Type	Static Structural
Solver Target	Mechanical APDL
<b>Options</b>	
Environment Temperature	22. °C
Generate Input Only	No

**TABLE 21**  
**Model (B4) > Static Structural (B5) > Analysis Settings**

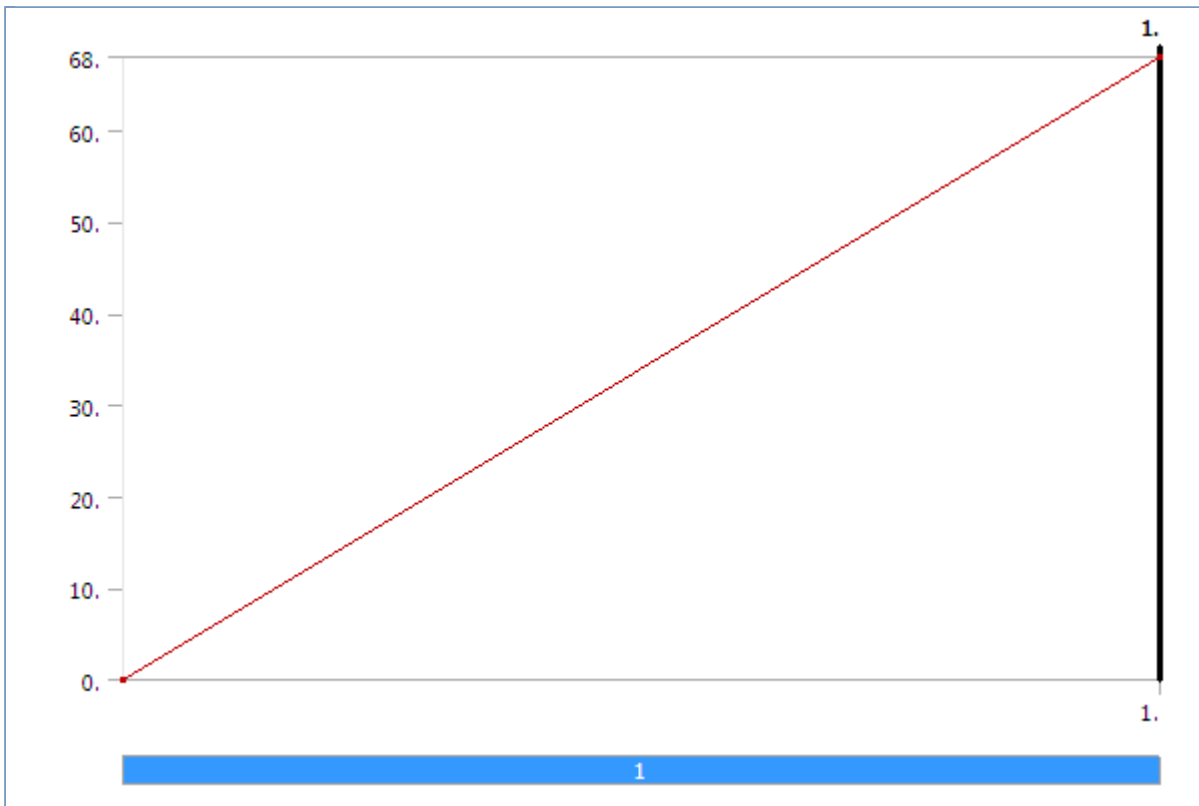
Object Name	<i>Analysis Settings</i>
State	Fully Defined
<b>Step Controls</b>	
Number Of Steps	1.
Current Step Number	1.
Step End Time	1. s
Auto Time Stepping	Program Controlled
<b>Solver Controls</b>	
Solver Type	Program Controlled

Weak Springs	Program Controlled
Large Deflection	Off
Inertia Relief	Off
<b>Restart Controls</b>	
Generate Restart Points	Program Controlled
Retain Files After Full Solve	No
<b>Nonlinear Controls</b>	
Force Convergence	Program Controlled
Moment Convergence	Program Controlled
Displacement Convergence	Program Controlled
Rotation Convergence	Program Controlled
Line Search	Program Controlled
Stabilization	Off
<b>Output Controls</b>	
Calculate Stress	Yes
Calculate Strain	Yes
Calculate Contact	No
Calculate Results At	All Time Points
<b>Analysis Data Management</b>	
Solver Files Directory	C:\TempDoc\Research\Ansys Models\Design5 All Spar\Design5 All Spar_files\dp0\SYS\MECH\
Future Analysis	None
Scratch Solver Files Directory	
Save MAPDL db	No
Delete Unneeded Files	Yes
Nonlinear Solution	No
Solver Units	Active System
Solver Unit System	mks

**TABLE 22**  
**Model (B4) > Static Structural (B5) > Accelerations**

Object Name	<i>Acceleration</i>
State	Fully Defined
<b>Scope</b>	
Geometry	All Bodies
<b>Definition</b>	
Define By	Vector
Magnitude	68. m/s <sup>2</sup> (ramped)
Direction	Defined
Suppressed	No

**FIGURE 1**  
**Model (B4) > Static Structural (B5) > Acceleration**



**TABLE 23**  
**Model (B4) > Static Structural (B5) > Loads**

Object Name	<i>Fixed Support</i>
State	Fully Defined
<b>Scope</b>	
Scoping Method	Geometry Selection
Geometry	23 Edges
<b>Definition</b>	
Type	Fixed Support
Suppressed	No

## **Solution (B6)**

**TABLE 24**  
**Model (B4) > Static Structural (B5) > Solution**

Object Name	<i>Solution (B6)</i>
State	Solved
<b>Adaptive Mesh Refinement</b>	
Max Refinement Loops	1.
Refinement Depth	2.
<b>Information</b>	
Status	Done

**TABLE 25**  
**Model (B4) > Static Structural (B5) > Solution (B6) > Solution Information**

Object Name	<i>Solution Information</i>
State	Solved
<b>Solution Information</b>	

Solution Output	Solver Output
Newton-Raphson Residuals	0
Update Interval	2.5 s
Display Points	All

**TABLE 26**  
**Model (B4) > Static Structural (B5) > Solution (B6) > Results**

Object Name	Total Deformation	Equivalent Elastic Strain	Equivalent Stress	Strain Energy
State	Solved			
<b>Scope</b>				
Scoping Method	Geometry Selection			
Geometry	All Bodies			
Shell	Top/Bottom			
<b>Definition</b>				
Type	Total Deformation	Equivalent (von-Mises) Elastic Strain	Equivalent (von-Mises) Stress	Strain Energy
By	Time			
Display Time	Last			
Calculate Time History	Yes			
Identifier				
<b>Results</b>				
Minimum	0. m	5.4288e-007 m/m	38001 Pa	7.9565e-008 J
Maximum	9.9639e-003 m	5.2604e-004 m/m	3.6823e+007 Pa	0.18695 J
Minimum Occurs On	Reference Surfaces\Geometrical Set.1 [skinIMLTopSurface]	Reference Surfaces\Spar Tube Surfaces[Spar 3 Surface]		Reference Surfaces\Geometrical Set.1 [skinIMLBottomSurface]
Maximum Occurs On	Reference Surfaces\Geometrical Set.1 [skinIMLTopSurface]	Reference Surfaces\Spar Tube Surfaces[Spar 6 Surface]		Reference Surfaces\Spar Tube Surfaces[Trailing Edge Spar Surface]
<b>Information</b>				
Time	1. s			
Load Step	1			
Substep	1			
Iteration Number	1			
<b>Integration Point Results</b>				
Display Option	Averaged			

**TABLE 27**  
**Model (B4) > Static Structural (B5) > Solution (B6) > Stress Safety Tools**

Object Name	Stress Tool 2
State	Solved
<b>Definition</b>	
Theory	Max Equivalent Stress
Stress Limit Type	Tensile Yield Per Material

**TABLE 28**  
**Model (B4) > Static Structural (B5) > Solution (B6) > Stress Tool 2 > Results**

Object Name	Safety Factor	Safety Margin	Stress Ratio
State	Solved		
<b>Scope</b>			
Scoping Method	Geometry Selection		
Geometry	All Bodies		
<b>Definition</b>			
Type	Safety Factor	Safety Margin	Stress Ratio
By	Time		
Display Time	Last		
Calculate Time History	Yes		
Identifier			
<b>Integration Point Results</b>			
Display Option	Averaged		
<b>Results</b>			
Minimum	> 10	> 9	1.4187e-005
Minimum Occurs On	Reference Surfaces\Geometrical Set.1 [skinIMLTopSurface]		Reference Surfaces\Spar Tube Surfaces [Spar 5 Surface]
Maximum			6.4856e-002
Maximum Occurs On			Reference Surfaces\Spar Tube Surfaces [Spar 6 Surface]
<b>Information</b>			
Time	1. s		
Load Step	1		
Substep	1		
Iteration Number	1		

## Material Data

### Carbon/Epoxy Composite Sheet (Smear)

**TABLE 29**  
**Carbon/Epoxy Composite Sheet (Smear) > Constants**

Density	1600 kg m <sup>-3</sup>
Coefficient of Thermal Expansion	2.1e-006 C <sup>-1</sup>

**TABLE 30**  
**Carbon/Epoxy Composite Sheet (Smear) > Compressive Ultimate Strength**

Compressive Ultimate Strength Pa
0

**TABLE 31**  
**Carbon/Epoxy Composite Sheet (Smear) > Compressive Yield Strength**

Compressive Yield Strength Pa
6.e+008

**TABLE 32**  
**Carbon/Epoxy Composite Sheet (Smear) > Tensile Yield Strength**

Tensile Yield Strength Pa
6.e+008

**TABLE 33**  
**Carbon/Epoxy Composite Sheet (Smear) > Tensile Ultimate Strength**

Tensile Ultimate Strength Pa
6.e+008

**TABLE 34**  
**Carbon/Epoxy Composite Sheet (Smear) > Isotropic Secant Coefficient of Thermal Expansion**

Reference Temperature C
22

**TABLE 35**  
**Carbon/Epoxy Composite Sheet (Smear) > Alternating Stress R-Ratio**

Alternating Stress Pa	Cycles	R-Ratio
2.758e+008	1700	-1
2.413e+008	5000	-1
2.068e+008	34000	-1
1.724e+008	1.4e+005	-1
1.379e+008	8.e+005	-1
1.172e+008	2.4e+006	-1
8.963e+007	5.5e+007	-1
8.274e+007	1.e+008	-1
1.706e+008	50000	-0.5
1.396e+008	3.5e+005	-0.5
1.086e+008	3.7e+006	-0.5
8.791e+007	1.4e+007	-0.5
7.757e+007	5.e+007	-0.5
7.239e+007	1.e+008	-0.5
1.448e+008	50000	0
1.207e+008	1.9e+005	0
1.034e+008	1.3e+006	0
9.308e+007	4.4e+006	0
8.618e+007	1.2e+007	0
7.239e+007	1.e+008	0
7.412e+007	3.e+005	0.5
7.067e+007	1.5e+006	0.5
6.636e+007	1.2e+007	0.5
6.205e+007	1.e+008	0.5

**TABLE 36**  
**Carbon/Epoxy Composite Sheet (Smear) > Isotropic Elasticity**

Temperature C	Young's Modulus Pa	Poisson's Ratio	Bulk Modulus Pa	Shear Modulus Pa
	7.e+010	1.e-002	2.381e+010	3.4653e+010

## *Aluminum Alloy*

**TABLE 37**  
**Aluminum Alloy > Constants**

Density	2770 kg m <sup>-3</sup>
Coefficient of Thermal Expansion	2.3e-005 C <sup>-1</sup>
Specific Heat	875 J kg <sup>-1</sup> C <sup>-1</sup>



**TABLE 38**  
**Aluminum Alloy > Compressive Ultimate Strength**

Compressive Ultimate Strength Pa
0

**TABLE 39**  
**Aluminum Alloy > Compressive Yield Strength**

Compressive Yield Strength Pa
2.8e+008

**TABLE 40**  
**Aluminum Alloy > Tensile Yield Strength**

Tensile Yield Strength Pa
2.8e+008

**TABLE 41**  
**Aluminum Alloy > Tensile Ultimate Strength**

Tensile Ultimate Strength Pa
3.1e+008

**TABLE 42**  
**Aluminum Alloy > Isotropic Secant Coefficient of Thermal Expansion**

Reference Temperature C
22

**TABLE 43**  
**Aluminum Alloy > Isotropic Thermal Conductivity**

Thermal Conductivity W m <sup>-1</sup> C <sup>-1</sup>	Temperature C
114	-100
144	0
165	100
175	200

**TABLE 44**  
**Aluminum Alloy > Alternating Stress R-Ratio**

Alternating Stress Pa	Cycles	R-Ratio
2.758e+008	1700	-1
2.413e+008	5000	-1
2.068e+008	34000	-1
1.724e+008	1.4e+005	-1
1.379e+008	8.e+005	-1
1.172e+008	2.4e+006	-1
8.963e+007	5.5e+007	-1
8.274e+007	1.e+008	-1
1.706e+008	50000	-0.5
1.396e+008	3.5e+005	-0.5
1.086e+008	3.7e+006	-0.5
8.791e+007	1.4e+007	-0.5
7.757e+007	5.e+007	-0.5
7.239e+007	1.e+008	-0.5
1.448e+008	50000	0
1.207e+008	1.9e+005	0
1.034e+008	1.3e+006	0
9.308e+007	4.4e+006	0

8.618e+007	1.2e+007	0
7.239e+007	1.e+008	0
7.412e+007	3.e+005	0.5
7.067e+007	1.5e+006	0.5
6.636e+007	1.2e+007	0.5
6.205e+007	1.e+008	0.5

**TABLE 45**  
**Aluminum Alloy > Isotropic Resistivity**

Resistivity ohm m	Temperature C
2.43e-008	0
2.67e-008	20
3.63e-008	100

**TABLE 46**  
**Aluminum Alloy > Isotropic Elasticity**

Temperature C	Young's Modulus Pa	Poisson's Ratio	Bulk Modulus Pa	Shear Modulus Pa
	7.1e+010	0.33	6.9608e+010	2.6692e+010

**TABLE 47**  
**Aluminum Alloy > Isotropic Relative Permeability**

Relative Permeability
1

## APPENDIX C

### GRUMMAN AEROSPACE CORPORATION'S HAND LAYUP PROCESS BREAKDOWN

## 2.1 GRAPHITE/EPOXY FABRICATION

### 2.1.1 Lay-Up Elements

#### 2.1.1.1 Preparation (Setup)

- Obtaining material from freezer storage area
- Normalizing material to room temperature
- Recording Lot, Batch & Roll No. in log book
- Installing roll in dispenser at work station

#### 2.1.1.2 Mylar Preparation

- Obtaining the designated mylar template
- Positioning mylar template on light table
- Taping outer template perimeter to light table
- Cleaning template surfaces
- Applying release agent to template surfaces

#### 2.1.1.3 Ply Lay-Up (Manual)

- Deposition of composite material onto mylar template(s) to template layout lines
- Simultaneous removal of backing tape, butting edges to previous strip and manually dewrinkling
- Trimming both ends of layout line of template

#### 2.1.1.4 Application of Temporary Film Covers

- Cutting off and application of protective polyethylene sheet over each layout
- Sequentially stacking of mylar/plies

#### 2.1.1.5 Ply Transfer to Master Stacking Template

- 
- Preparing master stacking template by cleaning and applying release agent
- Sequentially inverting each laid-up mylar, transferring to master tool and aligning to previously stacked lay-up
- This sequence is repeated until the maximum quantity of lay-ups for compacting is stacked (dependent on part configuration)

#### 2.1.1.6 Compacting In Flat State

- Preparing compacting tool by cleaning and application of release agent to cavity area of tool
- Fabricating two pieces of separator cloth for top and bottom of ply stack (Teflon impregnated cloth)
- 
- Fabricating one piece of 116/120 fiberglass bleeder for top of ply stack
- 
- Application of one separator cloth into tool cavity and trimming to size
- Transfer of laid-up plies from master tool into vacuum table
- 
- Application of one separator cloth and one fiberglass bleeder over lay-up
- Trimming material to size
- Cutting of plastic (disposable) vacuum bag material
- Application of sealing tape to fixture flanges
- Application of vacuum bag over lay-up onto sealing tape
- Applying vacuum

- Compressing vacuum bag edges to sealing tape to maintain vacuum
  - Utilizing a heat source, Stacked plies to dewrinkle
  - Allowing stack to cool
  - Removing vacuum bag, fiberglass sheet and separator cloth
  - Adding of additional stacks atop and repeating process
- 2.1.2 Forming Composites for Sine Wave Plain Web Channels
- Preheating, cleaning of tool and application of release agent
  - Application of fiberglass and peel ply up to tool flange on fixture
  - Apply separator film to tool
  - Apply bleeder system onto tool (plain web)
  - Apply lay-up onto tool (plain web)
  - Corrugate bleeder system onto tool (sine wave)
- 
- Rough forming of lay-up into sine wave configuration on corrugate fixture, simultaneously removing separator film during cycle
  - Application of steel rollers to sine wave web areas (sine wave)
  - Transferring tool lay-up to vacuum assist table
  - Silicone ridder baggin of assembly, and clamping of strips atop bag edges to seal
  - Vacuum application and forming of flanges and corrugations
  - Vacuum release, debuggin and lay-up checking
  - Repeating procedures for mating half of channel
- 
- Assembly of chennel halves fit and clamping of halves together as mates
  - Application of rope adhesive to fill gaps
- 2.1.3 Pre-Cured Trimming
- Setting and locating of trimming tamplate atop stack/tool
  - Manual trimming of plies to template outline
  - Trimming stack removal
- 2.1.4 Fabrication and Application of Bleeder System
- 2.1.4.1 Material Cutting
- Cut peel cly
  - Cut teflon impregnated separator cloth
  - Cut fiberglass bleeder cloth - quantity of plies utilized dependent upon number of plies in lay-up for purposes of maintaining bleeder cloth to laid-up plies ratio
  - Cut 0.015 thick silicone rubber sheet (sine wave spars only)
  - Cut scrim sloth (sine wave spars only)
  - Cut nylon disposable vacuum bag
- 2.1.4.2 Lay-Up Tool Preparation
- Heating and cleaning of lay-up tool to remove residue from previous curing operation
  - Release agent application
- 2.1.4.3 System Preparation

- Stacking and collating into sets of pre-cut bleeder system material in correct sequence of functional usage, and application to top and bottom of laid-up ply stack
- 
- Recutting of stacked/collated bleeder plies to finished part configuration using template or layout lines/straight edge method
- 2.1.4.4 System Application
  - Setting in of either flat or roll corrugating in one collated set of bleeders into tool cavity
  - Setting of laid-up stacked plies atop bleeders
  - Setting atop stacked plies of second set of bleeder plies (step is applicable only to web regions of parts shown in Table 1)
- 2.1.4.5 Vacuum Bag Application
  - Application of sealing tape to tool flanges
  - Draping of nylon vacuum bag over tool/lay-up onto sealing tape
  - Vacuum application
  - Compressing of vacuum bag edges to sealing tape to seal, using heat gun and roller
- 2.1.5 Autoclave Curing Operation
  - Checking of autoclave interior
  - Placing vacuum bagged detail/lay-up tool onto transfer car
  - Connecting thermocouple leads
  - Connecting vacuum lines and applying vacuum pressure
  - Rechecking vacuum bag sealing and fittings
  - Moving of transfer car with detail part(s) into autoclave
  - Closing autoclave door
  - Setting of curing cycle recorders
  - Starting of curing cycle
  - Part(s) curing per cycled procedures
  - Monitoring of curing cycle to assure adherence to procedures
  - Upon completing of cycle, system shut down
  - Removal of completed curing cycle charts
  - Opening of autoclave door
  - Disconnecting thermocouple leads
  - Disconnecting vacuum lines
  - Rolling transfer car/vacuum bagged parts to debagging area
  - Removing fixture(s)/bagged lay-up(s) from transfer car table
  - 
  - Removing vacuum bag, sealing tape, bleeder system from atop detail part
  - Removing part from tool
  - Removing bleeder system from tool cavity
  - Discarding vacuum bag, bleeder system plies
  - Returning lay-up tool(s) and completed part(s) to designated areas
- 2.1.6 Autoclave Post-Curing Operation
  - Checking of autoclave interior
  - Placing detail part onto transfer car table

- Moving of transfer car with detail part(s) into autoclave
- Closing autoclave door
- Setting of post-curing cycle recorders
- Starting of post-curing cycle
- Part(s) post-cured per cycled procedures
- Monitoring of post-curing cycle to assure adherence to procedures
- Upon completing of cycle, system shutdown
- Removal of completed post-curing cycle charts
- Opening of autoclave door
- Rolling transfer car with work piece(s) out of oven
- Removing work piece(s) from transfer car
- Returning post-cured part(s) to designated areas

## 2.1 FIBERGLASS REINFORCED PLASTIC

### 2.2.1 Material Cutting (Initial Cut)

- Walk to and from material dispensing/cutting area
- Unroll material into table from dispenser
- Flatten material on table for cutting
- Measure to specified length
- Mark two places for cutting
- Using straight edge, align to marks
- Cut prepreg fiberglass material to length
- Put aside cut piece for stacking

### 2.2.2 Material Cutting (Secondary Cut)

- Pick up pre-cut piece(s) from stack
- Set piece(s) on cutting table
- Measure and mark for specified width or length
- Locate template atop piece(s)
- Cut material to specified width or configuration
- Put aside cut piece(s) for stacking
- Move cut/stacked pieces to lay-up area

### 2.2.3 Lay-Up of Prepreg Piles

- Heating and cleaning of lay-up tool - application of release agent to tool surfaces
- Removal of one pre-cut prepreg piece of ply from stack
- Removal of backing paper from ply
- Aligning edge or centralizing ply on ply-on lay-up tool
- Draping of ply material over tool, manually compressing edges or surfaces to adhere to tool surfaces
- Molding of material onto tool surfaces including:
  - - Using teflon wiper and roller to dewrinkle surfaces
  - - Using utility knife during molding for trimming and removing overlap excess and arrowheads in corners
  - - Trimming of excess material from tool edge periphery

### 2.2.4 Repeating previous procedures until specified layers of plies are laid-up Compacting of plies

- Walk to and from material dispenser area
- Cutting off sufficient material to fabricate vacuum bag
- Application of sealing tape to tool flanges
- Draping vacuum bag material over lay-up, manually compressing material to sealing tape
- Hooking up vacuum line to fixture fitting
- Applying vacuum
- Using heat gun and roller, heating outer areas of vacuum bag atop sealing tape and compressing areas to seal in vacuum
- Using teflon wiper and roller, compacting seam areas and corner radii to blend
- Vacuum bag removal
- Removing of excess material in areas of lapped edges and corners utilizing utility knife
- Repeating previous procedures after each four ply lay-up (variable - dependt on tool/part complexity)

#### 2.2.5 Bleeder System Material Cutting (Initial Cut)

- Walking to and from material dispenser area
- Unrolling of bleeder material from dispenser onto table
- Measuring material to specified length
- Marking two pieces for cutting
- Using straight edge, alligning to marks
- Cutting of bleeder cloth and peel ply material
- Placing aside or stacking cut piece

#### 2.2.6 Bleeder System Material Cutting (Secondary Cut)

- Picking up of pre-cut piece(s) of bleeder cloth or peel ply material from stack
- Setting of piece(s) on cutting table
- Measuring, marking for specified width
- Locating template atop piece(s)
- Cutting material to specified width or configuration
- Placing aside or stacking of cut piece(s)
- Moving cut/stacked pieces to vacuum bagging area

#### 2.2.7 Bleeder System Application and Vacuum Bagging

- Cutting of sufficient length and width of vacuum bag material to cover lay-up
- Setting in of peel/bleeder plies atop laid-up part
- Trimming of excess bleeder colth material
- Applying of sealing tape to flange edges
- 
- Draping vacuum bag over lay-up, compressing edges to sealing tape
- Cutting and application of sealing tape to vacuum bag edges when necessary tp splice
- Hooking up of vacuum line to work table, vacuum application
- Compression of vacum bag edges to sealing tape, using heat gun, roll to seal
- Disconnecting vacuum line



- Moving of work table, tool and bagged lay-up to autoclave area
- 2.2.8 Autoclave Curing Operation
- Checking of autoclave interior
  - Placing vacuum bagged detail/lay-up tool onto transfer car
  - Connecting thermocouple leads
  - Connecting vacuum lines and applying vacuum pressure
  - Rechecking vacuum bag sealing and fittings
  - Moving of transfer car with detail part(s) into autoclave
  - Closing autoclave door
  - Setting of curing cycle recorders
  - Starting of curing cycle
  - Part(s) curing per cycle procedures
  - Monitor of curing cycle to assure adherence to procedures
  - Upon completion of cycle, system shut down
  - Removal of completed curing cycle charts
  - Opening of autoclave door
  - Disconnecting thermocouple leads
  - Disconnecting vacuum lines
  - Rolling transfer car/vacuum bagged parts to debuggng area
  - Removing fixtures.bagged lay-ups from transfer car table and setting on work table
  - Removing vacuum bag, sealing tape, bleeder system from atop detail part and discarding
  - Setting tool part on roll cart and moving to lay-up area
  - Removing part from tool
  - Returning lay-up.curing tool and completed part to designated areas

2.3 CORE DATA (ALUMINUM/NOMEX)

2.3.1 Bandsawing

- Walking to and from storage area to obtain core panel or section(s)
- Identifying and tagging core sections
- Heating in oven for core stabilization
- Application of masking tape to core for layout lines
- Clamping of template atop core section
- Marking core outline on masking tape using template
- Template removal after layout of outline
- Off-setting of bandsaw table to obtain correct face angle
- Bandsawing of edge(s) to layout line/template outline
- Repositioning of clamps for bandsawing remaining face(s)
- Vacuum cleaning and repackaging of core sections

2.3.2 Core machining

- Table routing undercuts or steps in core
- Table routing chamfers on step edges
- Table routing using indexing fixture, valve stem cutter and machining outer surfaces to shape (scarf)
- Sanding chamfer

- Manual routing using guide bar.locating pins on fixture for machining undercuts
- Bandsawing of cutouts outlined on masking tape
- Numerically controlled contour machining of assembled core sections
- Guide roller/template automatic indexing contour machining
- Multiple part machining, by means of hydraulically assisted multispindle equipment, template.light beam path control

### 2.3.3

#### Additional Core Operations

- Potting (powder form)
- Adhesive tape application
- Hand/power break forming
- Core section assembly into fixture/skin

## APPENDIX D

### MICROSOFT VISUAL BASIC REFERENCE ENGINE FOR MAXIMOST TIME MEASUREMENT KNOWLEDGE DATABASE

```

Private Sub Worksheet_SelectionChange(ByVal Target As Range)
'*****
'Created by Apinut Sirirojvisuth
'03/12/2009
'VBA for A-Action Distance
'This section provide list of appropriate values for range K4
  If Range("J4").Value = "Feet" Then
    'Range("K4:L4").ClearContents
    With Range("K4").Validation
      .Delete
      .Add Type:=xlValidateList, AlertStyle:=xlValidAlertStop, Operator:= _
        xlBetween, Formula1:="=$B$4:$B$21"
      .IgnoreBlank = True
      .InCellDropdown = True
      .InputTitle = ""
      .ErrorTitle = ""
      .InputMessage = ""
      .ErrorMessage = ""
      .ShowInput = True
      .ShowError = True
    End With
    Range("L4").FormulaR1C1 = "=VLOOKUP(RC[-1],RC[-10]:R[17]C[-7],4,FALSE)"
  Else
    If Range("J4").Value = "Meters" Then
      'Range("K4:L4").ClearContents
      With Range("K4").Validation
        .Delete
        .Add Type:=xlValidateList, AlertStyle:=xlValidAlertStop, Operator:= _
          xlBetween, Formula1:="=$C$4:$C$21"
        .IgnoreBlank = True
        .InCellDropdown = True
        .InputTitle = ""
        .ErrorTitle = ""
        .InputMessage = ""
        .ErrorMessage = ""
        .ShowInput = True
        .ShowError = True
      End With
      Range("L4").FormulaR1C1 = "=VLOOKUP(RC[-1],RC[-9]:R[17]C[-7],3,FALSE)"
    Else
      If Range("J4").Value = "Steps" Then
        'Range("K4:L4").ClearContents
        With Range("K4").Validation
          .Delete
          .Add Type:=xlValidateList, AlertStyle:=xlValidAlertStop, Operator:= _
            xlBetween, Formula1:="=$D$4:$D$21"
          .IgnoreBlank = True
          .InCellDropdown = True
          .InputTitle = ""
          .ErrorTitle = ""
          .InputMessage = ""
          .ErrorMessage = ""
          .ShowInput = True
          .ShowError = True
        End With
        Range("L4").FormulaR1C1 = "=VLOOKUP(RC[-1],RC[-8]:R[17]C[-7],2,FALSE)"
      Else
        MsgBox ("The index value cannot be found")
      End If
    End If
  End If
End Sub

```

```

Private Sub Worksheet_SelectionChange(ByVal Target As Range)
'*****
'Created by Apinut Sirirojvisuth
'03/12/2009
'VBA for B-Body Motion

    If Range("J13").Value = "Vertical Motions" Then
        With Range("K13").Validation
            .Delete
            .Add Type:=xlValidateList, AlertStyle:=xlValidAlertStop, Operator:= _
                xlBetween, Formula1:="=$C$3:$C$15"
            .IgnoreBlank = True
            .InCellDropdown = True
            .InputTitle = ""
            .ErrorTitle = ""
            .InputMessage = ""
            .ErrorMessage = ""
            .ShowInput = True
            .ShowError = True
        End With
    Else
        If Range("J13").Value = "Pass Through Openings" Then
            With Range("K13").Validation
                .Delete
                .Add Type:=xlValidateList, AlertStyle:=xlValidAlertStop, Operator:= _
                    xlBetween, Formula1:="=$C$16:$C$21"
                .IgnoreBlank = True
                .InCellDropdown = True
                .InputTitle = ""
                .ErrorTitle = ""
                .InputMessage = ""
                .ErrorMessage = ""
                .ShowInput = True
                .ShowError = True
            End With
        Else
            If Range("J13").Value = "Combined Body Motions" Then
                With Range("K13").Validation
                    .Delete
                    .Add Type:=xlValidateList, AlertStyle:=xlValidAlertStop, Operator:= _
                        xlBetween, Formula1:="=$C$22:$C$30"
                    .IgnoreBlank = True
                    .InCellDropdown = True
                    .InputTitle = ""
                    .ErrorTitle = ""
                    .InputMessage = ""
                    .ErrorMessage = ""
                    .ShowInput = True
                    .ShowError = True
                End With
            Else
                If Range("J13").Value = "Ladder with Light Load" Then
                    With Range("K13").Validation
                        .Delete
                        .Add Type:=xlValidateList, AlertStyle:=xlValidAlertStop, Operator:= _
                            xlBetween, Formula1:="=$C$31:$C$33"
                        .IgnoreBlank = True
                        .InCellDropdown = True
                        .InputTitle = ""
                        .ErrorTitle = ""
                        .InputMessage = ""
                        .ErrorMessage = ""
                        .ShowInput = True
                        .ShowError = True
                    End With
                Else
                    If Range("J13").Value = "Ladder with Heavy Load" Then
                        With Range("K13").Validation
                            .Delete
                            .Add Type:=xlValidateList, AlertStyle:=xlValidAlertStop, Operator:= _
                                xlBetween, Formula1:="=$C$34:$C$37"
                            .IgnoreBlank = True
                            .InCellDropdown = True

```

```

        .InputTitle = ""
        .ErrorTitle = ""
        .InputMessage = ""
        .ErrorMessage = ""
        .ShowInput = True
        .ShowError = True
    End With
Else
If Range("J13").Value = "Obstructed Ladder with Light Load" Then
    With Range("K13").Validation
        .Delete
        .Add Type:=xlValidateList, AlertStyle:=xlValidAlertStop, Operator:= _
            xlBetween, Formula1:="=$C$38:$C$40"
        .IgnoreBlank = True
        .InCellDropdown = True
        .InputTitle = ""
        .ErrorTitle = ""
        .InputMessage = ""
        .ErrorMessage = ""
        .ShowInput = True
        .ShowError = True
    End With
Else
If Range("J13").Value = "Obstructed Ladder with Heavy Load" Then
    With Range("K13").Validation
        .Delete
        .Add Type:=xlValidateList, AlertStyle:=xlValidAlertStop, Operator:= _
            xlBetween, Formula1:="=$C$41:$C$43"
        .IgnoreBlank = True
        .InCellDropdown = True
        .InputTitle = ""
        .ErrorTitle = ""
        .InputMessage = ""
        .ErrorMessage = ""
        .ShowInput = True
        .ShowError = True
    End With
Else
    MsgBox ("No Match")
End If
End If
End If
End If
End If
End If
End If
End If
Range("L13").FormulaR1C1 = "=VLOOKUP(RC[-1],R[-10]C[-9]:R[30]C[-8],2,FALSE)"
End Sub

```

```

Private Sub Worksheet_SelectionChange(ByVal Target As Range)
'*****
'Created by Apinut Sirirojvisuth
'03/12/2009
'VBA for P-Part Handling

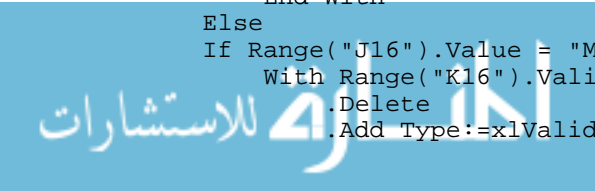
'-----For Range"J16" - Part Handling Type-----

    With Range("J16").Validation
        .Delete
        .Add Type:=xlValidateList, AlertStyle:=xlValidAlertStop, Operator:= _
xlBetween, Formula1:="=$B$84:$B$90"
        .IgnoreBlank = True
        .InCellDropdown = True
        .InputTitle = ""
        .ErrorTitle = ""
        .InputMessage = ""
        .ErrorMessage = ""
        .ShowInput = True
        .ShowError = True
    End With

'-----For Range"K16" - Object size-----

    If Range("J16").Value = "Handle Parts" Then
        With Range("K16").Validation
            .Delete
            .Add Type:=xlValidateList, AlertStyle:=xlValidAlertStop, Operator:= _
xlBetween, Formula1:="=$C$84:$C$86"
            .IgnoreBlank = True
            .InCellDropdown = True
            .InputTitle = ""
            .ErrorTitle = ""
            .InputMessage = ""
            .ErrorMessage = ""
            .ShowInput = True
            .ShowError = True
        End With
    Else
    If Range("J16").Value = "Handle Parts with Adjustments" Then
        With Range("K16").Validation
            .Delete
            .Add Type:=xlValidateList, AlertStyle:=xlValidAlertStop, Operator:= _
xlBetween, Formula1:="=$C$84:$C$86"
            .IgnoreBlank = True
            .InCellDropdown = True
            .InputTitle = ""
            .ErrorTitle = ""
            .InputMessage = ""
            .ErrorMessage = ""
            .ShowInput = True
            .ShowError = True
        End With
    Else
    If Range("J16").Value = "Move < 12in (30 cm)" Then
        With Range("K16").Validation
            .Delete
            .Add Type:=xlValidateList, AlertStyle:=xlValidAlertStop, Operator:= _
xlBetween, Formula1:="=$C$87:$C$89"
            .IgnoreBlank = True
            .InCellDropdown = True
            .InputTitle = ""
            .ErrorTitle = ""
            .InputMessage = ""
            .ErrorMessage = ""
            .ShowInput = True
            .ShowError = True
        End With
    Else
    If Range("J16").Value = "Move with Adjustments < 12 in (30 cm)" Then
        With Range("K16").Validation
            .Delete
            .Add Type:=xlValidateList, AlertStyle:=xlValidAlertStop, Operator:= _

```



```

        xlBetween, Formula1:="=$C$87:$C$89"
        .IgnoreBlank = True
        .InCellDropdown = True
        .InputTitle = ""
        .ErrorTitle = ""
        .InputMessage = ""
        .ErrorMessage = ""
        .ShowInput = True
        .ShowError = True
    End With
Else
If Range("J16").Value = "Move > 12in (30 cm)" Then
    With Range("K16").Validation
        .Delete
        .Add Type:=xlValidateList, AlertStyle:=xlValidAlertStop, Operator:= _
xlBetween, Formula1:="=$C$90:$C$91"
        .IgnoreBlank = True
        .InCellDropdown = True
        .InputTitle = ""
        .ErrorTitle = ""
        .InputMessage = ""
        .ErrorMessage = ""
        .ShowInput = True
        .ShowError = True
    End With
Else
If Range("J16").Value = "Move with Adjustments > 12 in (30 cm)" Then
    With Range("K16").Validation
        .Delete
        .Add Type:=xlValidateList, AlertStyle:=xlValidAlertStop, Operator:= _
xlBetween, Formula1:="=$C$90:$C$91"
        .IgnoreBlank = True
        .InCellDropdown = True
        .InputTitle = ""
        .ErrorTitle = ""
        .InputMessage = ""
        .ErrorMessage = ""
        .ShowInput = True
        .ShowError = True
    End With
Else
If Range("J16").Value = "Line Handling" Then
    Range("K16").Value = "-----"
End If
End If
End If
End If
End If
End If
End If
End If

```

'-----For Range"L16" - Handling Activity-----'

```

If Range("K16").Value = "Small" Then
    Range("L16").Value = "Pickup or Hold and Move"
Else
If Range("K16").Value = "Light or Medium Size and Weight" Then
    With Range("L16").Validation
        .Delete
        .Add Type:=xlValidateList, AlertStyle:=xlValidAlertStop, Operator:= _
xlBetween, Formula1:="=$D$85:$D$87"
        .IgnoreBlank = True
        .InCellDropdown = True
        .InputTitle = ""
        .ErrorTitle = ""
        .InputMessage = ""
        .ErrorMessage = ""
        .ShowInput = True
        .ShowError = True
    End With
Else
If Range("K16").Value = "Medium or Heavy Weight" Then
If Range("J16").Value = "Handle Parts" Then

```



```

        Range("L16").Value = "Position"
    Else
    If Range("J16").Value = "Handle Parts with Adjustments" Then
        Range("L16").Value = "Position"
    Else
        Range("L16").Value = "Draw"
    End If
    End If
End If
End If
End If
If Range("K16").Value = "Small, Light or Medium Size and Weight" Then
    Range("L16").Value = "Shove"
End If
If Range("K16").Value = "Heavy, Large and Bulky" Then
    With Range("L16").Validation
        .Delete
        .Add Type:=xlValidateList, AlertStyle:=xlValidAlertStop, Operator:= _
xlBetween, Formula1:="=$D$91:$D$92"
        .IgnoreBlank = True
        .InCellDropdown = True
        .InputTitle = ""
        .ErrorTitle = ""
        .InputMessage = ""
        .ErrorMessage = ""
        .ShowInput = True
        .ShowError = True
    End With
End If
If Range("K16").Value = "Light Weight Cart, Conveyor Table" Then
    Range("L16").Value = "Push or Pull"
End If
If Range("K16").Value = "Medium or Heavy Weight Rails, Conveyor Table" Then
    Range("L16").Value = "Slide"
End If
If Range("J16").Value = "Line Handling" Then
    With Range("L16").Validation
        .Delete
        .Add Type:=xlValidateList, AlertStyle:=xlValidAlertStop, Operator:= _
xlBetween, Formula1:="=$D$95:$D$96"
        .IgnoreBlank = True
        .InCellDropdown = True
        .InputTitle = "What Kind?"
        .ErrorTitle = "Wrong Input"
        .InputMessage = "Please select between two options"
        .ErrorMessage = "This option is not possible"
        .ShowInput = True
        .ShowError = True
    End With
End If

```

'-----For Range"M16" - Handling Activity-----'

'-----Handle Parts-----'

```

If Range("J16").Value = "Handle Parts" Then
    Range("M15").Value = "Number of Actions"
    If Range("L16").Value = "Pickup or Hold and Move" Then
        With Range("M16").Validation
            .Delete
            .Add Type:=xlValidateList, AlertStyle:=xlValidAlertStop, Operator:= _
xlBetween, Formula1:="=$E$3:$E$4"
            .IgnoreBlank = True
            .InCellDropdown = True
            .InputTitle = ""
            .ErrorTitle = ""
            .InputMessage = ""
            .ErrorMessage = ""
            .ShowInput = True
            .ShowError = True
        End With
    Else
    If Range("L16").Value = "Collect and Move" Then
        With Range("M16").Validation
            .Delete

```

```

.Add Type:=xlValidateList, AlertStyle:=xlValidAlertStop, Operator:= _
xlBetween, Formula1:="=$E$5:$E$7"
.IgnoreBlank = True
.InCellDropdown = True
.InputTitle = ""
.ErrorTitle = ""
.InputMessage = ""
.ErrorMessage = ""
.ShowInput = True
.ShowError = True
End With
Else
If Range("L16").Value = "Put" Then
With Range("M16").Validation
.Delete
.Add Type:=xlValidateList, AlertStyle:=xlValidAlertStop, Operator:= _
xlBetween, Formula1:="=$E$8:$E$10"
.IgnoreBlank = True
.InCellDropdown = True
.InputTitle = ""
.ErrorTitle = ""
.InputMessage = ""
.ErrorMessage = ""
.ShowInput = True
.ShowError = True
End With
Else
If Range("L16").Value = "Place" Then
With Range("M16").Validation
.Delete
.Add Type:=xlValidateList, AlertStyle:=xlValidAlertStop, Operator:= _
xlBetween, Formula1:="=$E$11:$E$14"
.IgnoreBlank = True
.InCellDropdown = True
.InputTitle = ""
.ErrorTitle = ""
.InputMessage = ""
.ErrorMessage = ""
.ShowInput = True
.ShowError = True
End With
Else
If Range("L16").Value = "Position" Then
With Range("M16").Validation
.Delete
.Add Type:=xlValidateList, AlertStyle:=xlValidAlertStop, Operator:= _
xlBetween, Formula1:="=$E$15:$E$18"
.IgnoreBlank = True
.InCellDropdown = True
.InputTitle = ""
.ErrorTitle = ""
.InputMessage = ""
.ErrorMessage = ""
.ShowInput = True
.ShowError = True
End With
End If
End If
End If
End If
End If
End If
'-----Handle Parts with Adjustments-----
If Range("J16").Value = "Handle Parts with Adjustments" Then
Range("M15").Value = "Number of Actions"
If Range("L16").Value = "Pickup or Hold and Move" Then
With Range("M16").Validation
.Delete
.Add Type:=xlValidateList, AlertStyle:=xlValidAlertStop, Operator:= _
xlBetween, Formula1:="=$E$19:$E$20"
.IgnoreBlank = True
.InCellDropdown = True
.InputTitle = ""

```

```

        .ErrorTitle = ""
        .InputMessage = ""
        .ErrorMessage = ""
        .ShowInput = True
        .ShowError = True
    End With
Else
If Range("L16").Value = "Collect and Move" Then
    With Range("M16").Validation
        .Delete
        .Add Type:=xlValidateList, AlertStyle:=xlValidAlertStop, Operator:= _
xlBetween, Formula1:="=$E$21:$E$22"
        .IgnoreBlank = True
        .InCellDropdown = True
        .InputTitle = ""
        .ErrorTitle = ""
        .InputMessage = ""
        .ErrorMessage = ""
        .ShowInput = True
        .ShowError = True
    End With
Else
If Range("L16").Value = "Put" Then
    With Range("M16").Validation
        .Delete
        .Add Type:=xlValidateList, AlertStyle:=xlValidAlertStop, Operator:= _
xlBetween, Formula1:="=$E$23:$E$25"
        .IgnoreBlank = True
        .InCellDropdown = True
        .InputTitle = ""
        .ErrorTitle = ""
        .InputMessage = ""
        .ErrorMessage = ""
        .ShowInput = True
        .ShowError = True
    End With
Else
If Range("L16").Value = "Place" Then
    With Range("M16").Validation
        .Delete
        .Add Type:=xlValidateList, AlertStyle:=xlValidAlertStop, Operator:= _
xlBetween, Formula1:="=$E$26:$E$27"
        .IgnoreBlank = True
        .InCellDropdown = True
        .InputTitle = ""
        .ErrorTitle = ""
        .InputMessage = ""
        .ErrorMessage = ""
        .ShowInput = True
        .ShowError = True
    End With
Else
If Range("L16").Value = "Position" Then
    With Range("M16").Validation
        .Delete
        .Add Type:=xlValidateList, AlertStyle:=xlValidAlertStop, Operator:= _
xlBetween, Formula1:="=$E$28:$E$30"
        .IgnoreBlank = True
        .InCellDropdown = True
        .InputTitle = ""
        .ErrorTitle = ""
        .InputMessage = ""
        .ErrorMessage = ""
        .ShowInput = True
        .ShowError = True
    End With
End If
End If
End If
End If
End If
End If
End If

```

```

'-----Move < 12in (30 cm)-----
If Range("J16").Value = "Move < 12in (30 cm)" Then
  Range("M15").Value = "Number of Actions"
  If Range("L16").Value = "Shove" Then
    With Range("M16").Validation
      .Delete
      .Add Type:=xlValidateList, AlertStyle:=xlValidAlertStop, Operator:= _
xlBetween, Formulas:="$E$31:$E$32"
      .IgnoreBlank = True
      .InCellDropdown = True
      .InputTitle = ""
      .ErrorTitle = ""
      .InputMessage = ""
      .ErrorMessage = ""
      .ShowInput = True
      .ShowError = True
    End With
  Else
    If Range("L16").Value = "Draw" Then
      With Range("M16").Validation
        .Delete
        .Add Type:=xlValidateList, AlertStyle:=xlValidAlertStop, Operator:= _
xlBetween, Formulas:="$E$33:$E$35"
        .IgnoreBlank = True
        .InCellDropdown = True
        .InputTitle = ""
        .ErrorTitle = ""
        .InputMessage = ""
        .ErrorMessage = ""
        .ShowInput = True
        .ShowError = True
      End With
    Else
      If Range("L16").Value = "Situate" Then
        With Range("M16").Validation
          .Delete
          .Add Type:=xlValidateList, AlertStyle:=xlValidAlertStop, Operator:= _
xlBetween, Formulas:="$E$36:$E$39"
          .IgnoreBlank = True
          .InCellDropdown = True
          .InputTitle = ""
          .ErrorTitle = ""
          .InputMessage = ""
          .ErrorMessage = ""
          .ShowInput = True
          .ShowError = True
        End With
      Else
        '---!
        If Range("L16").Value = "Manipulate" Then
          With Range("M16").Validation
            .Delete
            .Add Type:=xlValidateList, AlertStyle:=xlValidAlertStop, Operator:= _
xlBetween, Formulas:="$E$11:$E$14"
            .IgnoreBlank = True
            .InCellDropdown = True
            .InputTitle = ""
            .ErrorTitle = ""
            .InputMessage = ""
            .ErrorMessage = ""
            .ShowInput = True
            .ShowError = True
          End With
        Else
          If Range("L16").Value = "Position" Then
            With Range("M16").Validation
              .Delete
              .Add Type:=xlValidateList, AlertStyle:=xlValidAlertStop, Operator:= _
xlBetween, Formulas:="$E$15:$E$18"
              .IgnoreBlank = True
              .InCellDropdown = True
              .InputTitle = ""
              .ErrorTitle = ""

```

```
        .InputMessage = ""
        .ErrorMessage = ""
        .ShowInput = True
        .ShowError = True
    End With
End If
End If
End If
End If
End If
End If
End Sub
```

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## VITA

Apinut Nate Sirirojvisuth was born in Bangkok, Thailand on September 23, 1981. He graduated his Bachelor of Science degree in Mechanical Engineering at King Mongkut University of Technology Thonburi in 2001. He then spent the next three years working as Lead Maintenance Engineer at Mitsui Hygiene Material (Thailand) Co.,Ltd. In August, 2005, he enrolled in the School of Aerospace Engineering at the Georgia Institute of Technology in Atlanta, Georgia. He received his Master of Science degree in Aerospace Engineering, and immediately joined the Ph.D. program and pursued research in the areas of aircraft systems design, Computer-Aided Design and Manufacturing in Aerospace Industry, Lifecycle Cost modeling, and Robust Design Simulation.

# Development of Hybrid Lifecycle Cost Estimating Tool (HLCET) for Manufacturing Influenced Design Tradeoff

Apinut Sirirojvisuth

258 Pages

Directed by Professor Daniel P. Schrage

In complex aerospace system design, making effective decision requires knowledge from all disciplines, both product and process perspectives. Manufacturing knowledge integration is most valuable during the early phase of the design since designers have more freedom, and design changes are relatively inexpensive. Yet, there is still lack of structured methodology that will allow feedbacks from the process perspective to show the impact of the design decisions in a quantifiable manner. The major metrics in the design decision as far as process is concerned are cost, time, and manufacturability. To incorporate these considerations in the decision making process without sacrificing agility and flexibility required during conceptual and preliminary design phases, a new set of software analysis tools are proposed. To demonstrate the applicability of this concept, a Hybrid Lifecycle Cost Estimating Tool (HLCET) is developed, and integrated to existing design methodology, Integrated Product and Process Development (IPPD). The ModelCenter suite is used to develop software architecture that seamlessly integrate between product and process analysis tools, and enable knowledge transfer between design phases. HLCET integrates high fidelity estimating techniques like process-based and activity-based into a hierarchical lifecycle cost model to increase the sensitivities of the top-down LCC model to changes or alternatives evaluated at the part or component level where tradeoff is required. Instead of applying arbitrary complexity factor to existing CERs to account for difference material or process selection, high fidelity tool can be used to related product and process parameters specific to the design to generate new result that can then be

used to update top-level cost result. This new approach to lifecycle cost estimation allows for a tailored study of individual processes typically required for new and innovative designs. An example of a hypothetical aircraft wing redesign demonstrates the utility of HLCET.