A Method for Scenario-based Risk Assessment for Robust Aerospace Systems

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Victoria Katherine Thomas

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A Method for Scenario-based Risk Assessment for Robust Aerospace Systems

Approved by:

Prof. Dimitri Mavris, Advisor
School of Aerospace Engineering
Georgia Institute of Technology

Prof. Daniel Schrage
School of Aerospace Engineering
Georgia Institute of Technology

Prof. Vitali Volovoi
School of Aerospace Engineering
Georgia Institute of Technology

Dr. Peter Hollingsworth
School of Aerospace Engineering
Georgia Institute of Technology

Dr. Michelle Kirby
School of Aerospace Engineering
Georgia Institute of Technology

Dr. Gary Seng
Glenn Research Center
National Aeronautics and Space Administration

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To Reid, for everything

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LIST OF SYMBOLS AND ABBREVIATIONS

AHP	Analytic Hierarchy Process
ALCCA	Aircraft Life Cycle Cost Analysis
ANOVA	Analysis of Variance
ARP	Aerospace Recommended Practice
CDF	Cumulative Density Function
CEO	Chief Executive Officer
CFD	Computational Fluid Dynamics
DJIA	Dow Jones Industrial Average
DoD	Department of Defense
DoE	Design of Experiments
EASA	European Aviation Safety Agency
EPA	Environmental Protection Agency
ETOPS	Extended Range Twin Operations
FAA	Federal Aviation Administration
FDA	Food and Drug Administration
FEA	Finite Element Analysis
FHA	Functional Hazard Assessment
FLOPS	Flight Optimization System
FMEA	Failure Modes and Effects Analysis
FTA	Fault Tree Analysis
GDP	Gross Domestic Product
GNC	Guidance, Navigation, and Control
IPPD	Integrated Product and Process Development

IPT	Integrated Product Team
IRMA	Interactive Reconfigurable Matrix of Alternatives
LdgFL	Landing Field Length
NASA	National Aeronautics and Space Administration
NTSB	National Transportation Safety Board
OEC	Overall Evaluation Criterion
OEW	Operating Empty Weight
PDF	Probability Density Function
PDS	Product Design Specification
PSSA	Preliminary System Safety Analysis
QFD	Quality Function Deployment
RSE	Response Surface Equation
RQ	Research Question
TOFL	Takeoff Field Length
TOGW	Takeoff Gross Weight
SAE	Society of Automotive Engineers
SSA	System Safety Analysis
TOPSIS	Technique for Order Preference by Similarity to Ideal Solution
USSR	Union of Soviet Socialist Republics

SUMMARY

In years past, aircraft conceptual design centered around creating a feasible aircraft that could be built and could fly the required missions. More recently, aircraft viability entered into conceptual design, allowing that the product's potential to be profitable should also be examined early in the design process. While examining an aerospace system's feasibility and viability early in the design process is extremely important, it is also important to examine system risk. In traditional aerospace systems risk analysis, risk is examined from the perspective of performance, schedule, and cost. Recently, safety and reliability analysis have been brought forward in the design process to also be examined during late conceptual and early preliminary design. While these analyses work as designed, existing risk analysis methods and techniques are not designed to examine an aerospace system's external operating environment and the risks present there. A new method has been developed here to examine, during the early part of concept design, the risk associated with not meeting assumptions about the system's external operating environment. The risks are examined in five categories: employment, culture, government and politics, economics, and technology. The risks are examined over a long time-period, up to the system's entire life cycle.

The method consists of eight steps over three focus areas. The first focus area is Problem Setup. During problem setup, the problem is defined and understood to the best of the decision maker's ability. There are four steps in this area, in the following order: Establish the Need, Scenario Development, Identify Solution Alternatives, and Uncertainty and Risk Identification. There is significant iteration between steps two

through four. Focus area two is Modeling and Simulation. In this area the solution alternatives and risks are modeled, and a numerical value for risk is calculated. A risk mitigation model is also created. The four steps involved in completing the modeling and simulation are: Alternative Solution Modeling, Uncertainty Quantification, Risk Assessment, and Risk Mitigation. Focus area three consists of Decision Support. In this area a decision support interface is created that allows for game playing between solution alternatives and risk mitigation. A multi-attribute decision making process is also implemented to aid in decision making.

A demonstration problem inspired by Airbus' mid 1980s decision to break into the widebody long-range market was developed to illustrate the use of this method. The results showed that the method is able to capture additional types of risk than previous analysis methods, particularly at the early stages of aircraft design. It was also shown that the method can be used to help create a system that is robust to external environmental factors.

The addition of an external environment risk analysis in the early stages of conceptual design can add another dimension to the analysis of feasibility and viability. The ability to take risk into account during the early stages of the design process can allow for the elimination of potentially feasible and viable but too-risky alternatives. The addition of a scenario-based analysis instead of a traditional probabilistic analysis enabled uncertainty to be effectively bound and examined over a variety of potential futures instead of only a single future. There is also potential for a product to be groomed for a specific future that one believes is likely to happen, or for a product to be steered during design as the future unfolds.

CHAPTER 1

INTRODUCTION

The nature of engineering design has changed significantly since the dawn of powered flight in 1903. In the early 1900s, aircraft were often home-built and flown by amateurs. The First World War ushered in the era of professional aircraft designers, manufacturers, and pilots, many of whom continued to work in the aircraft industry boom during the roaring 20s. During the Second World War, aircraft design and production increased tremendously to meet the demand of the United States and allied armies and navies. After World War II, flying became a more common mode of transportation. The advent of commercial jetliners in the 1950s created an era of convenient, relatively low-cost, long-range transportation.

1.1 Changing Times

During the early years of commercially available aircraft, both military and civilian aircraft were, with some exceptions, designed and fabricated by private companies. These companies often began with a few partners designing or manufacturing a single airplane or engine, and then grew in size as demand for their products increased. Since the men who owned these companies often started out designing and building their own products, they were, like Jack Northrop for example, generally engineers by training. When these engineers became company owners and stopped doing engineering design, manufacturing, and testing, they hired more engineers to be in charge of design and manufacturing. During the pre and post World War II time period, employees were hired for life. There was little job turnover; once an employee was trained, there was little worry that he would leave and take his skills elsewhere.

During these time periods, before, during, and just after World War II, design cycles were very short, in some cases as short as a few months from design to production.

Companies used a large, motivated workforce to quickly turn paper designs into flying aircraft for testing. When a design did not work, it was modified, rebuilt, and tested again. Since the design cycles were short and companies had little overhead, presidents with large personal fortunes, and more government funding for research and development, they were often able to fund their own design cycles and consequently borrowed little money, which helped keep costs and overhead low.

These companies had significant numbers of engineers, designers, and drafters working on their aircraft. This large workforce was necessary as most work was completed by hand. Designs were completed using point performances calculation with little uncertainty. The focus was on increasing performance, with little worry about cost. Design freedom greatly decreased early on, with much of design cost locked in very early in the design process.

While the 1940s and 1950s may have been the golden years for aircraft design and innovation, much has changed since then. Many of the old aircraft manufacturers have either gone bankrupt or been bought by mega-corporations, such as Boeing and Lockheed Martin. These companies, while run by Chief Executive Officers (CEOs) and boards of directors, are publicly owned and traded. Designers and engineers, instead of satisfying the company owner, now must satisfy the board of directors, who, in turn, must satisfy the company's shareholders desire for increasing return on investment. Since engineers are no longer in decision making positions in these corporations, aircraft design decisions are being made by managers and marketing teams that often have little engineering knowledge. This desire to satisfy shareholders, coupled with increasing system complexity, ever more stringent certification requirements and lack of engineering input into design decisions, has led to an increase in design cycle time and design cost for large, multi-national corporations that make decisions less quickly than in years past. As the companies become less efficient and have longer design cycle times, they take on more debt to meet their obligations and end up with larger workforce turnover. The increased debt means debt repayment becomes prominent in a program's budget and the increased workforce turnover has led to increased training costs. Aircraft design programs, both commercial and military, are more expensive and time-consuming than ever before. An example of this phenomenon, for commercial aircraft, is illustrated below in Figure 1, taken from *Augustine's Laws* (Augustine 1997). The unit cost of commercial aircraft is increasing by one order of magnitude approximately every 18 years. Such an exponential increase in aircraft unit cost means that it is more important now than ever before to make sure that aircraft will be economically viable before beginning design.

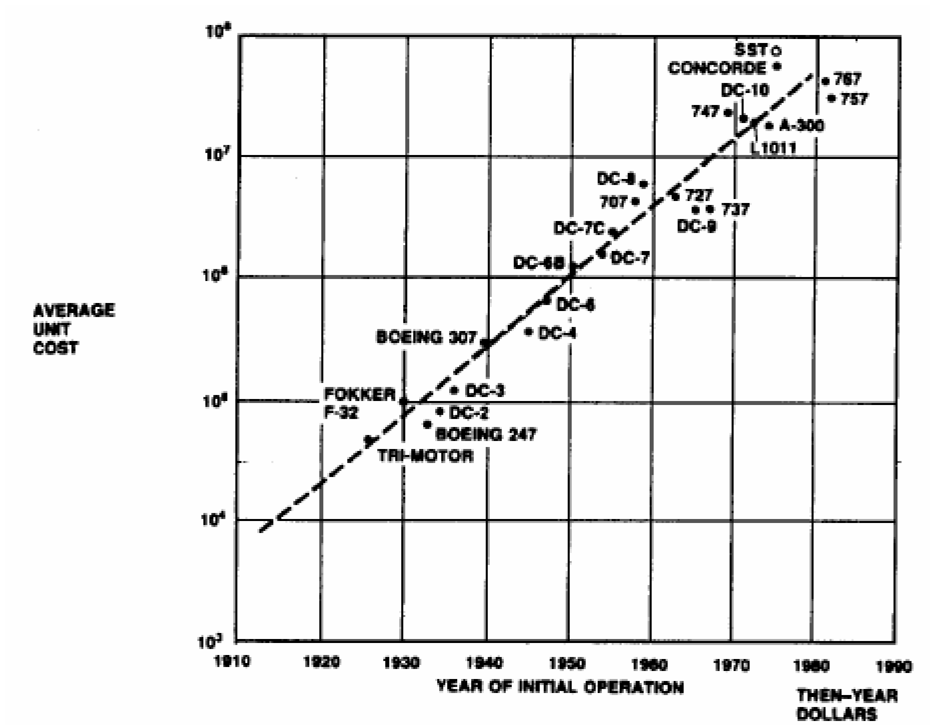

Figure 1: Increasing Unit Cost of Commercial Aircraft (Augustine 1997)

While much has changed with the design process over the past 60 years, the parts of design that take place before the engineers receive design requirements have changed little. For many years, marketing and finance departments at aerospace corporations have determined new design requirements. These groups or departments identify the market for a new commercial product, and then create a set of requirements and constraints for the engineers to meet. As design cycles are very long in the commercial aerospace industry, and it can take many years to create a new product, identifying a product's market is a difficult task. The marketing and finance team seeks to narrow the entire range of potential products into a more focused set of requirements to give to the engineers who are designing the aircraft. This narrowing of the design space is undertaken by trying to predict a market for a new product, and then designing a product to fit that market. The market needs to be predicted over a 15+ year timeframe, and some of the driving forces in the market, including technology and competition, are likely to deviate significantly from their current states over such a long period of time. The marketing team that undertakes the responsibility of identifying new product potential uses forecasting and scenario analysis tools to try to predict the market for a new product. These tools are able to take into account external risks that engineering designer tools cannot, including economic, political, and social risk. Since some of these tools are qualitative in nature, a human decision maker is required to interpret and determine the future market that should be filled with a new product. Once the marketing team determines the requirements and constraints for a new product, these requirements are handed over to the engineering design team. There is little or no interaction between the marketing team and the design team thereafter.

1.2 Traditional Design Process

The traditional design process, as outlined in countless undergraduate engineering texts, consists of conceptual, preliminary and detailed design, in that order (Anderson 1999, Raymer 1999). While definitions differ slightly from resource to resource, conceptual design consists of creating a "fuzzy outline" of the product (Anderson 1999). In this phase of product design, the overall performance, size and shape are determined and an initial feasibility question is answered. This phase of design was traditionally done by hand or with the aid of quick-running computer codes—during this design phase it is not necessary to get the perfect answer to all performance and sizing questions, just a reasonable estimate. During this phase of design, there is a lot of iteration between requirements and configuration settings and performance calculations as the configuration is set and the performance is calculated. Anderson (1999) lays out his Seven Intellectual Pivot Points for Conceptual Design for the design of an aircraft, as illustrated in Figure 2. The decision maker feels that basic performance parameters and configuration should be laid out before conceptual design is completed and that a performance analysis should be carried out to insure that the aircraft is on track to meet performance requirements.

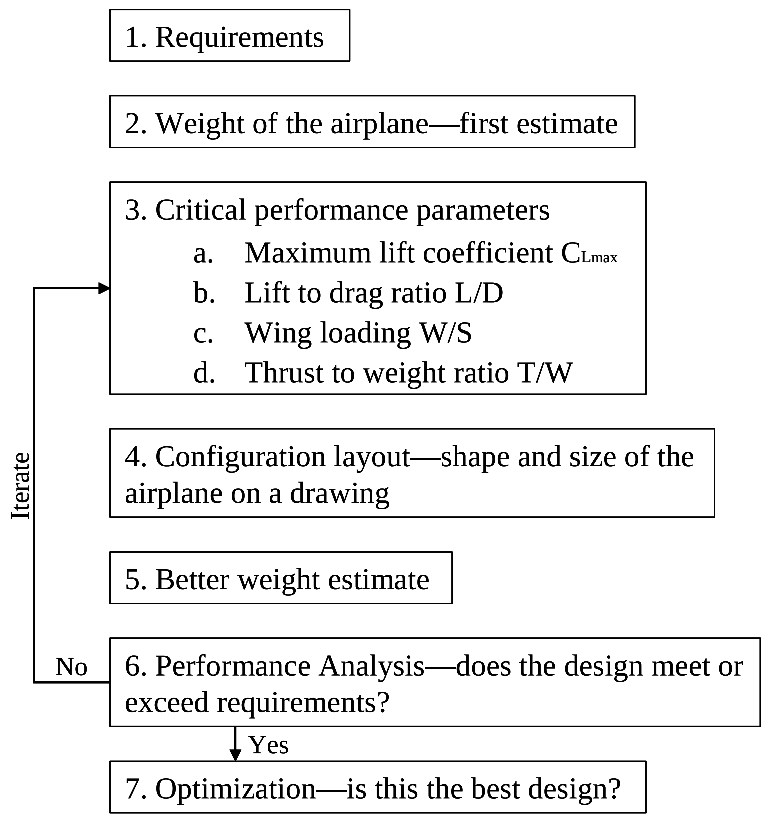

Figure 2: Seven Intellectual Pivot Points for Conceptual Design (Anderson 1999)

Assuming the product is deemed feasible at the end of the conceptual design phase, the product moves into the preliminary design phase. During the preliminary design phase, more details of the product's design are formulated. For an aircraft design, this phase includes more detailed performance analysis and component placement. During this phase, more detailed aerodynamic and structural performance calculations are carried out, more detailed drawings are created, and components are precisely placed (Raymer 1999). Computer models are more time consuming to use at this stage, but give better, more accurate answers. During this design phase, legacy codes, in the form of computational fluid dynamics (CFD) and finite element analysis (FEA) codes are often used to aide in performance evaluation. Wind tunnel or other models may be built and tested for aerodynamic and structural properties or to validate computer models. Each of these tasks are done by different individuals or teams: the aerodynamicists do the aerodynamics calculations, structural engineers do the structural calculations, guidance, navigation and control (GNC) engineers design the GNC system, etc. While there is some interaction between disciplines, traditional disciplinarians rule this phase of design. At the end of this phase, performance, size and component placement are set, and the company must decide whether to continue to detailed design.

During detailed design, detailed drawings of the product are created that show how it is to be manufactured. For aircraft design, detailed design consists of things like fastener placement and the determination of the order in which parts should be manufactured and assembled in order to maximize efficiency and minimize rebuilding and redesign. If there are any manufacturing processes that need to be created or updated, that is also done in the detailed design phase (Anderson 1999).

Traditional engineering design focused on and was driven by, performance, with cost, supportability, and so on as an afterthought. Much of design was completed on paper or old, slow computers. There was little integration of design tools and personnel, but each design group was able to make its own decisions. In order to complete designs in a reasonable amount of time, design was completed in a deterministic manner without including uncertainty, or including little, and only performance, uncertainty. Since requirements were limited primarily to performance requirements, requirements were not often conflicting and there weren't an overwhelming number of them. Significant design choices were made based on the limited amount of information available. Decision makers, both engineering and managerial, relied on intuition and heuristics to make design decisions.

1.3 Modern System Design Processes

Traditional design processes, while a nice remnant of an earlier era, simply do not reflect how design is conducted today. These three phases of design ignore economics, or finance, safety, and other things, while today's engineers and scientists know that life cycle cost is a large contributing factor in a design process ("Boeing…" 2003) and safety is necessary for certification. By the end of Research, Development, Testing and Evaluation (RDT&E), 70% of the life cycle cost is locked in (Porter, Navarre, and Hewitson 2005) for a design, so designing for cost has the potential to greatly reduce cost over a product's life cycle.

The level of effort spent during conceptual design on different aspects of the design has changed from traditional design to modern design. One of the goals of modern design processes and tools is to bring more information forward during conceptual design and to expand the scope of design to take into account a product's entire life cycle. The effort to bring information forward in is shown in Figure 3.

Today, designers are decision makers; they choose which metrics to base their design decisions on. Cost is one of the most important metrics for designers today. Deregulation forced airlines to compete with each other, which drove down ticket prices and increased competition. At the same time, there was an oil shortage that increased the price of fuel and forced airlines into decreasing profits. Increasing government regulations for emissions, safety, and reliability have forced manufacturers to increase the length of design cycles and design for more stringent requirements. All of these factors drive up costs for airlines and aircraft manufacturers.

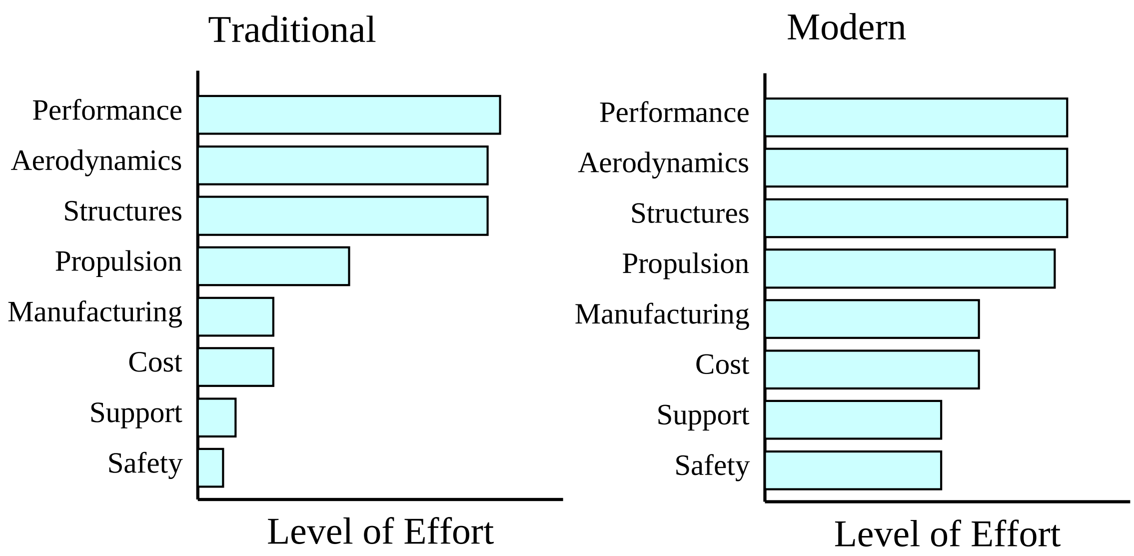

Figure 3: Effort Changes during Conceptual Design

For the private sector, using cost as a major driver makes sense: a company has the responsibility to its owners or shareholders to be profitable and a company's resources are not infinite; therefore, a product that is too costly will decrease shareholder return. A similar principle applies to the public sector: the supply of tax money is finite, and when the general public becomes aware of government waste, programs that are too costly get cut out of the budget. Safety, from a liability perspective, is more important now than ever before: a negative safety record can mean investigations, fines, and loss of business ("Jetliner Safety" 2003), which most aerospace manufacturing companies and airlines cannot afford if they are to compete in today's environment.

Traditional design is also discipline-specific, with discipline integration, synthesis, and manufacturing as an afterthought. Modern design processes incorporate system engineering as a sort of overarching discipline that integrates the results from each discipline into a coherent, optimized product. The goal of the design engineers is to incorporate disciplines as early in the design process as possible. Turning design into a social, rather than an individual activity adds value to the design project: more of the correct people will bring more ideas and concepts to the project (Callopy 2001). Such as design process for conceptual and preliminary design is illustrated in Figure 4.

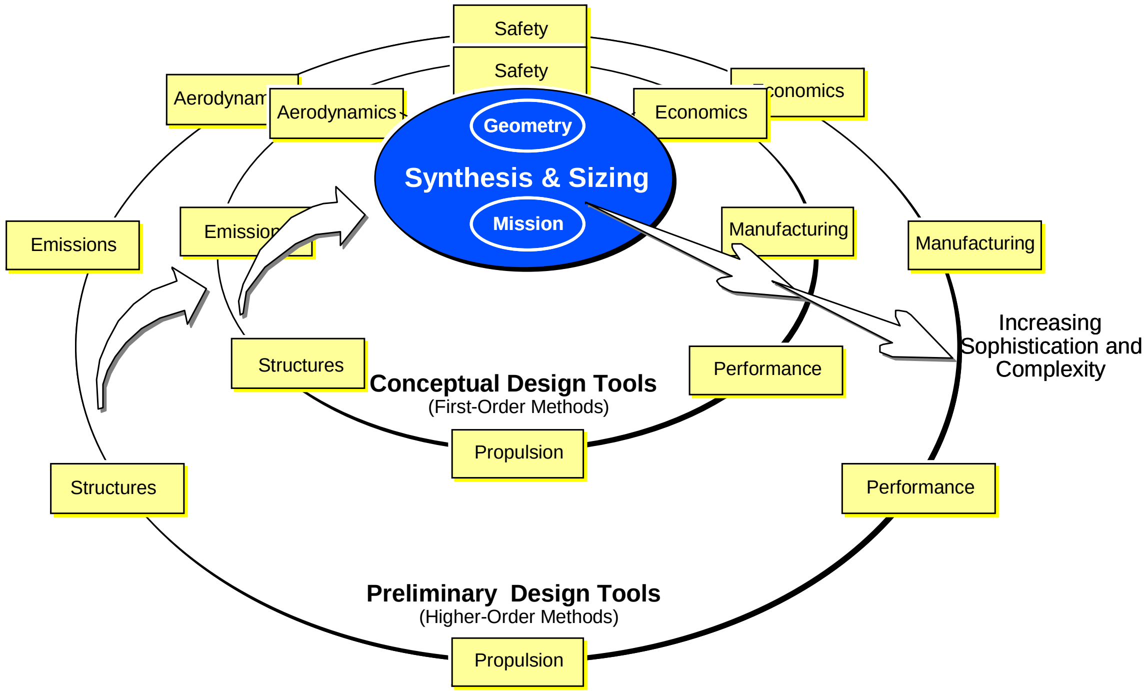

Figure 4: Sizing and Synthesis Process (Mavris et al 1998)

The design engineers, who are the sizing and synthesis experts, sit at the top of the pyramid. Their job is to pass down information about the aircraft geometry, mission and any other special needs or functions. During conceptual design, they take information from first-order analyses and refine the aircraft with that information. When the aircraft configuration is optimized, they send information down to the disciplinarians that complete the preliminary design analyses using more refined, more accurate methods. During both conceptual and preliminary design, the sizing and synthesis team passes information between disciplines and makes sure that each discipline is incorporated into the design process and as much information as possible is gathered.

Many changes over the years have allowed for an increased role for systems and design engineers. Newer, faster computers have paved the way for the creation of better system models and better modeling and simulation environments. Newer computers have allowed for a decrease in design engineering personnel, decreased design turnaround time, and an increased number of disciplines to be taken into account early in the design process. While this increasing amount of information has had many benefits, there is now the problem of an overwhelming amount of information that a decision maker must sort through and a set of conflicting requirements between performance, cost, safety, and so on. With the increased focus on cost, design synthesis, and product life cycle, several tools and methods have been developed to aid in conceptual design.

1.3.1 Design for Life Cycle Cost

The advent of the Department of Defense's (DoD) design for life cycle cost and National Aeronautics and Space Administration's (NASA) faster, better, cheaper philosophy in the 1990s (Porter and Hewitson 2005) created a shift toward designing for life cycle cost instead of designing for performance with cost as an afterthought. With cost as an overriding factor in modern design, the definition of the design process needs to be modified. Unlike the traditional design process, which ended at detailed design, newer design processes take into account the entire product life cycle as illustrated in Figure 5.

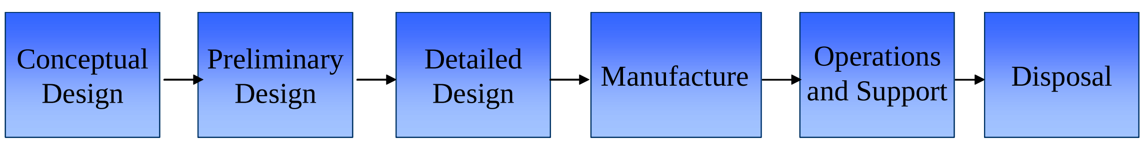

Figure 5: Modern Product Life-Cycle

For a commercial aircraft, the first three phases of the product design are similar to those detailed above; however, beginning with conceptual design, a cost analysis is included with all the discipline analyses. Now the designer must also project future costs as early in the design as possible and take into account the costs and problems associated with the rest of the life cycle: manufacture, operations and support, and disposal. For large-scale aerospace systems, such as commercial aircraft, the manufacturing phase of the design sounds pretty straightforward: someone has to build the aircraft. The manufacturing phase of the product’s life cycle takes into account all the manufacturing processes and any associated problems, such as product storage, before the product is purchased and shipped. The operations and support phase begins when the aircraft enters service. While operations costs are generally absorbed by the customer (the airlines, in this case), it must still be taken into account during the initial design phases. Preliminary and detailed design can impact operations costs a great deal. Design changes that decrease drag, increase fuel efficiency, or make an aircraft easier to load and unload are made during these phases can decrease operations costs for the airline. Support costs can be airline or manufacturer costs. Support includes maintenance, and while airlines often do their own maintenance, engines are generally maintained by the engine company. Small increases between scheduled engine down-times can decrease maintenance costs and increase profit for both engine manufacturers and airlines. The final life cycle phase is disposal. During this phase, the aircraft is either mothballed and stored out in the desert for future use, or cannibalized for parts and destroyed. For a new aircraft family, the three design phases of the life cycle can take up to ten years, with orders for manufacture coming for many years after that. The operations part of the life cycle is generally scheduled for approximately twenty years, and after disposal an aircraft can sit in the desert indefinitely. A new aircraft family can expect its total life cycle to be forty years or more, with some updates along the way.

1.3.2 Integrated Product and Process Development

Integrated Product and Process Development (IPPD) was a design trend that came into use by the Department of Defense in the 1990s (Department of Defense 1996). Like design for life cycle cost, IPPD takes into account the product’s entire life cycle during the conceptual design process. The IPPD process involves the development of an integrated product team (IPT) that has members from all disciplines throughout the product's entire life cycle (Marx 1994, Department of Defense 1996). An example of the IPPD process is illustrated in Figure 6 and Figure 7.

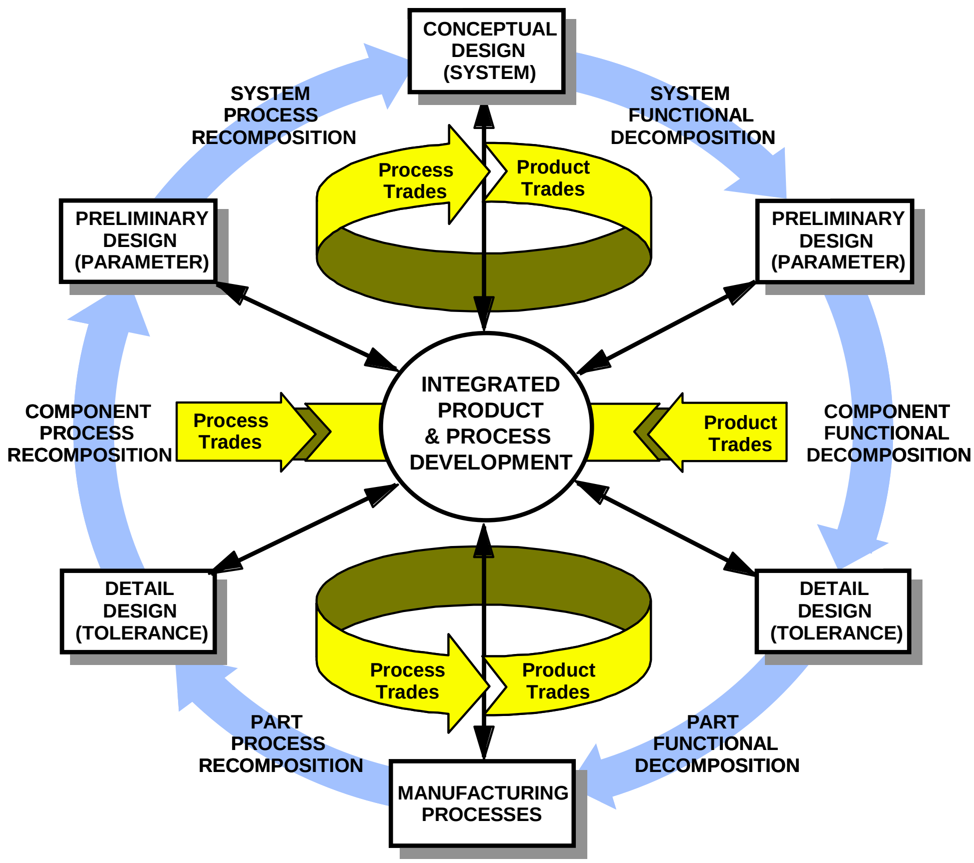

Figure 6: IPPD Process (Schrage and Mavris 1995)

The purpose of IPPD is to bring together people from all life cycle phases of both product and manufacturing process development and in order to optimize life cycle cost and performance. The net goal of IPPD is to reduce design time and life cycle cost. One way IPPD is able to do this through product and manufacturing process trades and analyses (Department of Defense 1996). By using functional and process decomposition, the IPT is able to develop the manufacturing and support processes necessary to build and maintain the product at the same time as the product is being designed. This decomposition and recomposition process decreases product redesign during the manufacturing and support stages and thus saves the designing company and customer time and money.

Bringing people from all life cycle phases together early in the design process also reduces programmatic risk. Having team members from all disciplines will help create realistic performance, cost and scheduling milestones, reducing the potential for cost overruns and scheduling conflicts (Department of Defense 1996). Creating an IPT also reduces friction between disciplinarians within a company or design group, since every discipline will have its voice heard. Disciplinarians from all over the company will be able to see and understand the entire product life cycle process. A greater understanding of how all the life cycle pieces fit together should allow for more sharing of ideas and less territorial behavior among different disciplines.

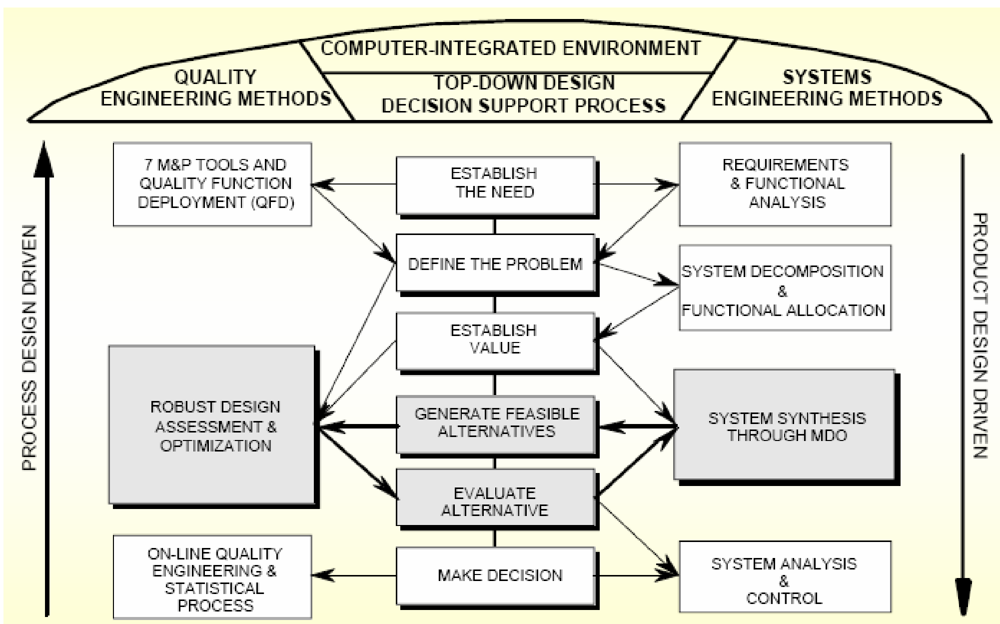

Figure 7: IPPD Process II (Schrage 1999)

1.3.3 Robust Design

Since cost has become as important as performance, design quality, or a combination of performance and cost, has become important. Robust design has traditionally been a synonym for quality. The traditional robust design process was developed by Japanese manufacturers in the 1980s and involved using statistics to decrease product variability and improve quality (Dieter 2000). Robust design was originally concerned with manufacturing processes and products; the question at hand was what could be done to reduce manufacturing variability while also creating a product as close to the design specification as possible.

An extension of the traditional definition of robust design is to extend robustness from variability in manufacturing to potential variability in the future (DeLaurentis and Mavris 2000). Since design requirements change, a product that can do not only the job it is was originally designed to do but also many other jobs that may or may not be necessary in the future is a robustly designed product. These designers were able to foresee a future where new uses would be developed, and designed the product around potential changes in requirements and future uses. This is not to say that these designers were able to predict the future; instead, these designers created their product to handle foreseeable upgrades and perform well in a variety of situations beyond the original design specification.

The overriding idea behind robust design, using either definition, is to reduce cost and increase performance by having as much information as possible as early in the design process as possible. Costs can be reduced and performance can be increased through the use of statistical methods or by creating modular products that are easily adapted to new situations. Robust design, by both definitions, is practiced by many companies today. The Six Sigma process as used by General Electric is built on these principles (Breyfogle 1999), and they were used extensively by Toyota in the 1980s to create high quality, competitively priced products (Dieter 2000).

1.3.4 Increases in Computing Resources

For the past century, there has been a push toward automation in engineering design and manufacturing. From the time Henry Ford created his first assembly line to produce the Model T, this process has been used to standardize products and reduce labor requirements and their associated costs (“Henry Ford” 1996). For many years, the push for automation was mostly limited to manufacturing. Companies wanted to make manufacturing processes standardized and safer. Automated manufacturing reduced the need for highly skilled craftsmen and created a market for lower skilled, lower wage workers that don't need to spend seven to ten years learning a trade.

While most design used to be done with pencil and paper, the advent of faster, better and cheaper computers has led to more automation during the design process. However, the new and better automation technology can also leave the human out of the loop. Just as skilled craftsmen were no longer necessary when machines became powerful enough to manufacture everyday items, some engineers are afraid of being left out of the design process by computers codes that are too complicated to understand and too much trouble to use. If the computer codes used to aid in the design process are not transparent to the user, and the user doesn't know all the inputs, outputs, and assumptions, the design process can become too daunting for the designer and the product will not be as good as it can be.

1.4 Decision Making in Design

Decision making factors heavily in design. Modern conceptual design processes require decision making to settle on a product design. These decisions are made with uncertain information early in the design process. While there is information from many disciplines, and that information seems vast, much of it is uncertain and will change before the system is completely designed. Traditionally, there was less information that had to be taken into account during design, and so decisions were more easily made. Today, design decisions can be more difficult to make.

1.4.1 Where, When, and How

With the continued push toward better computer products, one might believe that computers create designs and make design decisions; however, this is not the case.

Computers are very useful tools later in the design process, but during the early parts of the design process, when many important design decisions are being made, a piece of software is of limited use: there is too much uncertainty in the design and evaluation for a machine to make a decision. A human has more tools at his disposal when making decisions than a computer does. A human decision maker has the accumulated knowledge of a lifetime, as well as the ability to learn, and the ability to use intuition; a machine is not yet capable of using intuition and has only a limited ability to learn and apply new ideas. A computer is also incapable of taking credit for a job completed well or blame for a job completed poorly; a machine is also difficult to fire or promote. Human beings are the center of design decisions and will be for the foreseeable future. However, humans can still have difficulty making design decisions. When a large amount of information is available the decision maker may have difficulty distinguishing between options and may rely on traditional engineering methods to make decisions.

Small design decisions are made continuously throughout the design process. Small changes to a wing or fuselage design, component placements, etc, are all refined on an almost daily basis during conceptual design. These decisions are made on a small scale, often by lower or mid-level engineers or managers approval. They can be made on the basis of a conversation or short document or illustration and generally affect only a small number of people.

Larger-scale design decisions are often made by managers or committees and occur less frequently. Such decisions include initial product launch, final configuration selection, selection of major partners or suppliers, and so forth. These decisions take more time to make and more time to prepare. They can be made on the basis of documents, presentations, or decision making and support tools. Since these decisions are often made by people who have little day-to-day contact with the designers and engineering decisions, it is important to display information in such a fashion that it is useful to someone whose background is not engineering or design. What types of information are displayed and how much information is displayed become crucial questions to answer before giving a presentation for decision making purposes. It is important to display cost information for each alternative, since cost is a very important decision making attribute; however, it is also important to display other pieces of information about design alternatives, such as pertinent performance, maintenance, and manufacturability data. Too much information can make decision making difficult, so presented data should be kept to a minimum and presented in graphical, rather than tabular, form as large tables of numbers can easily overwhelm even the most experienced decision maker.

1.4.2 Decision Making

Traditional decision theory suggests that the best way to choose between options is to evaluate each option to the fullest extent possible and then choose the optimal solution based on a pre-defined objective function that maximizes the outcome utility (Hsee et al. 2003). This type of decision making is called strategic decision making. However, in real life the decision maker often does not have the time or resources available to investigate each option to the fullest extent possible (Simon 1955), and is also unable to limit uncertainty in future conditions. Also, decision makers are usually unclear about *how* they make decisions: they cannot describe their decision making process or the figures of merit used. Instead, decision makers don't use utility maximization decision making processes and may end up at non-optimal solutions.

Even though engineering projects in the aerospace industry are long in scope and planning, decision makers still are not be able to fully take advantage of the strategic decision making process. The decision maker usually has a limited period of time in which to gather information and make a decision; therefore, the decision maker does not have the ability to gather as much information as he would like on every option. Often, he must cut down a large list of available options into a manageable number of options that he is willing to consider. He must choose to investigate further the options he believes have the greatest potential to meet the company's needs and the smallest potential of decreasing the company's value. He is doing this with almost no information except his engineering intuition and experience.

The decision maker is also limited by his ability to foresee the future, and is further compounded by the types of predictions he is required to make. This decision maker must not only anticipate the availability of future technology and the future economic conditions, he must also anticipate future political and social conditions that could affect his product. All of the future predictions that he uses when making decisions have a degree of uncertainty in them. The further in the future he is trying to predict, the greater the uncertainty. Unfortunately, engineering projects often require decision makers to try to make predictions for many years in the future, when uncertainty is large and the value of such predictions is small. Traditional engineering design decision making doesn't take these factors into account; instead, the marketing and finance teams that set initial design requirements deal with non-engineering factors. However, these factors can be design drivers and should be dealt with during concept design.

In aerospace programs, incorrect decisions can lead to significant consequences for a decision maker and a company. Companies are forced to sink billions of dollars into these projects before realizing any profit. The long timeframe for aerospace projects couples with future uncertainty to compound the decision making process. If a company makes the incorrect decision, it could lose a great deal of money and potentially go out of business. The consequences arising from future uncertainty create risk for a company and a decision maker. While definitions of risk differ slightly between industries and sources, all definitions contain the ideas of probabilities of occurrence and consequences arising from not being able to fully predict the future (Kuhn and Budescu 1996). So the decision maker must not only contend with the uncertain future, but also be responsible for any consequences that arise from the decisions.

How is a decision maker able to make these decisions? The decision maker must rely on experience and judgment to do a risk-benefit analysis and discard the options that are too risky or have too low a payoff. Even though the decision was made with little, uncertain or qualitative information, the decision must be defendable when questioned. He needs to be able to show why he discarded some choices before putting time and effort into researching them and why he kept others. Current decision making theories seek to understand the real-life context in which people make decisions, but do not provide a framework for making quick decisions with little and uncertain information. A framework that enables a decision maker to systematically explain why some decision options were discarded and others were kept and help explain and defend why his decisions were made and what his judgments were in the time leading up to the decision would fill an existing gap in conceptual design phase decision making. Such a framework needs to take into account the different ways people downselect between design options.

1.4.3 Information for Decision Making

Decisions are made based on available information. When too little information is available, design decision makers use what information is available and are left to infer additional information using a best guess or engineering intuition (Dieter 2000). While this approach works well for experienced designers, it is difficult for an inexperienced designer to implement with a high degree of accuracy.

On the other hand, too much information can be just as damaging. Too much information or too many disparate pieces of information can make it difficult to determine whether the information is correct or incorrect and figure out what pieces of information are actually useful for the decision at hand (Ashford 2005). Since it is the decision makers job to complete a “sanity check” to determine whether the information presented makes sense and is useful, additional information requires more human time to make such determinations. While the multi-attribute decision making tools and procedures prefer more information over less and seek to help the user determine what information is actually important, increasing information still leads to increasing problem complexity and more difficult tradeoffs.

While decision makers will have some level of information about each alternative, there is often a dearth of information about the analysis process for alternative comparison. Even if all the information the decision maker wants is available, if design concepts are not all analyzed the same way than design comparisons may provide misleading information. Each concept design has a list of assumptions that the initial designer or design team should be aware of. If the decision maker is unaware of these assumptions, he may not be able to accurately compare products. The same theory holds true for analysis tools and concept analysis: each analysis tool and concept model has many built-in assumptions. These assumptions could be technical performance assumptions such as cruise altitude or component weights or economic performance assumptions such as interest or inflation rates. If these assumptions differ between concepts or the assumptions are not well defined, concept comparison for decision making can be difficult.

1.4.4 Information Wanted during Conceptual Design

In general, a decision maker wants all the information available about the design options. For long time-scale projects such as those found in the aerospace industry, there is significant pressure on decision makers to make the “right” decision—generally the one that maximizes corporate profit. Since most people feel that the amount of information they possess correlates to how well they understand a problem, having more information makes decision makers *feel* that they can make better decisions. As explained above, having more information does not necessarily correlate to being able to make better decisions and too much information, in fact, correlate to worse decisions.

For aerospace systems, the information that decision makers want is related to performance feasibility and economic viability. Performance and feasibility information comes from the engineering design team, while economic and viability information comes from the marketing and business team. In a perfect world, the engineering team, marketing team, business management team, and the final decision makers would all work together to provide the information necessary to compare products; however, this perfect scenario rarely occurs. Often, the engineers design to the requirements they receive and do not interact, or rarely interact, with the marking team and almost never interact with the business managers, whose job is to determine product viability (Augustine 1997). In real-life cases, the decision maker is often left with disjointed, non-overlapping information about product feasibility and viability.

The decision maker also wants information about customer requirements and preferences, and would like this information to be as specific as possible. Some requirements are very specific, such as regulatory requirements, but often a customer wants a product to be “better” than an existing product or to complete a mission that an existing product cannot complete. In these cases, forming specific requirements is sometimes left to the design engineers and final decision makers.

This desire for specific information also extends to specific information from the design engineers, marketing team, and business team. Ideally, a decision maker would like a 100% confident prediction of the product’s performance and economic metrics. Since the product is not yet designed and built, such a prediction is impossible to make. Most times, everyone working on the design problem, from the design engineers to the business case analyst to the final go/no-go decision maker must content himself with less than perfect information.

1.4.5 Information Available during Conceptual Design

The information actually available during conceptual design can be vastly different than the information wanted by designers and decision makers. The first, and one of the most troubling, points of difference is in the elucidation of design requirements. As stated above, many times the customer has a specific problem to solve and wants a product that solves that problem. While the creation of such a product is a laudable goal, the problem at hand may not lend itself to the dictation of specific requirements. For example, a customer wants a product to transport 300 people from New York to San Francisco. This problem can be solved in a variety of ways: train, caravan of cars, aircraft, ship, etc; however, more information is needed to provide the customer with the service he desires. At this stage of design, customer requirements are often fuzzy and changing. While there may be some specific performance or economic requirements, often the requirements are some variation of faster, better, cheaper, and it is up to the designer and decision maker to translate these requirements into something that is useful.

Once the customer requirements and wants are agreed upon and initial solutions are identified, solution modeling can take place. During conceptual design, modeling is often crude; zero- or first-order models that can be quickly created and run are generally used since requirements change often. These models produce the performance and economic characteristics of the identified solutions. While the technical and economic characteristics of each solution are a simulation output and are deterministic, there is some fuzziness associated with these numbers due to the limited amount of data available to use for model creation.

For the designers and decision makers, there is generally both quantitative and qualitative information available to use for design and decision making. Some of this information is fixed and/or deterministic, while much of it is still changing until later in the design process.

1.4.6 Decision Evaluation

After a decision is made, an evaluation of the decision ensues. Decision evaluation is most often based on the outcome of the decision (Chater et al. 2003), not the thought process that let up to the decision, although a case can be made for evaluating decisions based on either set of criteria.

Since decision evaluation is based on decision outcome, this evaluation can take many years and can change depending on the current circumstances of the world. Since the initial decision involved future predictions, decision evaluation based upon decision outcome is really evaluation based upon how good the decision maker was at predicting the future from a specific point in time. Increasing time between decision making and evaluation correlates with increasing chance that the predicted future differs from the actual future. One of the problems with evaluating decisions using outcomes as the criteria is that "good" decision making can be based on nothing more than luck, which makes it difficult to separate decision makers who will be able to consistently make good decisions from those who may randomly make lucky decisions that end up being good.

1.4.7 Decision Support

There are many decision support tools available. The goal of many of these tools is to organize and display information for the decision maker.

One tool is quality function deployment (QFD), which is a process and a tool that allows a designer to translate the customer's wants and needs into "engineer-speak" to facilitate the design of the correct product for the customer (Dieter 2000, "Quality Function Deployment" 2006). Its goal is to increase customer satisfaction with products by enabling the engineer to understand what the customer wants from the product through the use of a singe visualization interface. The interface helps facilitate communication between the customer and the engineer: the customer is also able to understand what variables the engineers can use to satisfy his wants and is also able to see any conflicting requirements.

An example house of quality is depicted in Figure 8. A QFD process works by first letting the customer determine what he wants: the customer requirements, which fill out the list in the yellow section numbered one. Once all the customer requirements have been determined and ranked, the engineer must brainstorm ways he can address these requirements through engineering characteristics, represented by the orange section, number two. When both the customer requirements and the engineering characteristics have been identified, the next step is to see how they are related in the matrix shown in green, section number three. Other pieces of the QFD process allow for importance ranking of the customer requirements and a matrix that demonstrates the relationships between different engineering characteristics.

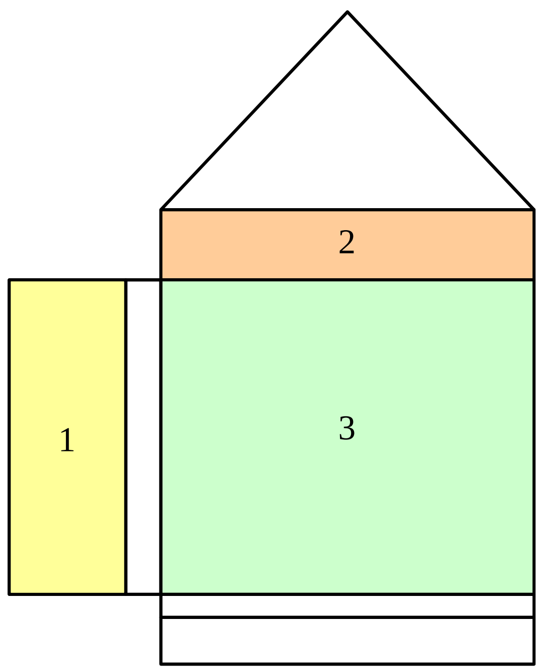

Figure 8: Quality Function Deployment

Another tool is a matrix of alternatives, sometimes called a morphological matrix, aids the user to choose a product configuration. It lists out all the major components of a system and the important subsystems, and the user is able to see all the available configuration options for a system. Its purpose, along with the rest of the tools, is to decrease project planning and development time and increase project knowledge early in the design process. As a conceptual design tool, it was first proposed by Fritz Zwicky in 1948 (Zwicky 1948) as a way of creating revolutionary design concepts. It is not often used in this form, since most designs are evolutionary instead of revolutionary; however, a morphological chart can still add value to the conceptual design process. It allows the designer to quickly and easily see many alternative solutions to the design problem and allows the designer to downselect each part of the system separately while still keeping the entire system design development in mind. An example morphological chart is illustrated in Figure 9.

Alternatives

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

Figure 9: Morphological Matrix (Kirby 2002)

While the traditional morphological chart has several advantages over the traditional “go down a path until it fails” design, it also has some shortcomings that any user should understand. The first shortcoming to understand is that all options listed are discrete. Having only discrete options works well when deciding whether an aircraft should have one, two, three or four engines, but for continuous variables, such as engine overall pressure ratio, having only discrete options is a disadvantage. Another problem of the traditional morphological chart is that it provides no logic showing how different design choices interact. For instance, when launching a missile, choosing a fighter aircraft over a long-range bomber or land-based launch platform will have an impact on the maximum allowable size and weight of the missile.

There are many other available tools to aid in decision making and support. One of these tools is the Ishikawa, or fishbone diagram, which helps to break down a system. Flow charts can help visualize and regulate the flow of information in a system. A conflict analysis matrix helps to determine whether conflicting requirements exist within a system. Benchmarking processes help to determine what parts of the system are existing and what need to be created. Gantt charts can aid in creating a project schedule. Prioritization tools help groups of decision makers determine which parts of the system or design are most important, or which concerns are most important to address.

1.5 Risk and Uncertainty in Design

Large, complicated engineering systems, like those seen in the aerospace industry, have some additional issues associated with their design and development. As Miller noted, "Large engineering projects are high-stakes games characterized by substantial irreversible commitments, skewed reward structures in case of success, and high probabilities of failure." (Miller and Lessard 2001). The initial cost of designing and building a new system is very large, and any profit is years away. If the system cannot be designed, or cannot be sold for the anticipated profit, the company can lose a substantial amount of money and potentially go out of business. This future uncertainty in potential outcome leads into the concept of risk.

There are many definitions of risk used by different industries, but all use some measure of the probability of an event's occurrence and the severity of its consequences. Risk is generally something that companies, as well as people, want as little of as possible. Large companies can be risk averse when dealing with large potential monetary losses (Callopy 2003). These companies strive to plan projects and choose alternatives with as little technical and economic risk as possible; for example, airframers will often choose to keep creating derivative aircraft to meet new missions instead of designing an entirely new aircraft for each new mission. Along with being risk averse, companies also try to eliminate risk. Risk elimination can take many forms, including specifying a design as quickly as possible and lining up suppliers and project partners as early in the design process as possible in order to eliminate uncertainty. Uncertainty is the state of not knowing something. Airlines try to eliminate uncertainty in future fuel prices by fuel hedging and in labor prices by signing multi-year contracts with union laborers. Companies will also choose to cooperate in order to spread the risk and cost of doing business. While decreasing project risk is always a worthy goal, the choices made to decrease project risk can also decrease potential project return and stifle innovation within companies.

Uncertainty has been dealt with differently in traditional and modern design processes. The traditional design process treats design deterministically. There is little uncertainty examined, and what is examined is entirely performance-based. In modern design processes, uncertainty and risk are examined. Robust solutions are desired, so uncertainty in performance due to technology development and changing requirements is examined. Methods exist to examine uncertainty and risk associated with technology development time and cost and technology impact. On the economic side, methods have been developed to examine some economic uncertainty and risk. In general, these methods are less well developed for use by engineers than those on the performance side. Robust solutions can be developed with respect to some economic factors, including fuel cost and labor rates. When handling uncertainty, on both the performance and economic metrics of interest, the focus to date has been on bounding uncertainty. In general, the best and worst cases of the future are used to give uncertainty bounds. While bounding uncertainty leads to an increase in design fidelity over a deterministic design, simply setting uncertainty bounds doesn’t allow for examination of circumstances that provide the uncertainty and lead to risk. There is also a large number of sources of uncertainty that are not examined by engineers. Some of these sources are examined by marketing and finance teams before design requirements are set; however, these sources can have a significant impact on engineering design.

1.6 Motivation

The inspiration for this research comes primarily from changes in the role of design decision makers. No longer is a product design carried out by an engineer able to work alone in his cubicle designing his small part of the overall plan. Now this engineer must interact with other engineers, managers, customers and end users. Each member of the design team works with others to meet time, cost and performance goals for the overall system. The days of drawing an aircraft on the back of a napkin and going down to the shop to build it are gone, while the days of global competition and small profit margins are here to stay (“Return on Equity” 2005).

From both a cost and performance perspective, the most important phase of the design process is the earliest; as the design progresses, more and more of the performance and cost parameters are locked in, leaving less design freedom (Mavris 1998).

1.6.1 Research Goals

The recurring themes throughout conceptual design are that there is a large amount of uncertain information, there is risk from a great variety of sources, and that there is uncertainty about the future as it relates to the system design. The use of so much information requires a human decision maker in the loop to exercise judgment as to which information should be used for decision making. Some different facets of risk are already dealt with during design, particularly technical risk. Others are not. Some aspects of risk that engineers typically do not address during design are those that the marketing and finance teams address before setting performance requirements for engineers, including economic, employment, political, and social aspects of risk. Engineers typically do not know how, or even whether, these risks are addressed, but these types of risk can have a significant impact on the future of any engineering design.

A method for the examination of programmatic risk including employment, political, social, and economic risk would be a useful addition to the modern design process. Research questions were created to help identify necessary pieces of this process. To create such a method, one would need to understand how decision makers use judgment to make decisions under uncertain conditions with large amounts of conflicting information, which makes research question one:

> Is it possible to harness the act of human judgment and use it as a conceptual design decision aid for an aerospace system design?

Since the goal of such a method is to complete a risk analysis, current risk analysis methods also need to be researched to see what methods, if any, are applicable to this problem. To complete a risk analysis, research question two is:

> Do any systems or methods currently exist that allow the user's judgment to make decisions in the beginning stages of conceptual design? While using a risk-benefit type of approach?

Aerospace systems design processes are long time-scale designs, with predictions about the future made 15+ years in advance. Uncertainty about the future must be bound and understood, which leads into research question three:

> How do we deal with uncertainty in the early phases of design when doing a risk-benefit analysis?

These three research questions will be examined in more detail in the following chapters. The information in those chapters will aid in the creation of a risk analysis process that will help engineers create aerospace products that are robust to external environment factors.

CHAPTER 2

JUDGMENT AND DECISION MAKING

The previous chapter described the motivation for the creation of a new risk analysis process. Decision making and judgment are necessary pieces of a risk analysis process. In this chapter, the first research question will be explored:

> Is it possible to harness the act of human judgment and use it as a conceptual design decision aid for an aerospace system design?

Human decision making models and theories will be examined to determine whether any can be used to help in the creation of the new risk analysis process. Some traditional engineering and mathematical multi-attribute decision making models will also be explored and contrasted with the human decision making models for usefulness in the creation of a risk analysis.

2.1 Strategic Decision Making

Decision making is defined as the selection between options. There are many levels of decision making and many ways that humans can make decisions. Borrowing from Hollnagel's model of cognitive contextual control (Hollnagel 1993), four ways that model how humans make decisions can be identified, and are listed in Table I. Each decision making model is used in a different decision making environment. Scattered decision making is random, and is associated with a person who is in a panic and has no time or ability to do anything more than just react to the environment. Opportunistic decision making involves more time and opportunity to make a decision. The opportunistic decision maker does not plan for the future; he just reacts to his current situation. Unlike the scattered decision maker, who is chaotic, the opportunistic decision maker searches for a decision to make. This decision maker takes the first option available, and then continues to react to the environment. The choices, while they have some reasoning behind them, are not usually the most efficient way to reach his goal. The tactical decision maker has more time to make decisions than the opportunistic decision maker. He is able to search for a solution to a problem and is able to analyze many solutions until he finds a solution that fits his criteria. This decision maker can take into account many aspects of the context and can do some future analysis. The strategic decision maker has a lot of time to make his decisions. This decision maker can search the complete design space and can optimize his decision to fit the criteria he has laid out (Hollnagel 1993).

Table I: Decision Making Models

	Scattered	Opportunistic	Tactical	Strategic
Type of Search	None	Jump on 1st available option	Search until find "good enough" solution	Complete design space search
Type of Solution	Unrelated to problem	Whatever is available	Satisficing	Optimal

In recent years, there has been a movement toward strategic decision making techniques and numerical optimization procedures. Engineers and managers want an ordered, rational, mathematical approach to design for justification purposes and in case of litigation. The development of good engineering intuition and judgment are taking a back seat to the development of ever more sophisticated pieces of engineering optimization software and strategic decision making initiatives. Even though most optimization processes are treated as strategic decision making techniques, no decision making technique is entirely strategic (Harrison 1993). Most of the optimization procedures used are actually satisficing procedures, and would fall under the umbrella of tactical decision making. Taken to the extreme, strategic decisions would take infinite time and consume infinite resources to fully understand the problem and solution space; these decisions would produce no value to the decision maker. Real life decisions and decision makers, on the other hand, don't have infinite time or resources to commit to a decision. Therefore, in a practical sense, most decisions made are tactical, not strategic (Harrison 1993).

It is the hope that design decisions for large-scale, aerospace engineering projects are tactical to strategic in nature. Hopefully, the designers and decision makers do their best to examine as much of the design space as can be reasonably handled with the amount of time and other resources they have available. In general, designers will claim that designs are optimized; however, designers do not, and should not be expected to, use a global optimization procedure. One cannot examine all the design options in the entire design space, so the designers examine as many as they can until they find one that meets their criteria and constraints.

2.2 Judgment

Before a tactical or strategic decision is made, a judgment must take place where a decision maker differentiates between options and determines a ranking and/or differentiation between options. While the multi-attribute decision making techniques and decision aids, which will be described in later sections, can give a list of answers and a computer can differentiate between larger and smaller numbers, a human must still be present to make some judgments and determine whether the computer's answers are legitimate. The human judgment may take place on the input end, the output end, or both, but it will always be present. There are an abundance of models, methods and theories on human judgment and human decision making. The questions regarding how people make decisions and what factors they take into account when making decisions are being debated and many will be discussed in the following sections.

2.2.1 Bounded Rationality

One complaint about human decision making and judgment is that humans are not rational decision makers (Leland 1998, Hsee et al. 2003) and don't use logical processes to make decisions. With probability theory and expected utility as the standard for rationality in decision making and judgment, this is obviously true. Human decision makers are “irrational” in the sense that they do not generally use a computed expected utility to make decisions. However, since most decisions are made under some degree of uncertainty, and “rational” decision making techniques don’t allow for uncertainty, most decisions are made by humans using a process that doesn’t end with traditional utility theory. To get around the “irrationality” complaint, and to begin to help explain how humans *actually* make decisions, Herbert Simon developed the theory of Bounded Rationality (Simon 1955). Simon proposed that humans are adaptive organisms, but are limited cognitively by what they can remember and predict, and the calculations they can perform. Instead of a full optimization procedure that analyzed the entire problem and solution space, Simon proposed a search procedure in which a decision option is chosen as soon as one is found that meets all criteria and constraints (Simon 1972). This decision is carried out within a physical and operational environment, which should also be studied. Bounded rationality requires an understanding of both the human and the environment: decisions are made in context, and decisions that appear irrational from the perspective of maximization of expected utility often appear rational when viewed with respect to both the goal and the environment (Todd and Gigerenzer 2003).

Bounded rationality was one of the first attempts to explain human decision making behavior within the limits of cognitive processes. While it is a utility-based theory, bounded rationality was one of the first economic theories to treat both the human and the environment as if they were one unit instead of separate and non-interacting.

2.2.2 Intuition

Even with the current trend of having design and optimization be computerized, conceptual design level decision makers often have little time and money to invest in design investigation and so cannot always use or create optimization tools. As a result, a good designer will often use “intuition” to arrive at an acceptable answer, making design both an art and a science (Anderson 1999). This intuition is the heart of many design decisions, yet it is difficult to quantify and explain fully. As human beings are learning, adaptive animals, some intuition is the result of previous experience (Simon 1955). Humans judge behavior by its results, and learn from those results. Humans are able to quickly assess patterns and determine, without using any rational modeling or optimization methods, what a future outcome will be and can make decisions and act accordingly (Arthur 1994). Such use of quick, unconscious pattern recognition is often called intuition, since the decision maker cannot generally articulate his decision method (Chater et al. 2003). Previous experiences will lead a designer to develop preferences for or against certain aspects of a design or certain evaluation criteria.

A designer’s intuition may also allow him the ability to use attributes he feels are important to the design but the company’s management would not feel is important (Hsee 1996). If the designer understands the environment, he may know that the manager or executive is most concerned about the money-making potential of a product, while, as the designer, he may feel that aesthetic appeal (a “coolness” factor in the aircraft and missile world) is also important and will influence the company’s bottom line. If the designer is in a situation where there is uncertainty in the cost analysis, he may know that he can use “coolness” as a type of tiebreaker in the event that there is no clear-cut best design (Schweitzer and Hsee 2002).

2.2.3 Fallacies and Heuristics

Decision makers for large-scale aerospace projects want to have as much information as possible in order to make decisions. Unfortunately, decision makers often find that the information wanted isn’t available and the available information does not allow them to use rational decision making models, such as analytic hierarchy process

(AHP) or utility theory. Therefore, these decision makers either fall into the trap of decision making fallacies or they use decision making heuristics.

There are many decision making fallacies that designers can fall victim to. A common one for scientists or engineers is using small amounts of data as representative of large amounts of data (Tversky and Kahneman 1974). An engineer may gather a small amount of data for several design options and assume that, because this limited data points to one option as the best that that option is, in fact, the best. If the designer had gathered more data, he may have come up with a different solution. When a design decision maker is trained as an engineer, he may unconsciously decide that he cannot justify a decision unless he has hard data to back up his decision. He may believe that making a decision based on facts is more scientific and believable even if the decision wasn't made that way (Saaty 1994), and search for facts to back up any decision that he makes.

Other decision makers will fall victim to the sunk cost fallacy, which says that human are more likely to continue a project if a significant amount of time, money and other resources have already been spent even if the projected outcome is poor (McCray et al. 2002). Due to organizational constraints, many managers and designers are pressured to continue failing projects (Rizzi 2003), and the design decision maker may not want to admit a failure (Main and Rambo 1998) or feel as though money would be wasted if a new, untested design were suggested (Arkes and Ayton 1999). Another fallacy that can be a problem for strategic decision makers, particularly those whose decisions involve a large amount of uncertainty, is overconfidence. The overconfidence fallacy occurs when decision makers and managers believe that the future can be predicted with better accuracy than is actually possible (Lovallo and Kahneman 2003). The inability to correctly predict the future creates risk (Miller and Lessard 2001), especially if one doesn't understand how inaccurate predictions may be (Gigerenzer 2004). A designer who made good predictions in the past may believe that a project outcome was due to good decision making and predictive capabilities, rather than just luck (Newell et al. 2004) and so he becomes overconfident in his abilities. He increases programmatic risk not only by being unable to accurately predict the future, but by being overconfident in his ability to make those predictions (McCray et al. 2002). NASA’s space shuttle program and Concorde are examples of designers, managers, and politicians falling victim to the sunk cost and overconfidence fallacies (Arkes and Ayton 1999).

Decision makers are often tasked to make decisions quickly with little information and a large degree of uncertainty. One way to manage the uncertainty in the decision making process is through the use of heuristics, or rules of thumb. There are many heuristics that have been identified in many different decision making fields; however, only those deemed useful in this context are highlighted here.

One heuristic that can aid decision making is availability. When decision makers are looking over a large number of design choices, they can be more likely to choose a design that they have information about (Tversky and Kahneman 1974). The availability, or the ease at which information can be found or brought to mind, may have an impact on the final choice. When a decision maker can readily recall the pertinent information about system A but cannot recall pertinent information about system B, the decision maker may prefer system A since it is the more well-known and experienced system. The designer “perceives” less uncertainty in performance from the known system, than from the unknown system (Wickham 2003). An additional heuristic is recognition: the decision maker is more likely to choose a design that is recognized, rather than a design that is unknown, even if little is known about both designs (Gigerenzer and Goldstein 1996). The use of recognition and availability heuristics depends on the person making the decisions. A person is more likely to recall or recognize something from a situation that involves strong emotions (Muramatsu and Hanoch 2005), and that recollection makes a decision maker more likely to use the information, whether or not it accurately represents the situation at hand (McCray et al. 2002).

2.2.4 Biases

Biases can push a decision maker toward a particular decision at the expense of other, perhaps better decisions. Many of the above fallacies and heuristics could also fall under the definition of biases, but these are presented as occurring in the original literature. Some biases were discussed earlier: a decision maker is biased toward the company's product over the competitor's.

Other biases include status quo bias, whereby the decision maker sees less risk in continuing the status quo than in making a decision that would create a new product (Kahneman et al 1991). The new product design would have substantial start-up costs even before a determination could be made whether or not the project will be feasible and viable. If the project is successful, the reward may be great, but the probability or consequences of failure may be too large. It is much safer to just keep updating the existing designs than to risk bankruptcy if a new design goes poorly.

Corporate decision makers also face the anchoring bias, where the decision makers base what they think will happen on plans and scenarios rather than a reliable future assessment (Tversky and Kahneman 1972). Often the anchoring bias provides decision makers with the ability to make overly optimistic predictions based on future plans that may never materialize (Kahneman and Lovallo 1993). Because so many people believe that developing a future plan is important, other individuals are discouraged from questioning the plan and providing negative feedback; therefore, the future plan is used more and more often and the true situation outcome is a surprise instead of being expected.

2.3 Multi-Attribute Decision Making Techniques

As mentioned in the previous chapter, decisions made during the conceptual phase of product design and development have lasting consequences on system design. A design engineer would like to be able to do an exhaustive design space search and gather all available information about each and every design alternative before making a decision, but this is not practical. In contrast, most of these decisions are made with little or uncertain information and without examining all the possible alternatives for each situation.

Even when decision makers have only a limited set of options, engineering decision making is often modeled as an optimization problem using some multi-attribute decision making technique with attributes such as system performance and cost. Traditional techniques often assume that the user has a plethora of information about the system and its environment both now and in the future. For multi-attribute decision making techniques in general, the designer needs to know both preference weightings for attributes and future outcomes of a design choice, and these values are fixed in the assessment (Drake 1992).

2.3.1 Overall Evaluation Criterion

The overall evaluation criterion (OEC) is a multi-attribute decision making technique that allows the user to compare designs using many different design features in the same equation and on a similar scale. Hwang (1981) calls such techniques scoring models, since these techniques yield a model with the highest score or best utility. The OEC provides one number as a comparison, and can be set up such that either the maximum or minimum is the best solution, although it is usually set up as a maximization problem. The OEC equation needs a baseline design to use for comparison, and then information from any other models. The baseline can be a model or can be the best or worst for each criterion. An example generic OEC equation is given in Equation 1.

$$OEC = \alpha\left(\frac{Criterion\_1}{Criterion\_1_{BL}}\right) + \beta\left(\frac{Criterion\_2}{Criterion\_2_{BL}}\right) + \gamma\left(\frac{Criterion\_3_{BL}}{Criterion\_3}\right) + \ldots + \omega\left(\frac{Criterion\_n}{Criterion\_n_{BL}}\right) \quad (1)$$

The criteria to be used can vary from problem to problem, but for aerospace programs are generally performance and cost metrics. For criteria to be maximized—“benefit” criteria, such as profit, the equation is maximized when the criteria for the new design is divided by the criteria for the baseline, while for criteria to be minimized—"cost" criteria, the baseline is divided by the new design. The Greek letters are the weighting factors that allow for some criteria to be more important than others (Roy 2001) in order to rank customer preferences.

The OEC is very useful in that it provides a single metric with which to compare different designs. The single metric is simple and easy to use and understand. The OEC is easy to set up and transparent to use, since it involves a single step and simple mathematics. However, it cannot support trade studies showing which criteria are more important and can have scale problems if one criterion varies orders of magnitude from the baseline and others vary only 10%. As it is one equation, it is also difficult to show which criteria are driving the design and are having the biggest impact on the OEC. The OEC equation also assumes a linear relationship between criterion improvement and importance: a criterion may only be important if it is below or above a certain threshold, i.e. must meet minimum range requirements, but the OEC will continue to treat any increase in range above that value as important as a range increase below that value. The OEC also has the problem of only being able to use criterion that have quantitative values, so a mapping process is necessary for qualitative metrics.

2.3.2 Technique for Order Preference by Similarity to Ideal Solution

Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) is a multi-attribute decision making technique that allows for easy comparison between design solutions. Like an OEC, TOPSIS breaks down the different design attributes into one number that can be compared between designs. Also like an OEC, a TOPSIS problem is a maximization problem. The TOPSIS methodology is able to rank design alternatives based on their distance from a Euclidean ideal solution. Like an OEC, it uses criterion weightings to take into account customer preferences. Unlike the OEC, which is one equation, the TOPSIS analysis is a series of steps.

The first step is to create a decision matrix, as illustrates in Table II. This matrix has a list of the alternative designs and their attributes or evaluation criteria.

Table II: TOPSIS Decision Matrix

Alternatives

	Attribute 1	Attribute 2	Attribute 3	Attribute 4	Attribute 5
Concept 1	1.6	18.4	6.2	Low	Average
Concept 2	2.1	11.6	6.4	Low	High
Concept 3	1.8	14.7	7.7	Average	Average
Concept 4	2.2	16.9	7.5	Average	Low
	Objective			Subjective	

Evaluation criteria can be quantitative or qualitative. Qualitative criteria must be quantified using a mapping process over an interval scale—for example: excellent=9, good=5, poor=1. Now each box in the decision matrix is normalized by diving each attribute value by the norm of the total output vector of the criterion at hand; for the first attribute of Concept 1, this formula would be the one given in Equation 2.

$$\frac{1.6}{\sqrt{(1.6)^2 + (2.1)^2 + (1.8)^2 + (2.2)^2}} = 0.4124 \qquad (2)$$

Once the matrix has been normalized, the relative importance of each criterion is established using customer weightings and all values in each column are multiplied by the relative importance of that criterion. Then each criterion is determined to be either a benefit or a cost. The goal is to maximize the benefits and minimize the costs, so the positive ideal solution is the one that takes the maximum value of each benefit criterion and the minimum value of each cost criterion while the negative ideal solution is the one that has the minimum value of each benefit criterion and the maximum value of each cost criterion. The distance from each new concept or design to the positive and negative ideal solutions are calculated using Equation 3, and then the relative closeness to the ideal solution is calculated using Equation 4.

$$S_i{}^{*}\!\!\diagup_{-} = \sqrt{\sum\left(ConceptValue - Positive / Negative\_IdealValue\right)^2} \tag{3}$$

$$C_i = \frac{S_i^-}{S_i^* + S_i^-} \tag{4}$$

The alternatives are then ranked by the relative closeness to the ideal solution. All alternatives will fall on a zero to one scale, with larger values being better.

The TOPSIS methodology is a good multi-attribute decision technique for simple concepts where the results can be generated and regenerated very quickly. Its answers are very sensitive to changes in the mapping process for qualitative criteria and the customer preference weightings. It also only gives an overall “best” answer and alternative ranking, so a person with no knowledge of the process would be unable to figure out where that answer came from. The mathematics involved are more complicated than the OEC evaluation, but there is more information to be gleaned for the experienced user. A user familiar with the TOPSIS evaluation would be able to see which attributes contribute the most to the solution and whether any tradeoffs can or should be made in the customer preference weightings. TOPSIS, as an evaluation and decision support tool, is quick and easy to use and provides a great deal of information for the experienced user. Unfortunately, it can difficult to use qualitative information with TOPSIS due to the sensitivity in mapping. When many concepts are close in rankings, the uncertainty in attributes that is inherent early in the design process may make it difficult, if not impossible, to accurately distinguish between alternative concepts.

2.3.3 Expected Value and Utility Theory

The idea of an expected value was born of probability theory in the 1720’s (Apostol 1969). It is a measure of the value or, often, the “goodness” of a potential outcome. Expected value is often used in risk analyses and optimization procedures for complex engineering systems. Expected value is nothing more than the sum of the probabilities of a series of outcomes times the value of the outcomes, as given in Equation 5 (Hayter 1996).

$$E(X) = \sum_i p_i x_i \tag{5}$$

In a technical situation, expected value can be used to calculate the expected outcome of a set of solutions or a set of potential situations. Probability theory was also used to determine monetary values for engineering projects, but it had many drawbacks. Probability theory requires certain probability and outcome information, while in reality information is often uncertain. Just as with TOPSIS, uncertainty can overwhelm the differences between design options. Another problem with using probability theory and expected value to determine monetary value is that people are not rational when dealing with possibilities of gains and losses. The expected value function treats gains and losses as exactly the same in terms of value: an expected gain of $100 of one already possesses $1000 has exactly the same increase in value an expected gain of $100 if one already has $100,000, with the losses being the opposite.

In real life, people do not generally behave this way, and so utility theory was developed to better model how people behave. Utility theory was developed by Daniel Bernoulli in the 1730's ("Judgment, Choice and Decision Making" 2001). It is similar to expected value, except that Bernoulli postulated that marginal monetary increases have decreasing utility as the initial monetary value increases, with the same being true for decreases. He postulated that these increases and decreases will follow a logarithmic rather than a linear scale ("Judgment, Choice and Decision Making" 2001). A graph illustrating Bernoulli's theory is shown below in Figure 10. Expected utility allows for a more accurate representation of how people think than probability theory does, however, it also has some drawbacks. Along with the drawbacks associated with probability theory, a logarithmic function is more difficult to handle than a linear function, and different people argue over what, exactly, the function should be. People also have a difficult time understanding and handling the probabilities necessary to use utility theory (Gilboa and Schmiedler 2002). Human decision makers also understand, intuitively, that a monetary loss and a monetary gain should not be treated the same way, which they are in Bernoulli's utility theory (Schweitzer and Hsee 2002). This criticism is addressed later, by more cognitive theories of decision making and judgment.

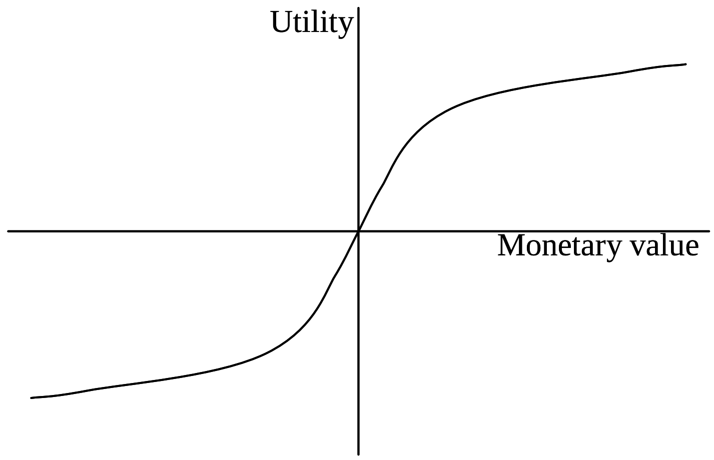

Figure 10: Utility vs. Monetary Value

For all the problems with utility theory, it is still the "gold standard" of decision making techniques (Gilboa and Schmiedler 1995). The majority of modern decision making techniques are based, in some way, on utility theory. Economists use it, with a few updates, to predict how people will behave in different economic situations. Marketing experts and businessmen can use it to determine how much to charge for a new product, and risk analysts can use it to determine and compare different risks.

CHAPTER 3

RISK BACKGROUND AND ASSESSMENT METHODOLOGIES

Risk is present throughout almost all aspects of life; as human beings, people often try to reduce risk but cannot eliminate it. Many different risk analysis methods exist in different industries. The goal of this chapter is to benchmark existing risk assessment systems or methodologies in an effort to answer research question two:

RQ4: Do any systems or methods currently exist that allow the user's judgment to make decisions in the beginning stages of conceptual design? While using a risk-benefit type of approach?

To answer this question, a basic understanding of risk is necessary. Risk will be defined and the aspects of risk that influence decision making will be introduced and briefly reviewed. Then, several industries will be reviewed for current risk assessment practices to determine whether these methods meet the criteria laid out in research question two: allowing the user's judgment to help make decisions while using both risks and benefits. If such a methodology is found to exist, then it needs to be tailored to the needs of the aerospace industry, and if such a methodology does not exist, what methods or information can be borrowed from other industries to help build this type of method?

3.1 Background and Literature Review

Risk is generally defined in terms of a probability and a consequence: the probability of some situation occurring and the outcome, or consequence, if that situation does occur. In a practical sense, the probabilities are generally small (significantly less than one) and the consequences are generally negative (Winfrey and Budd 1997). Risk assessors and decision makers rarely talk about the risk that an outcome will be better than projected, but often spend a significant amount of time and money to determine the risk of a project outcome that is worse than expected.

Due to the large design costs and, in the commercial world, a concern for customer safety, risk is inherent for large, long-term aerospace projects, so a risk management strategy is necessary for these projects. Risk management must take several forms: technical, managerial, operational, social, and financial risks, for example, must all be examined and managed (Winfrey and Budd 1997). While the risks of interest to a company are monetary, even those risks can take many different forms. Many of these risks are known risks with some certainties. For military systems, the direct monetary consequences are relatively certain: the DoD states the monetary value of the contract before it is signed and is required to adhere to contract stipulations. Technical risks, such as performance uncertainty, are also monetary in nature. Evolutionary designs also have less performance uncertainty than revolutionary designs, but again, for military systems the contract amount is dictated before the design is tested. For other new designs that use newly developed processes and/or products, there is uncertainty in the new technology performance and costs. When making new products, companies also must worry about the social risks, such as health consequences for both the workers and the general public. Healthcare costs for sick workers can be financially devastating for a company. Long-term projects in and of themselves can also have indirect monetary consequences for a company. Publicly traded companies, which American aerospace companies generally are, must also make money for their investors. Investors want to see stock price increases and dividends every quarter, so a company cannot choose to create a product that will put it in the red for an extended period of time. Large-scale engineering systems take many years to develop, so a company cannot devote too many resources to any one project and expect to continue to make money.

3.1.1 Definition of Uncertainty

There is often some confusion between the terms risk and uncertainty. Webster's New World College Dictionary's definition of uncertainty is lack of certainty, or doubt, while the definition of risk is the chance of injury, damage or loss, or dangerous chance or hazard. While the sense of uncertainty conveys vagueness or doubt, the sense of risk conveys a chance for damage or loss. So while uncertainty about an event's outcome means that the outcome is in doubt, the risk associated with that event means that the outcome is not only in doubt, but also that the outcome is potentially bad. In summary, uncertainty conveys only doubt or vagueness about an outcome or circumstance, while risk conveys that there is uncertainty about an outcome and that there are also potentially negative consequences associated with that outcome.

3.1.2 Risk Perception

Companies making commercial products, which include aerospace companies, must deal with the perceived risks of the customer base, which in many cases is the general public, as well as the actual risks associated with technical, financial, political, and other uncertainties. Risk perception is often more important than risk reality: after the terrorist attacks on September 11, 2001, many people thought that flying was very dangerous; however, even in 2001, a traveling American was 7.5 times more likely to be killed per passenger mile in a car than an aircraft (Bureau of Transportation Statistics 2004). Even though the statistics say that it is safer to fly than drive, many people still choose to drive and say that they feel safer driving; this irrationality shows the difference between "risk perception" and "risk reality" (Slovic et al 1976). Decision makers must understand the risk perception part of the equation in order to create viable products.

There are many factors that a decision maker should understand when learning about risk perception. The general public is concerned primarily about risks that fall into the following three categories (Crouch and Wilson 1982):

- Known risks that have occurred and have the potential to occur in the future
- Risks that are catastrophic, even if the probability is very small
- Risks that conflict with long or strongly held opinions

Slovic, Fischhoff and Lichtenstein listed three factors that influence public perception of risk as familiarity, dread and exposure (Slovic et al 1979 and 1981), so there is some overlap between these two theories. Public perception of risk can have other components: the wording or framing of a potential risk can also have an effect on how the risk is perceived. A positively framed outcome will have a lower perceived risk than a negatively framed outcome (Gonzalez et al 2005). The media also helps frame risks for the general public. Attention by the media makes risks appear more real and more likely to many people. The media's attention to some types of risk, and the consequential public perception of those risks, has led to large amounts of government money being spent to reduce already small risks at the expense of other, larger risks (Ashford 2005). Since there is often some disagreement within the scientific community about the exact nature of a particular risk, the general public with a comparatively lower level of scientific expertise, perceives many aspects of daily life to be more risky than he should (Fischhoff et al 1978); the public is not necessarily capable of making the distinction between possible risks and potential risks. Potential risks are actually plausible, while possible risks may only be a figment of the imagination, but public perception is often influenced by possible, not potential risks (Salaun-Bidart and Salaun 2002).

Emotions, especially fear and trust, play a role in the perception of risk and choices people make (Muramatsu 2005). People often overestimate the risk of very emotional events, such as a commercial aircraft or space shuttle accident. Public perception of the safety of a product has an influence on whether or not customers purchase the product and therefore the company's bottom line. Strategic marketing practices can help alleviate customer safety concerns in many cases (Slovic 2003), but not all. It has also been observed that happy decision makers are more optimistic and more inclined to take risks than unhappy decision makers. Happy decision makers anticipate feeling better after making a decision, whatever the outcome, than unhappy decisions makers and so may be more risk taking than their depressed counterparts (Loewenstein and Hsee 2001).

3.1.3 Risk Aversion

It has long been noted that, in general, people are risk averse: they prefer a "sure thing" over a chance outcome when expected values are the same (Kahneman and Lovallo 1993, Lane and Cherek 2000). People are also generally loss averse—most people feel that potential losses represent a larger risk than potential gains (Kahneman et al 1991, Thaler et al 1997). This is one of the places where utility theory fails to accurately portray real human behavior, since it assumes that gains and losses are perfectly offset. Understanding this behavior can help decision makers better evaluate their own sense of risk aversion and their management's feelings on risk taking, since organizations, as much as people, tend to be risk averse (Callopy 2003). This theory on risk aversion helps explain some company inertia regarding the creation of revolutionary systems. Companies that are risk averse will continue to use and refine an existing system as long as possible before undertaking the design of a revolutionary system. The revolutionary system has too large a potential for loss, and the decision maker does not want to be responsible for such a large potential loss.

One caveat to the theory of risk aversion is Prospect theory. Prospect theory states that people are risk seeking with low probability gains and high probability losses while being risk averse over high probability gains and low probability losses (Kahneman and Tversky 1979). Prospect theory also postulates that people are more sensitive to small and moderate losses than they are to small and moderate gains (Byrns 2004). This theory helps explain why people continue to play the lottery even when the probability of wining is very low or why people will continue to gamble on gameshows even though the probability of winning a large amount of money is smaller than the expected value of the buyouts offered: there is no loss associated with failing to win the large prize.

3.1.4 Social and Political Risk

Social and political risks can have many definitions. A broad definition of political risk encompasses any and all impacts of the political process on business practices. In a more practical sense, political risk is the potential negative impact of politics and associated politicians on a product life cycle (Bremmer 2005). Social risk is more difficult to define. One definition, from Miller and Lessard, is that social acceptability risk is “the likelihood that sponsors will meet opposition from local groups, economic-development agencies, and influential pressure groups” (Miller and Lessard 2001). Another definition is that social risk “refers to the impact of organized behavior—business, the public sector or civil society—on society as a whole” (de Jongh 2004). By whatever definition is chosen, the behavior of the general public or subsets thereof will have an impact on the decision making processes of a company engaged in a design process.

Social risks have varying impacts across the decision making spectrum. Some decision makers worry about social risks from lobbying groups or other well-organized non-governmental organizations who challenge and try to change business practices, while other decision makers worry about the potential for grass-roots, unorganized groups to impact the company’s financial future (Yaziji 2004/2005). Worries in the aerospace industry can include social risks associated with groups who are opposed to overseas manufacturing and overseas labor practices, groups who are opposed to environmental practices here in the United States, and labor unions who are opposed to changes in business practices. Other company worries take the form of human and environmental health and safety. It is very costly for a company to do an environmental cleanup or to deal with a human safety issue, so most companies try to avoid these types of conflicts. Companies in the aerospace and other industries need to understand and take into account changes that may occur in the social landscape during their product’s life cycle.

Political risks are generally more easily recognized than social risks. It is well known that political factors can influence decision making (Schwartz 2001), especially in the aerospace industry. Aerospace corporations worry about politicians and governments changing policies (Miller and Lessard 2001), and about changes in the politicians themselves during election years. The industry has pro-industry lobbies at the state and national levels, but companies still worry about lobbies that target the aerospace industry for vilification. Aerospace companies also worry about unintended consequences from other laws passed, such as those that regulate the environment or imports and exports of parts and labor.

3.1.5 Calculating Risk – Risk Assessment

Risk calculation is an issue for any engineering project. The calculation of risk allows for comparison between risks and projects and enables the selection of risks for mitigation. The goal of a risk assessment is to help decision makers to understand risks and enable decision makers and managers to make more informed decisions (Black 2001). While unfavorable risk assessments can sometimes cause projects to be downscaled or eliminated, it is not the goal of any risk assessment to eliminate risk; viable risk-free projects are non-existent and cannot be created (Callopy 2003, Manuele and Main 2002). Successful engineering projects aren't necessarily the ones that are safest and have the lowest risk, but they are often the ones where the risk is understood and managed from early in the design process (Miller and Lessard 2001).

A risk assessment often takes the form of a single number that encompasses an expected loss (Yellman 2000, Winfrey and Budd 1997). Traditional decision theory uses utility theory to measure the expected loss or expected outcome for risks (Slovic et al 1974). Utility theory is the most widely used risk assessment approach because it takes into account both probabilities and consequences for a risk and is able to collapse the risk into one number that is easily comparable across risks and projects. Utility is also an intuitive way to calculate risk and, due to its deterministic nature, is easy to understand and use.

However, the use of utility theory as a risk assessment approach has some limitations. One of the limitations, explained above in the utility theory section, is that it requires deterministic information for an assessment. Using average probabilities and consequences in a utility-based risk assessment can greatly underestimate actual risk (Elmaghraby 2005). Utility theory is difficult to use for low-probability, high consequence events (Chichilnisky 2000, Haimes 2004). When the probability of an event occurring goes to zero and the consequences go toward infinity, a mathematical assessment of risk becomes almost meaningless. There is difficulty in assessing both the probability and the consequences in such a situation. For example, since there has never been a large-scale, catastrophic nuclear accident in the United States, a risk assessment has no data to back it up. The assessors and decision makers know that the probability of such an event occurring is low but may not know how low: 1 in 10^9 vs. 1 in 10^{12} are both very small probabilities that may, in fact, be so small that it is difficult to differentiate between them even though there is a difference of three orders of magnitude. The same problem occurs on the other end with consequences: it can be difficult to differentiate between large consequences of different orders of magnitude. For example, a disaster could claim the lives of 1,000,000 civilians vs. a disaster that claims the lives of 10,000,000 civilians could be treated equally even though the loss of life was an order of magnitude greater in the second example. These issues make it difficult to compare the risks of low-probability, high consequence events to the risks of other events. One of the ways to get around this problem is to add another term to the utility assessment that accounts for a decision maker's desire to avoid a situation with catastrophic consequences (Chichilnisky 2000). Another problem with using utility theory as a risk assessment tool is the difficulty that one has placing a monetary value on human life and safety (Ashford 2005). It can be difficult for a company to accurately assess the value of a particular life, even if a general formula is available for assessing the value of a human life.

Another problem that is inherent to any risk assessment algorithm is that many times probabilities are not numerical but verbal. Risk assessors are often left trying to figure out the probability of a “low probability event.” Does that mean that the probability is 1 in 10, 1 in 1000, or 1 in 1,000,000? Since probability terms are vague, and differ between individuals, risk assessors can have a difficult time with this task (Gonzalez-Vallejo 1994). Risk assessors and decision makers generally want to quantify the probabilities of events occurring as much as possible in order to avoid vagueness (Kuhn and Budescu 1996).

3.2 Current Risk Assessment Methodologies

Many industries complete risk assessments before providing a product or service. While Section 3.1 provides a brief literature review of different aspects and schools of thought on risk assessment and calculation, this section will provide a brief review of some industries and their current risk assessment practices. In an effort to provide a cross-section of assessment methodologies and practices, both technical and non-technical examples will be cited. The purpose of this section is to see what methods currently exist and what information or suggestions can be borrowed from different industries and used for a conceptual design phase, business-case risk assessment in the aerospace industry.

3.2.1 Commercial Aerospace Applications

Commercial aerospace companies, such as the Boeing and Airbus Corporations, conduct risk analyses during the design, development, and certification of all new aircraft. For commercial aircraft, safety, reliability, and maintainability are of utmost importance (“ARP 4754” 1996). Safety and reliability are of particular importance to government regulatory agencies, such as the FAA and the European Aviation Safety Agency (EASA), who eventually certify the aircraft as safe enough for commercial transport. Regulatory agencies are less worried about the business case than the corporation and do not complete a business case risk analysis. The corporation designing and building the aircraft completes a business case analysis for the aircraft's potential life cycle; however, it is not necessarily in the form of a classical risk analysis.

Since risk in the commercial aerospace sector is usually defined in terms of safety and reliability, the techniques developed to analyze risk use safety and reliability as their overarching metrics. The procedures for completing a safety assessment for a commercial aircraft are laid out in Aerospace Recommended Practice (ARP) 4761, compiled by the Society of Automotive Engineers (SAE) Technical Standards Board. The safety assessment process includes a functional hazard assessment (FHA), preliminary system safety assessment (PSSA) and a system safety assessment (SSA) ("ARP 4761" 1996). An FHA is defined as "a systematic, comprehensive examination of functions to identify and classify failure conditions of those functions according to their severity" ("ARP 4761" 1996). FHAs are carried out on at least two levels, aircraft and system, and are updated as necessary throughout the design and redesign processes. The PSSA lists failure conditions and corresponding safety requirements while the SSA is used to evaluate whether the system design meets the safety requirements laid out in the PSSA. Tools for use at this level of safety and reliability assessment include failure modes and effects analysis (FMEA), fault tree analysis (FTA), dependence diagrams, and Markov analysis ("ARP 4761" 1996).

Safety and reliability analyses of commercial aerospace systems are completed in a top-down fashion, going from system to sub-system to component. In the commercial aviation world, the goal is to create a fail-safe system: a system which can withstand multiple failures without a catastrophic effect ("ARP 4761" 1996). All of the approaches and methods listed in the paragraph above are utility-based, numerical methods that do not take into account uncertain or changing data.

Commercial space industries are similar to commercial aircraft transportation in that they also complete safety and reliability risk assessments; however, after the launch phase, the risk assessment almost totally involves component and system reliability with little thought to human safety. Boeing Corporation uses a total risk management procedure, in which the company completes a risk assessment not only for its own systems, but also for sub-contractors' and financiers' systems. ("The 'Services' at…" 2003).

At the corporate level, a significant amount of money is needed to finance the development of new commercial products and to bring new technologies to the point where they can be utilized. Having to acquire large sums of money necessitates a different sort of risk analysis than one dedicated toward safety and reliability. This type of financial risk analysis is carried out by both the corporation borrowing the money and the creditor lending the money and involves making a determination of whether the corporation will be able to pay back the money it has borrowed. Section 3.2.3 explains this process in further detail, but this process involves looking at the borrowers current assets, projected assets, and projected income to determine whether the borrower can repay the loan.

In general, aerospace commercial risk analysis processes are designed to examine risk in the forms of safety and reliability. While these analyses are necessary, the analyses are not designed to examine risk arising from external factors, such as socio-political factors.

3.2.2 Government Aerospace Applications

The National Aeronautics and Space Administration and the Department of Defense have sets of risk assessment and mitigation policies and procedures for defense department and aerospace missions. The DoD is charged with making sure that DoD personnel, including military personnel and civilian contractors, can complete their missions as safely and effectively as possible. NASA, similarly, is determined to see that NASA personnel, especially NASA astronauts, can complete their missions as safely and effectively as possible.

NASA is the governmental branch charged with space exploration and aeronautics development. Since it involves completing missions no one has completed before, space exploration is risky; therefore, it is not surprising that there are procedures in place to calculate and mitigate risk. NASA has a continuous risk management plan in place that shows the five steps to risk management at NASA. An illustration if this plan is shown in Figure 11. The risk mitigation plan contains five steps and is iterative: identify, analyze, plan, track, and control risks. Interspersed throughout all the steps is communication and documentation (“Risk management…” 2004).

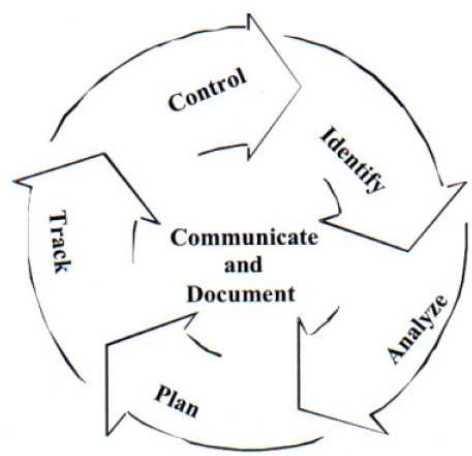

Figure 11: NASA's Continuous Risk Management Plan (“Risk Management…” 2004)

The purpose of this set of procedures is to first identify and analyze risks, then take steps to mitigate any risks that need mitigation, and, finally, to document the process for use by later projects. The continuous risk management process is outlined in more detail in Figure 12 below. The process begins with project outlines and constraints, and involves the identification of risks, risk mitigation plans and tracking requirements, risk status reports as time goes on and the project moves forward, and decisions about a project's risk. The goal of this process is to reduce the risk for a given project and to track the remaining risk. Elimination of all risk is not a feasible goal, and so risk reduction is considered to be the state of the art.

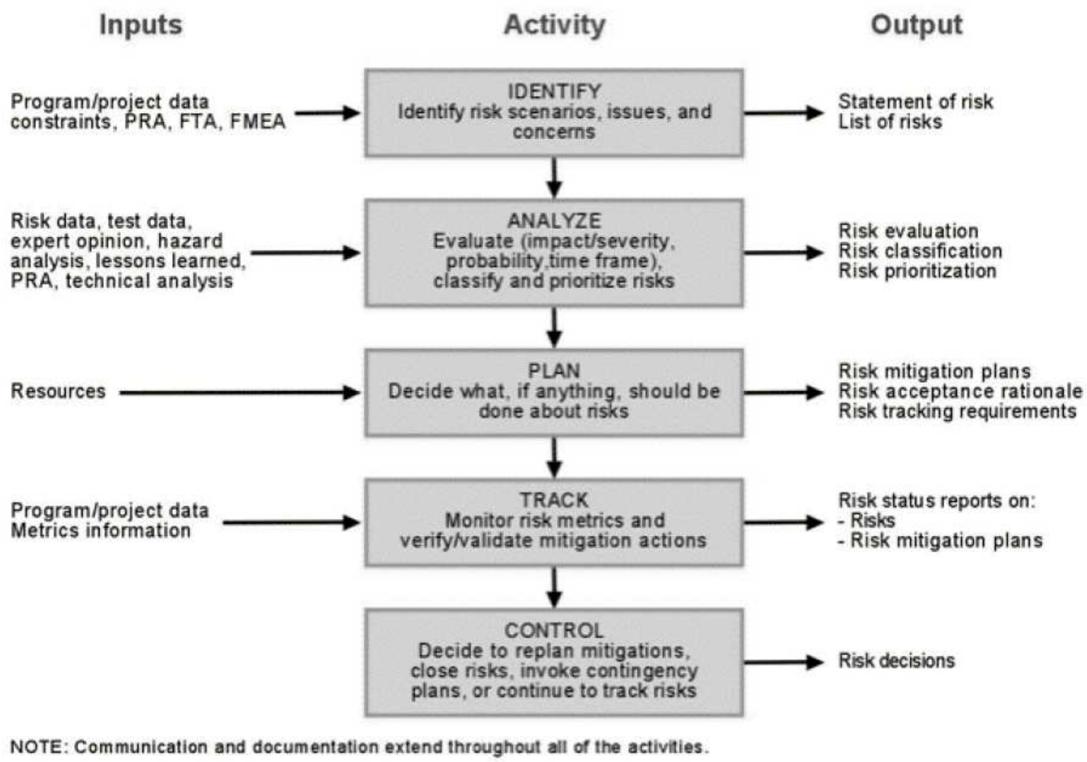

Figure 12: NASA's Continuous Risk Management Process Steps ("NASA Program…" 2005)

For each project, NASA completes a 10-step probabilistic risk assessment procedure ("Probabilistic Risk Assessment…" 2004):

1. Definition of Objectives: state study objectives including time-frame, analysis goals, rules, and product configuration. Also state any undesirable consequences (end-states) that can occur.
2. System Familiarization: understand the system in question through the use of drawings, operating and maintenance procedure manuals, and, if possible, an actual inspection of the system.

3. Identification of Initiating Events: identify and analyze any events that can cause accident scenarios. Event identification can take the form of logic trees, FMEA, etc during different phases of the mission.
4. Scenario Modeling: using event trees or similar tools/techniques, break down each accident scenario into a series of events that ultimately lead to the accident or system breakdown.
5. Failure Modeling: model failure causes identified in the scenario models above using fault trees or similar tools.
6. Quantification: link fault trees and scenario modeling to estimate the probability and consequence of end-states that are undesirable, using the scale in Figure 13.
7. Uncertainty Analysis: through the use of Monte Carlo simulation or related methods, add uncertainty to probabilities and consequences determined above.
8. Sensitivity Analysis: analyze uncertainties in assumptions and models.
9. Ranking: identification of dominant contributors to the project risk.
10. Data Analysis: collection and analysis of data to support the risk assessment.

	LIKELIHOOD ESTIMATE				
CONSEQUENCE CLASS	A	B	C	D	E
I	1	1	2	3	4
II	1	2	3	4	5
III	2	3	4	5	6
IV	3	4	5	6	7

Figure 13: NASA's likelihood and consequence risk estimate ("Risk Management…" 2004)

The probabilistic risk assessment is designed to be able to be completed for every project. The amount of risk will differ from project to project, and the risk tolerance differs between manned and unmanned space project. As a human life is more important than a computer, risk tolerance is lower for manned space projects than for unmanned.

However, since astronauts are specially trained professionals and volunteered for their positions, risk tolerance for manned space programs is much higher than risk tolerance for commercial airline traffic. NASA considers the safety of crew and ground personnel to be of utmost importance when completing a risk assessment.

The DoD has a risk management procedure for acquisitions that is similar to the NASA procedure. It has five steps, and is an iterative process through these steps: risk identification, risk analysis, risk mitigation planning, risk mitigation plan implementation, and risk tracking ("Risk Management Guide…" 2006). These five steps are similar to those listed in NASA's Continuous Risk Management Plan. An illustration depicting the DoD's risk management process is in Figure 14.

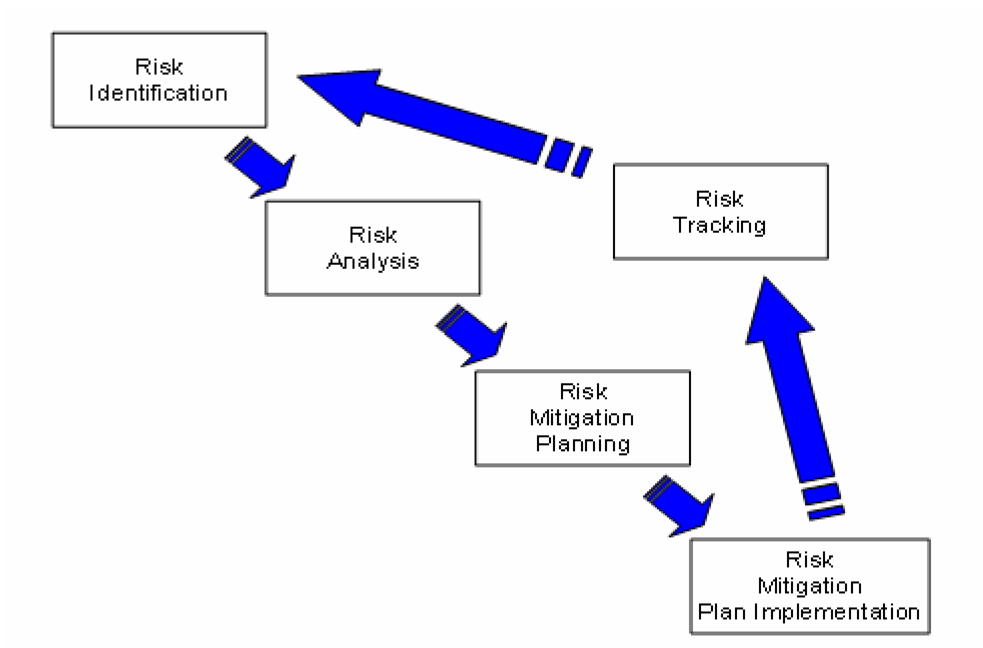

Figure 14: DoD Risk Management Process ("Risk Management Guide…" 2006)

The five key activities are carried out over the life of the program. The DoD does not consider a risk analysis to be static, rather, it should be something that is continuously updated as new information is available. The goal of the risk management process is not to eliminate risk, rather, it is to track the risk associated with a project and determine whether the risk falls into an acceptable range. Tracking the risk of a project through time is an important component of the DoD risk management process ("Risk Management Guide…" 2006).

The first key activity in this process is risk identification. This task identifies the risk associated with technical, cost, and schedule parameters and goals as well as the root causes of a risk. This task breaks down risk into root causes that can be identified and explained. After this, the risk is analyzed in terms of performance, cost, and schedule parameters. Levels of likelihood and consequences of each risk are determined, similar to the NASA procedure, and the corresponding level of risk is also determined using a risk reporting diagram similar to the one in Figure 15. The risk reporting diagram is then amended to include the risk mitigation plan. Once the plan has been determined, it can be carried out and the result tracked ("Risk Management Guide…" 2006). Since NASA and the DoD are both part of the federal government, it is not surprising that their risk analysis and mitigation plan procedures have some similarity.

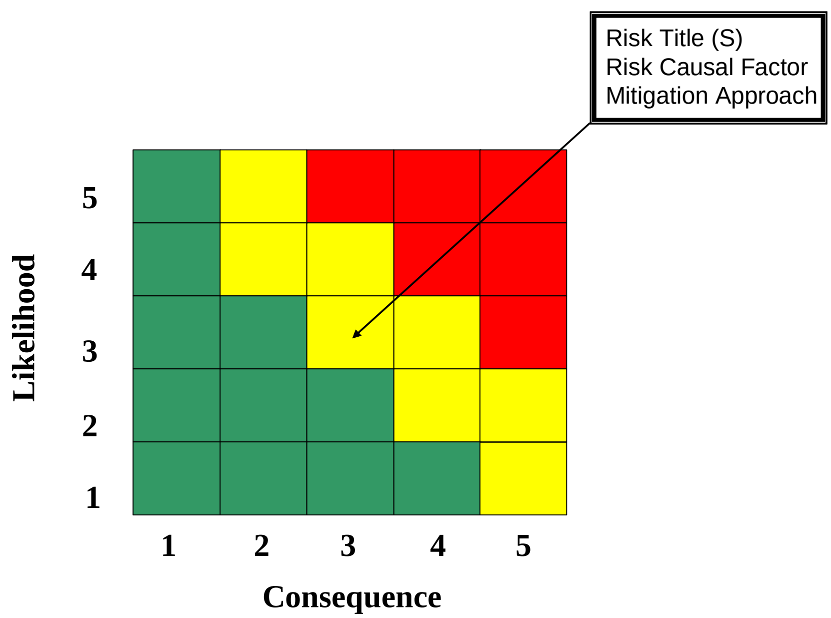

Figure 15: Risk Reporting Diagram ("Risk Management Guide…" 2006)

NASA and the DoD, along with other government agencies, do their best to decrease risk as much as possible. If risk cannot be decreased, it must be tracked to the fullest extent possible. Like the commercial sector, the goal of both communities, particularly NASA, is to ensure the health and safety of their personnel, and the agency feels that risk analysis, mitigation, and tracking is the best way to do this. Again, these risk analysis processes were not designed to be used to determine risk levels from outside sources.

3.2.3 Nuclear Industry

The nuclear industry, including the Nuclear Regulatory Commission, is in the business of creating a very safe, very reliable energy source. Since there is a lot of fear among the general public about nuclear reactor safety (Slovic, Fischhoff, and Lichtenstein 1976), safety is a top priority. Risks in the nuclear industry fall into the category of low-probability, high-consequence events. These types of events are not well-served by traditional measures of risk, such as utility. Since the potential damage done by a nuclear reactor accident is so large, the consequences of such an event outweigh the small probability of such an accident. No matter how small the probability of an accident may be, many people will continue to fear nuclear power and the industry will continue to try to reduce the risk of an accident.

Risk assessment in the nuclear industry involves copious amounts of data and analysis of that data. Risk assessors, along with reactor workers, managers, and regulators, try to assess what situations could cause a failure, evaluate the likelihood of such a situation, and reduce the likelihood that a particular situation occurs. Plant workers, assessors, and statisticians evaluate each piece of the nuclear reactor and plant to determine what is most likely to fail and when that should happen. The risk assessment is usually carried out by statisticians and government officials from the nuclear regulatory commission, who determine what pieces of equipment should be tested and monitored and how often this should happen ("What We Do" 2007). The emphasis is on reducing the probability that an adverse event will happen, not on decreasing the consequences of that event. Since a massive nuclear accident has not happened in the United States, the exact nature of the consequences of such an accident is largely unknown, but can be inferred by looking at data from other, overseas, nuclear accidents. No matter how much time and effort is put into evaluating the safety of nuclear power plants and fixing any known flaws, the probability of a catastrophic event will always be greater than zero; therefore, many people will always consider the creation of electricity by nuclear fission to be a very risky endeavor.

Risk assessments carried out by the nuclear community are generally good at determining situations that can cause mechanical or human failure and compromise the safety of those in and around the reactor. These assessments are designed to be precise and mathematical and to reduce the probabilities of failure; the assessments are not designed to assess political or economic events.

3.2.4 Banking and Loans

The banking industry is in the businesses of lending and investing. While different banks manage their investments in differing ways, lending policies are more standard across different institutions. Banks can lend money to individuals or families for individual purposes, such as purchasing a house or automobile, or banks can lend money to individuals and businesses for business purposes, such as starting a business or making purchases to increase business capital.

For smaller banks, individuals and families make up the majority of their loans and for many larger banks these loans still make up a significant percentage of the total loan dollars given out. Loans to individuals are given out based on a risk assessment that seeks to determine the likelihood of the individual defaulting on the loan and the interest rate that such a borrower should receive for a particular loan. In most cases, this assessment uses a combination of factors, including the individual’s credit score, income and current debt obligations as well as large-scale economic data such as inflation and prime interest rate trends (Brumbaugh 2004).

Information about income is provided by the loan receiver, and credit score information, including debt obligations, is gathered by the loan grantor. Income comprises any income that the loan receiver wants to be counted for the purposes of qualifying for the loan, and the credit score is used as a predictor of the loan receiver's chances of defaulting on the loan (Gutner 2005). Credit scores are individual and calculated based on an individual's loan repayment history, length of the credit history, amount of new credit applied for, the types of credit used, and the individual's total debt. The risk of defaulting on a loan is linked to an individual's credit score and debt/income ratio (Gutner 2005). Interest rates reflect this risk along with the type of loan being considered. For example, home mortgage loans are lower-risk than many other loans, for both the borrower and lender, because real estate generally increases in value; however, other major purchases, such as boats or electronic toys, generally decrease in value once they are purchased. For this reason, banks often charge higher interest rates for boats than for homes.

Loans given by banks and investment companies to businesses are structured differently than loans to individuals. Businesses, like individuals, are judged to be risky based on their credit-worthiness, which includes information about past, current and projected profits and/or losses, the current debt/income ratio and the short or long-term company business plan. Loans to businesses are often variable interest rate instead of fixed-rate, and can have requirements attached to that rate. For example, the lender can require that the borrower change business plans or maintain a certain revenue in order to keep the interest rate low (Ng 2006). Lenders have an interest in making sure the borrower doesn't default on the loan and so are able to impose these restrictions on higher-risk borrowers.

In summary, the risk assessments in the banking industry take the form of assigning risk based on statistics and monetary information. While these techniques are good at assigning a risk level to a borrower, transparency is lacking for many of the analyses.

3.2.5 Personal Insurance (Home, Automobile, etc.)

Personal insurance, such as homeowners, renters, and automobile insurance, is issued by companies that are prepared to assume the risk of loss that corresponds to a particular person and asset. Since many people cannot rebuild a house or purchase a new automobile if a disaster should happen, insurance companies offer to assume the risk of the losses in exchange for money. Insurance companies complete a risk assessment before issuing an insurance policy and price. As the insurance company's goal is to make money, it behooves the company to have an accurate risk assessment. The insurance industry is a government regulated industry with limits on what will be covered and how much can be charged for that coverage, and so any changes to insurance underwriting policies must be approved ("Northeast…" 2006).

For automobile insurance, a company risk assessment takes into account where the recipient lives, the recipient's age and gender, the make and model of the automobile(s) being insured and the number of miles driven per year ("Insure Your Auto" 2006) in order to put the recipient into a general risk pool. This risk pool depends heavily on the availability and use of statistics, and can have a significant impact on the price the recipient pays for automobile insurance. For example, teenage drivers have a much higher accident rate than middle aged drivers and so teen drivers pay higher car insurance rates ("Insuring Teen Drivers" 2006).

After the insurer has assigned the general risk pool, he then wants more personal information about the recipient and car driver to determine a more personal risk rating and see if the recipient is more or less risky to insure than other, similar, insured persons in their risk pool. Certain groups of people have lower average insurance losses than others, and that lower risk can mean better insurance prices. One of the newer trends for assessing risk in the automobile and homeowner insurance industry is to use an individual's credit score as an assessment tool ("Surviving the 'hard market'…" 2004), since people with lower credit scores tend to average more losses.

Homeowners insurance providers do similar types of risk assessments. Insurers must consider the location of the home and the potential for catastrophic loss in the area (Arnold et al 1997a), as shown in Figure 16 for earthquake potential losses.

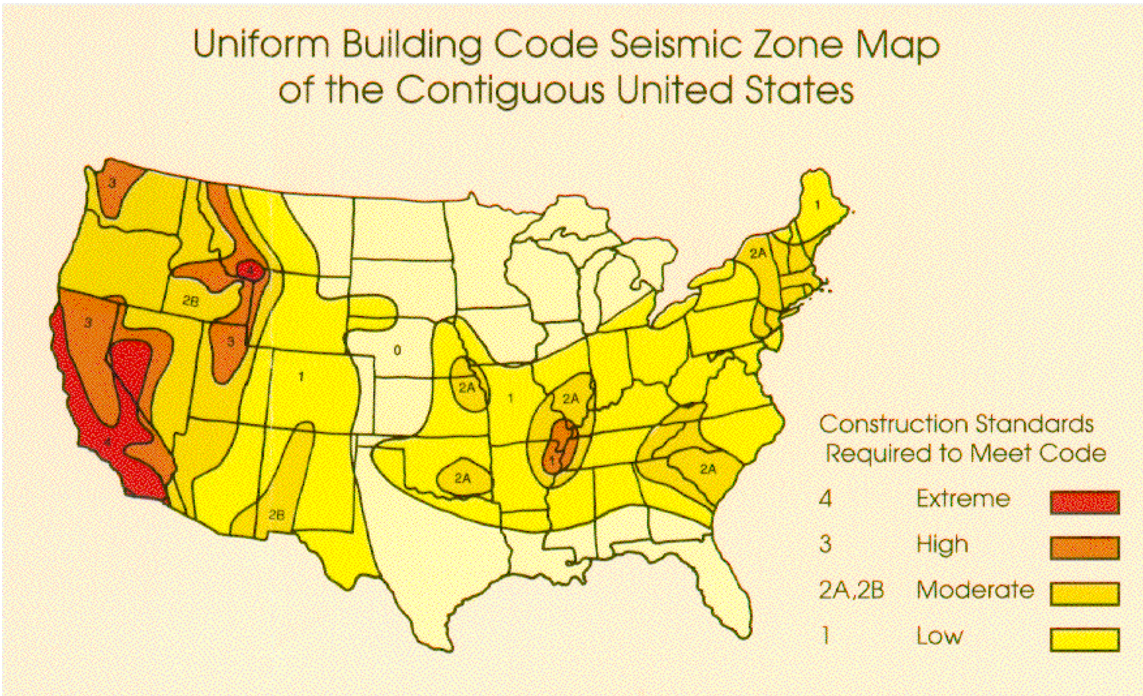

Figure 16: Earthquake Hazard Map ("Uniform…" 2006)

Catastrophic losses account for approximately 85% of insurance payouts (Arnold et al 1997a), so understanding the potential for loss can have a significant impact on the insurance company's profit. Predicting these losses involves sophisticated computer models that predict potential hazards, including earthquakes, tornados, hurricanes, floods, and fires (Arnold et al 1997b). For individual policies, the location and associated hazards along with the building construction determine the coverage offered and cost of said coverage to the consumer (Arnold et al 1997a). The computer models have proven inadequate in recent years, and insurance companies have paid out more in claims than they have taken in in premiums (“Surviving…” 2004). Many insurers are now choosing to discontinue or limit coverage in high-hazard area of the country due to the historical underestimation of risk in these areas, or are substantially raising premiums (“Surviving…” 2004, Ramirez 2006). In many cases, this trend has forced the federal government to play a role in homeowners insurance: the government provides flood and earthquake insurance in high-risk areas (Prahl 2000).

The home and automobile insurance industries base their risk assessments on statistical data and computer models. Insurers are currently leaving high-risk markets due to catastrophic losses; this is example of what happens when the statistics and models are incorrectly predicting the future.

To summarize, insurers complete risk analyses based on statistical information about all clients. While these analyses are quite good at determining the level at which to set an insurance premium in order to remain competitive but still remain profitable, there is little transparency in how the underwriting is completed. Also, homeowners and automobile insurance is designed to prevent physical and monetary loss for the insurer and insured, but it does not take into account how macroeconomic conditions can affect these losses.

3.2.6 Government Influence to Personal Safety

The United States government has an interest in a safe and healthy populace; therefore, various government agencies have been created to protect and serve the needs of the US population in risky situations. Government regulations cover everything from automobile emissions to the required reporting of certain contagious illnesses by doctors. For example, the Food and Drug Administration’s (FDA) stated mission is (“FDA...” 2006):

- *To promote and protect the public health by helping safe and effective products reach the market in a timely way,*

- *To monitor products for continued safety after they are in use, and*
- *To help the public get the accurate, science-based information needed to improve health*

The FDA regulates most food and legal pharmaceuticals consumed by people living in the US. It is the job of the FDA to test the safety of new food and drug products before they are marketed to the general public. To do this, new food and drug products are first laboratory tested and then tested on animals and finally tested on human volunteers before being evaluated for general public safety. If the new products meet the safety (for food) or safety and efficacy (for pharmaceuticals) standards, than these products are released ("FDA…" 2006) for public consumption. This process can take months or years, and is not perfect; sometimes products previously thought to be safe are discovered to have long-term side effects and are removed from the market.

Other government entities, such as the Environmental Protection Agency (EPA), and the Federal Aviation Administration (FAA) have similar mandates to protect public health and safety. These agencies, like the FDA, complete a risk vs. benefit analysis for new products or technologies before certifying them. The goal is for the product's benefit to society to outweigh the public health risk associated with that product. As with new food and drug products, there is sometimes a long time period between when a product is first certified and when public health concerns are raised and products are removed from the market.

One of the problems associated with products whose side effects only show up in a long time-scale is that public trust in the certifying agencies is eroded (Slovic, Fischhoff, and Lichtenstein 1979). Some products, such as leaded gasoline, x-ray machines in shoe stores, and some pain medications, have been defined as dangerous after they have been on the market for many years; consumers feel difficulty in determining what products are actually safe and what will be declared dangerous at a later time. This problem has led to more stringent regulations for certifying a new product, and increasing time and cost to get a new product certified.

Risk analyses completed by government agencies stress public safety. These agencies and analyses are necessary to regulate the consumption and/or use of dangerous products. The analyses are purposefully designed to not take into account any political risk, although some social risk is analyzed.

3.2.7 Risk Analysis Needs

For the goal first identified in Chapter 1: to set up a risk analysis procedure that can be used by engineers during conceptual design to track and evaluate economic and socio-political risk for use in decision making, many of these risk analysis processes have some necessary pieces. There are seven aspects of a risk analysis that are useful:

- Uses quantitative information
- Uses qualitative information
- Evaluates technical risk
- Evaluates economic risk
- Evaluates socio-political risk
- Can be completed with little information
- Is intuitive to human thinking and allows human to be final arbitrator

Both quantitative and qualitative information are available during the early phases of design, so a risk analysis that can handle either qualitative information or a mapping process is necessary. Since risk comes in many forms, a good aerospace system risk analysis process should be able to evaluate technical, economic, and socio-political risk. Since there is little, uncertain information available during conceptual design, the analysis should be doable with the information available. The human needs to be the final decision maker in design, so a risk analysis should be intuitive to human thought.

Unfortunately, none of the procedures examined meets all the criteria of a risk analysis process that this author has determined are necessary for this problem. The technical risk analysis procedures, such as those used in the engineering world, are very good at evaluating technical risk and using quantitative information. Some also have the ability to evaluate certain types of economic risk and use some qualitative information. In the banking and insurance worlds, evaluation of economic and socio-political risk is normal, and both quantitative and qualitative information is used. In general, risk analysis procedures require as much information as possible, and procedures are not necessarily intuitive to human thinking.

Since none of the industries benchmarked above fulfills all the wants for a risk analysis, a new procedure needs to be developed that takes some information and processes from the existing methods. This new method should be able to use quantitative and qualitative information, evaluate technical, economic, and policy risks, and provide decision support for the human decision maker so he can understand and trace how his decisions are made.

CHAPTER 4

WORKING WITH FUTURE UNCERTAINTY

In the previous chapter risk analysis techniques were benchmarked as per research question two. As risk arises from uncertainty, uncertainty is also present. Since the future is unknown, it is uncertain and that uncertainty needs to be modeled. In this chapter, research question three will be examined:

> How do we deal with uncertainty in the early phases of design when doing
> a risk-benefit analysis?

Uncertainty is inherent in any prediction of future events. The question above asks how to handle that uncertainty. There are several ways of doing this. Uncertainty can be ignored, and all data can be treated as deterministic. This is not recommended, since it does not reflect the actual uncertainty in real life. Two other ways of dealing with uncertainty are probabilistic analysis and scenario based analysis.

4.1 Probabilistic Analysis

One way to deal with uncertainty in large, long time-scale engineering projects is probabilistic analysis. Probabilistic analysis helps to bound uncertainty and analyze it. Probabilistic analysis is the first step toward analyzing uncertainty after a deterministic analysis is complete. In a traditional deterministic analysis, uncertainty about the future is ignored and a “best guess” is made about what value a parameter will have in the future. For example, if one is trying to analyze an airline’s total operating cost per seat-mile for a new aircraft, one of the parameters that is assumed is the cost of fuel. In a deterministic analysis, the cost of fuel would be set to a fixed number, which would represent the user’s best guess as to what the cost of fuel will be in the future. In a probabilistic analysis, that fuel price would be set as a range with high and low values. Setting the fuel price as a range, instead of a value, also implies that the output, or total operating cost per seat-mile, will also be a range, instead of a fixed value.

To complete a probabilistic analysis, one must first identify the input parameters that are uncertain in the analysis. Once those variables are chosen, a range and probability density function are also chosen. Probability Density Functions (PDF) generally take a standard shape under a standard probability distribution, such as the uniform distribution in which only the upper and lower bounds are specified, a triangular distribution in which the upper and lower bounds as well as a most likely value are specified, or a normal distribution, in which a mean and a standard deviation are specified (Hayter 1996). Examples of uniform and triangular distributions are illustrated in Figure 17. Uniform and triangular distributions are widely used for continuous inputs, since they require little information and are easy to construct. Normal, Weibull, and other distributions can also be used, but they have the disadvantages of needing more information about the variable's distribution in the future and have long tails such that a variable has a non-zero chance of being either very small or very large. If historical data is available and can be used for the creation of distributions, the distribution that best models the data should be used.

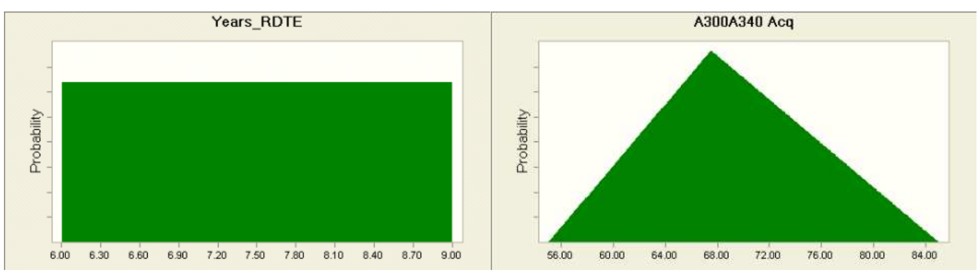

Figure 17: Probabilistic Analysis Variable Distribution Plots

Points for each variable are sampled randomly according to the distribution provided and used to analyze the design. The output of such an analysis is also a distribution, as indicated above. The probability density function of one such distribution is illustrated in Figure 18 below. Notice that this output is not a normal distribution. The distribution of the output will depend on the distributions on the inputs and the analysis being performed. The PDF can then be translated into a Cumulative Density Function (CDF) to show what the probability is of falling above or below a certain threshold, which can be useful when trying to track the probability of meeting a target or a set of targets.

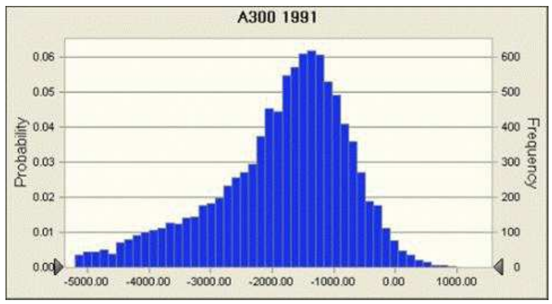

Figure 18: Probabilistic Analysis Output

Determining the distribution or PDF for each input can be challenging. Since design is usually completed in teams, it is often a team consensus, but can also be the will of the person with the strongest personality or the most experience (Cetron 1972). Team consensus is this author's preferred way to determine variable distributions, since a determination made by a team doesn't reflect the values or prejudices of any one team member. The team will also be more knowledgeable as a whole than one team member will be; therefore, the potential for accuracy in variable distributions is greater. Whether the distributions are made by one designer or set up by an entire design team, they should be set up by a person or people knowledgeable about the industry (in this case the aerospace industry) and about current and potential events. The team should understand the drivers behind the uncertainty that characterizes different variables. For example, fuel cost is partially determined by domestic happenings, including the political and economic climate, and partially determined by international concerns, such as a war or other governmental instability in the Middle East. Those who determine the variable ranges and uncertainties should understand what drives the cost of fuel and what those drivers are likely to do in the future.

In summary, probabilistic analysis is a tool that is relatively easy use. It can be quickly set up using any of several commercially available programs that interface with Microsoft® and other well-known products. However, the determination of variable ranges and distributions can be difficult to complete and even more difficult to trace.

4.2 Scenario-Based Analysis

One way to deal with future uncertainty is by using scenario based analysis. Scenario based analysis is a form of scenario based planning, which uses potential future scenarios to facilitate future planning. No one can predict the future accurately, so other techniques are used to help analyze the future and how it will impact decision made today. Scenario based decision making allows decision makers to bound future uncertainty through the use of a scenarios to prune a decision tree (Pomeral 2001). Scenario decision making involves the creation of plausible future scenarios and then the application of those future scenarios to the set of design decisions or decision tree (van der Werff 2000).

Scenario based decision making involves understanding the problem at hand and having potential solutions in mind. The decision maker must understand the uncertainties that prevent an optimal solution from being chosen without regard to the potential future. Once the decision maker understands the problem, future scenarios are generated. These scenarios can be as detailed as necessary, but should address the uncertainties that have been identified as important (Shoemaker 1995). The decision maker then maps his uncertainties to the future scenarios, thereby bounding the future uncertainty and allowing the decision maker the ability to justify future uncertainty predictions. With the future uncertainty bounded, the decision maker now has more information with which to make design choices and understand potential consequences of those choices. Unlike probabilistic assessment, in which the assessor is limited in what form of future can be chosen, scenarios can be combined into almost any form, as illustrated in the plots below, Figure 19 and Figure 20.

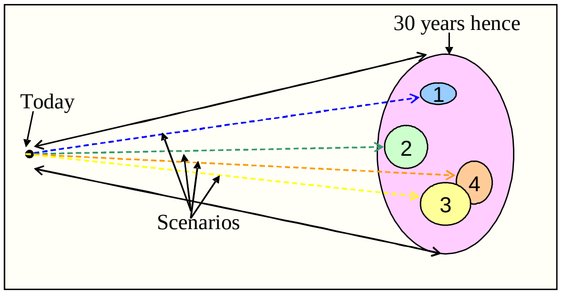

Figure 19: Illustration of Future Scenarios

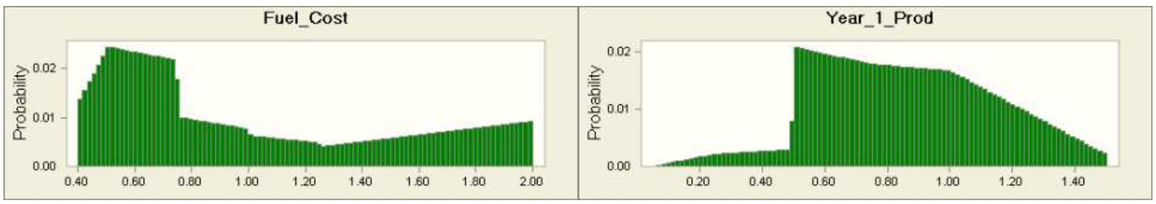

Figure 20: Scenario Variable Distribution Plots

4.2.1 Scenario Creation

Scenario creation can be as simple or complex as necessary. Scenarios should reflect plausible futures, which is a concept always open to interpretation. When determining how to create a set of scenarios, it is important to understand the scope and time-scale of the scenarios that will be necessary.

For near-future scenarios, data forecasting methods can be useful. If the scope of the scenario is limited and quantitative historical data exists for use, the scenario-creator may be able to use traditional data forecasting techniques. To use these techniques, one must first determine the time-scale of the scenario: if one is trying to predict the price of a commodity over the next 90 days, extrapolating from historical data may provide an accurate answer; however, if one were trying to predict the price of the same commodity over a 10 year time, that extrapolation will likely prove less accurate (Walonick 2006).

If there is a significant amount of historical data over a period of time and one is trying to extrapolate, there are several different techniques available for use; a few will be explained here. Many of these techniques are more widely used in the business world, rather than the engineering world, and so were developed for that purpose. One extrapolation technique is regression with time. The raw data can be regressed using whatever curve-fitting technique best fits the data. Common regression equations are linear, 2nd order polynomial, exponential, logarithmic (Arsham 2006). Since these equations fit the earlier trend, they may be useful in predicting the future.

For situations where historical data shows a high degree of volatility but an overall trend, smoothing techniques can be used to assess the overall data trend and, potentially, produce a more accurate future prediction (Arsham 2006). Simple smoothing techniques include moving average techniques, where a number of data points are averaged and the averages are used to determine the data trend (Arsham 2006). Smoothing techniques can be combined with regression techniques.

While data forecasting works well in situations where there is abundant data and the forecast time period is short, it could prove difficult to implement over a long time horizon, such as those present in aerospace systems. For short-term scenario creation, data regression analysis methods have the potential to be very useful.

For the creation of longer-term scenarios, different forecasting techniques need to be employed. No matter what technique is employed, two questions should be addressed first: what is the scenario timeframe and what is the scenario scope (Shoemaker 1995). Once these questions are addressed, scenario creation becomes a more bounded problem. Many scenario creation methods follow some variation of the first six steps of Schwartz's scenario creation checklist (Schwartz 1991).

1. *Identify focal issue or decision*. Identify why the scenarios are being created and what question these scenarios will aid in answering

2. *Key forces in the local environment*. Identify the micro-environmental forces that influence the decision makers in a given industry for a given problem.
3. *Driving forces*. Identify macro-environmental forces that will influence the decision. Determine how these interact with the micro-environmental forces.
4. *Rank by importance and uncertainty*. Identify the most important and uncertain factors to examine.
5. *Selecting the scenario logics*. Determine how the driving forces and local environmental forces will interact.
6. *Fleshing out the scenarios*. Embellish the scenario logics to make a compelling storyline that makes sense and addresses the local- and macro-environmental forces.

This checklist can be used to create scenarios of any scope or timeframe. The steps can be easily followed because the process is relatively intuitive: identify the problem, understand the industry, understand how the global environment affects the industry, determine the most important factors affecting the decision, and creating scenarios around those factors. While Schwartz's method details the steps one should go through to create scenarios, it does not specify how to complete these steps.

One class of methods/tools to aid in scenario-creation is morphological approaches. In this class of methods, scenarios are created around a set of questions or uncertainties. A set of uncertainties about the future is chosen to be examined, and assumptions are made about these uncertainties. The assumptions are then combined, using some logic, in different combinations to create a set of future scenarios ("Rural Futures Project" 2005). The assumptions and uncertainties can be quantitative, qualitative, or a mix, depending on the metrics being measured and the timeframe being examined, and are often set up in a matrix format. Expert judgment is one method of combining the assumptions into plausible futures. With this method, futures that the experts feel are extremely implausible are discarded (Ringland 1998). For example, if two aspects of a scenario are wages and consumer spending, a situation in which wages decrease and consumer spending increases may be judged to be unlikely and discarded. If expert judgment needs to be formal and explicit, other types of analyses, such as cross-impact analysis, can be employed to help combine the assumptions into appropriate scenarios. Cross-impact analysis is a technique that allows for dependencies between events to be modeled (Walonick 2006). For example, if two uncertainties that must be addressed in a future scenario are the cost of housing relative to historical norms and percentage of family income that is disposable, these two uncertainties are correlated. If housing costs are high relative to historical norms, it is likely, although not certain, that there will be a smaller percentage of disposable income. Cross-impact analysis helps to assign that likelihood. If a large enough number of scenarios is being created, a computer program with some internal logic regarding combining scenarios can also help with this process. Morphological methods work particularly well for making certain that all aspects of a future that one is interested in are addressed. Scenario matrices and other tools are often used early in the scenario creation process to help define the scenario scope.

A more inductive approach to scenario-creation, and one that is somewhat less formal, is a brainstorming approach to creating scenarios. In this approach, instead of creating a matrix of scenario possibilities, the scenario creators are asked to determine what could be significant events in the future and construct scenarios around these events (Fahey and Randall 1998). This technique has the advantage of being more open-ended and less structured than the matrix approaches; however, it is also significantly less structured.

There are consensus building techniques that aid in the identification of key scenario drivers and the scenarios themselves. One of the most famous is the Delphi method, created by RAND Corporation in the 1950s. The method polls expert opinion in the form of anonymous surveys and then has a moderator analyze the gathered data and collate it. The data is given back to the experts and the process is repeated until the experts converge on a scenario or set of scenarios (Ringland 1998). The major advantage of this process is that the surveys are anonymous, so all participants have an equal voice in the process. The disadvantage is that the final result is a set of consensus scenarios, not a set of individual scenarios, and consensus scenarios have the risk of being similar.

The European Commission's Forward Studies Unit also has a methodology for scenario creation called Shaping Factors-Shaping Actors. Small groups of consultants are used for their expert opinions in this method. Initially, the shaping factors and shaping actors are identified. Shaping factors are the factors that have a significant influence on the future; factors can be economic, socio-political, or otherwise. Likewise, shaping actors are those people or groups that have the ability to shape the future. Linkages between the factors and actors must be identified, and then scenarios are created around those linkages (Ringland 1998). Like the Delphi method, the factors-actors method uses expert opinion to construct scenarios; however, it is less structured than the Delphi method and encourages disparate scenarios instead of consensus.

There are other schools of though that also encourage non-consensus when creating scenarios. Chandler and Cockle encourage a subset of scenarios to be "wild cards;" that is, be unlikely to happen, but plausible nonetheless (Chandler and Cockle 1982). Other scenario creation guidelines recommend examining the possibilities of disruptive events, as well as the creation of "best" and "worst" scenarios (Fahey and Randall 1998).

There are also computer-based methods and tools to help with scenario generation. One such tool is the BASICS methodology and computer program created by Battelle Institute. The method involves determining the problem and factors surrounding the decision to be made, the factors are researched and likely trends are established, and then a cross-impact analysis is carried out to determine likely scenarios (Ringland 1998). This analysis also relies heavily on expert opinion.

In general, scenario-creation processes and tools rely heavily on the opinion of many different experts. These experts can be industry experts or experts from within a company. Some methods advocate consensus; some advocate the creation of disparate futures. There are a variety of tools available to aid in scenario creation that can be either created as needed or purchased.

CHAPTER 5

PROPOSED SOLUTION PROCESS

The previous four chapters have discussed the background and the need for a risk analysis process that takes into account political, social, and economic risks that are not well addressed by traditional engineering risk analysis processes. Chapters two through four discuss the literature review and benchmarking for: judgment and decision making, risk analysis processes, and uncertainty modeling for the three research questions, listed again below.

1. Is it possible to harness the act of human judgment and use it as a conceptual design decision aid for an aerospace system design?
2. Do any systems or methods currently exist that allow the user's judgment to make decisions in the beginning stages of conceptual design? While using a risk-benefit type of approach?
3. How do we deal with uncertainty in the early phases of design when doing a risk-benefit analysis?

Research question one attempted to understand how people make decisions and the effect judgment has on a decision making process, as well as how that judgment can be used in a design process to analyze risk and other decision making metrics. Research question two benchmarks current risk assessment methods used in the aerospace engineering field and elsewhere, while research question five outlines probabilistic and scenario-based decision making processes for dealing with uncertainty.

5.1 Process Goal

Observations about changing times and decision making procedures outlined in Chapter 1 led to the development of an overall research goal: create a process that allows for the examination, for the purpose of decision making, of technical and economic objectives, as well as programmatic risk and risk control and mitigation strategies, for use by engineers at the conceptual design level. “Radical innovation is delivered by program managers who embrace risk rather than shunning uncertainty. Risk free development can only lead aerospace into becoming a sunset industry.” (Callopy 2003). Traditional risk analysis techniques in engineering explore technical risk and some economic risk, but do not explore the effects of other types of programmatic risk. Like the program managers Callopy mentions, engineers also need to embrace risk to support and aid the program managers who will lead the aerospace field in the 21st century.

Many engineering risk analysis methods have similar steps, such as those illustrated in Figure 21. These steps are found, in some form, in the DoD Risk Management Guide (“Risk Management Guide for…” 2006), the NASA PRA Guide (Goldberg et al. 1994) and other IPT risk management process guides.

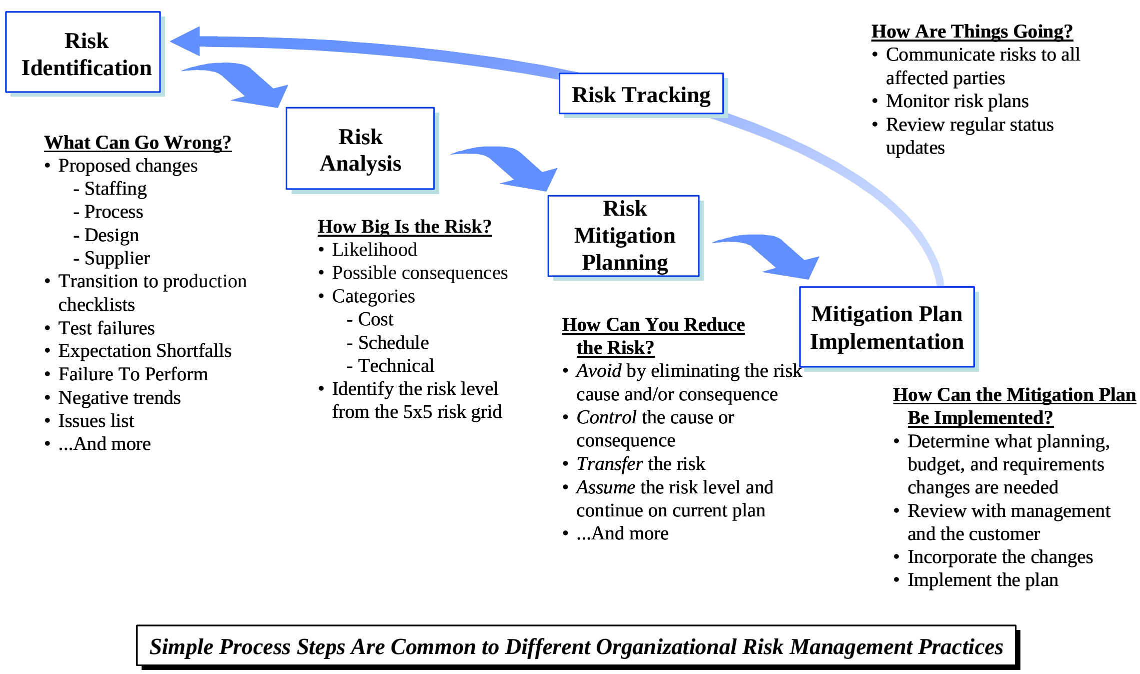

Figure 21: Sample Generic Risk Management Process (Skalamera 1998)

The procedure contains five main steps, each with some further explanation for their usefulness. The risk identification step is the first step, and it involves understanding the problem well enough to identify what can go wrong. After risks have been identified, the risk is analyzed to find out how significant it is. If necessary, risk mitigation planning and then implementation are carried out. The process then iterates back through a risk tracking process to continually update; as time goes on, more risks may be identified or new information becomes available for use in the risk analysis.

Many other risk analysis methods use a similar process. For engineering risk analyses, such as those benchmarked in Chapter 3, risk identification, analysis, and mitigation, with iteration between the steps, is common. While this type of risk analysis works very well for technological risk at the engineering level, particularly that of the cost, schedule and performance variety, it fares less well when it comes to identifying higher-level political, economic, and social risk. These analyses are not designed to identify risks that cannot be mitigated or controlled by engineering design, and were not designed to allow for the examination of different types of future scenarios. The risk analysis process laid out in Figure 21 asks lays out an easy to follow process; however, for this problem a different implementation is necessary to analyze a slightly different set of risks.

While the previous paragraph discussed, briefly, what risk assessment methodologies exist today, what is wanted for this new methodology should also be discussed. As mentioned earlier, there is risk associated not only with meeting technical objectives, there is also risk associated with the political, social, economic, and employment operational environment. A new technique that allows for the examination of these risks would help to fill a gap that exists in current engineering risk analyses, and allow engineers to examine another set of risks that can affect engineering project outcomes. A risk analysis that takes into account all of these factors and allows for tradeoffs to be made between risk mitigation strategies and different economic conditions would be an asset to the decision making process by adding information and helping to create a system that is robust to changes in external operating environment.

The next step was to figure out how to reach this goal, so research questions one through five were used to benchmark existing processes and ideas for use. However, no existing method met all the qualifications for a process that this author needed:

- Evaluating uncertainty from technical, economic and policy sources over a product's life cycle
- Using quantitative and qualitative information
- Containing a risk mitigation model that allows for game-playing and tradeoffs
- Providing information in a way that is intuitive to human thinking and understands the human as final arbitrator

Many of the methods and processes outlined above met some of the qualifications, but all were deficient. Since this is the case, a new method must be developed to meet all the outlined goals.

5.2 Hypotheses

One overarching research statement and three hypotheses were created to attempt to address the overall research goals. These hypotheses were derived based upon the answers to research questions one through three. The purpose of these hypotheses is to determine what analyses or processes are necessary to create a rigorous risk analysis and mitigation process and to allow for structured testing and comparison of the developed process with existing processes or other options for different pieces of the process.

The overarching research statement following the research goal is as follows:

> A systematic method can be developed to use human judgment to assess risks and benefits in the early design phases of a large-scale engineering project.

This statement is derived from research questions one and six. It states that it is possible to create a systematic, repeatable, risk assessment and mitigation methodology that can be used during conceptual design. Even though many conceptual design parameters are uncertain and the customer's wants, needs, and constraints may still be fluid, it is still possible to create a repeatable process that conceptual design can support; the need for such a risk management technique has been identified, notably by Walkovitz (1999). Many conceptual design processes are systematic and repeatable. However, there are several implications of this statement. Since conceptual design differs from project to project—no two large-scale, complicated systems can have the exact same set of assumptions; there are too many differences to address—any process for use in conceptual design must be adaptable to different systems. The process should work for both military and civil systems and for aircraft, missile, ship, space, and other systems with few modifications. Along the same lines, the process must be flexible in how it can be used: for example, different modeling and simulation environments should work within the process framework.

The first hypothesis is based on research questions one and two. Feasibility and viability are necessary pieces of the business case analysis; however, decisions based purely on these factors ignore consequence and uncertainty. Future uncertainty and potential consequences must be understood when determining what a project's future outcome will be.

> Hypothesis 1: A risk analysis coupled with the outcome analysis will allow consequences and uncertainty to permeate the business case and increase information available for decision making without overwhelming the decision maker.

Thus, a risk analysis is a necessary part of conceptual design, as per research question two, and also stated by Callopy (2003) and Miller and Lessard (2001). As risk analysis is a necessary part of design, it should be completed in a manner that allows for comparison and testing between different types of risk analyses to determine which methods, or parts of each method, are applicable to the current problem. As with the research statement above, there are several ideas that are rolled up in this hypothesis. One such idea is that of judgment: as stated in previously, decision making is inherently a human activity and therefore judgment based. Judgment-based decision making and not overwhelming the human decision maker links from research question two. Another such idea is that feasibility and viability are important parts of the decision making process. The roles of feasibility and viability are discussed in Chapter 1; both are important factors in the decision making process, and a risk analysis, with its uncertainty and decision consequence models, is also a necessary piece of the decision making process.

Hypothesis two is based background information gathered in Chapter 1 and research question one. Quantitative and qualitative information with differing degrees of uncertainty will be available; however, many traditional decision making methods require quantitative information that has a high decree of certainty. Unfortunately, this information is not always available; often, both types of information are available with varying degrees of fidelity. In risk analysis problems, as much information as possible should be used to produce the most accurate result.

> Hypothesis 2: Both qualitative and quantitative information are available and can be used in decision making; the ability to use both types of information increases the number of applications for a risk-benefit analysis without overwhelming a human decision maker.

This hypothesis states that different types of information are available for use in decision making during conceptual design. Human decision makers can use both quantitative and qualitative information for decision making (Arthur 1994, Larichev and Brown 2000), so all relevant information available should be used to the extent that its quality allows. The investigation following research question one, in Chapter 2, backs up this assertion. Also, as stated in Chapter 1, in the earlier stages of conceptual design, information about the design is often qualitative and information about customer requirements and preferences can be either qualitative or quantitative. Since both quantitative and qualitative information is available, any risk and cost analysis and risk mitigation process should use both types of information. The ability to use both types of information will increase the applicability of the developed process, thus enticing more people to use it. As more people use it and understand how it works, more people will believe the results and feel more inclined to use it again. Also, the ability to use both quantitative and qualitative information means that the developed risk analysis and mitigation process can be completed with differing levels of fidelity. It can be completed early on in the conceptual design process and then more information can be added as it becomes available later in the design process.

There are also some assumptions intrinsic to this hypothesis. One such assumption is that the data provided is relevant, i.e. that it is actually useful to the decision maker. As some information is useful to a decision maker and some is not, not all data should be assumed to be useful. The distinction between useful and useless data can be difficult; however, it should be decided upon as quickly as possible. Some metrics for making that decision can include the customer requirements and industry metrics of interest. Another assumption is that the data available is correct. Doing an analysis with incorrect data has the potential to lead to incorrect results.

Hypothesis three is based on research question three. Uncertainty is a part of conceptual design. There are changing requirements, designs, and analyses that need to be understood from the design perspective, and there are existing tools that help keep track of design and analysis code changes. From a risk perspective, uncertainty takes the form of changing or evolving requirements and uncertainty in future predictions and calculations. Traditional probabilistic analysis is how uncertainty is dealt with today in engineering risk analyses; however, this type of analysis provides little traceability and it is difficult to assess its accuracy. A method that provides better traceability is necessary.

> Hypothesis 3: Too much uncertainty can render a risk analysis meaningless; the use of future scenarios can bound uncertainty and tie it to specific circumstances.

This hypothesis states that a risk analysis needs some sort of future uncertainty model. Research question five asks how to handle uncertainty during conceptual design. The current method to handle uncertainty is a probabilistic analysis. An emerging method, that this author intends to use, is scenario-based analysis. A detailed explanation of this method is given in Chapter 4. Too much uncertainty makes a risk analysis difficult to use for decision making. With very large uncertainties, it can be difficult or impossible to distinguish between different design options, so decision making becomes no more meaningful than throwing darts. Being able to distinguish between options, however, allows for meaningful comparisons for decision making purposes. While scenario based analysis does not guarantee to limit uncertainty such that otherwise indistinguishable design options become distinguishable, it will be helpful in tracking uncertainty and understanding where it comes from (Shoemaker 1995, Pomerol 2001). Scenarios add a level of traceability to uncertainty modeling that is missing in more traditional probabilistic analysis.

This research statement and these three hypotheses are the backbone of the risk analysis method proposed in the next section. These hypotheses, along with the research questions from Chapters 2 through 4, have laid out the problem at hand and pointed toward a solution.

5.3 Proposed Method

The method to be proposed looks, on the surface, like many other engineering risk analysis methods, but it is setup to fill in the gaps listed in Section 5.1 and evaluate the hypotheses listed in Section 5.2. The process not only needs to meet these requirements, it should also be useful to the decision maker. In order to be useful, a newly created decision making process for this problem should do the following things:

1. Be a systematic, transparent process (Saaty 1982)
2. Be simple to construct (Saaty 1982)

3. Take into account both risk and monetary and performance outcomes
4. Allow for comparison of both risks and outcomes
5. Show what risks have the largest impact
6. Show risks and benefits across different scenarios
7. Be completable at differing levels of fidelity
8. Allow a human to determine level of acceptable risk
9. Present information so human expert can make decision
10. Be natural to our intuition and thinking (Saaty 1982)
11. Encourage compromise and consensus building (Saaty 1982)

The top two items on the above list are very important. Very few people will want to use a process they do not think they understand for decision making purposes. Also, since the process can be used during conceptual design and by both engineering and management personnel, it should be easy and quick to construct and use and quick to update. The next four bullets have been discussed previously; since this is a risk assessment and decision making process, it makes sense that risks and economic outcomes should be compared between design solutions and across different scenarios. For the next bullet, conceptual design involves ever-increasing levels of fidelity as a project progresses. The ability to update a risk assessment with new information is critical. The last four points have to do with decision making. As demonstrated earlier, humans make important design decisions, so presenting information in such a way that a human can make a decision is very important. Since decisions are often made in groups rather than by individuals, a process that is natural to our intuition and encourages consensus building rather than one that needs to be constantly explained and encourages arguments will probably work better.

The risk analysis and mitigation process created using the above research questions and hypotheses is outlined in Figure 22. The process itself is hypothesized to address the gaps in traditional risk analysis processes identified during the literature review. It has three focus areas containing a total of eight steps.

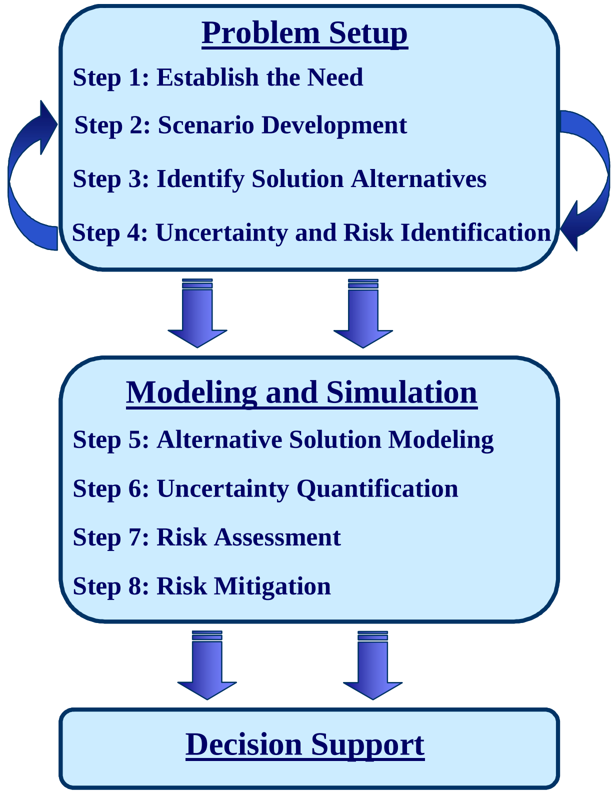

Figure 22: Risk Analysis and Mitigation Process

Most risk analysis processes contain similar steps, and this one is no exception. Risk identification, analysis, and mitigation are present in the new process. The new process is designed to be familiar for people working in the risk analysis and systems engineering fields. Like a traditional IPPD process, the risk analysis process begins with establishing a need for a new system. Included in step 1 of the new process is also problem definition and the determination of metrics to be used for decision making. These metrics will include a measure of risk as well as systems performance and economic metrics specific to the problem being evaluated. The goal of this process is to aid in the creation of a robust design solution, so the important applications of this process will fall into robust design assessment in the traditional systems engineering process.

The gaps listed earlier are being addressed by this process. Risks are identified for technical, economic, political, and social uncertainties in step 3 and evaluated in steps 6 and 7. Any type of information can be used throughout the design process. The decision support framework contains a mitigation process that will allow for tradeoffs and the goal of decision support is to provide information for the human to make a final decision.

The overall research statement is the process base: the developed method is systematic and explicitly uses human judgment as a decision making process. Hypothesis one states that both a risk and (monetary) outcome analysis are necessary pieces of the business case; both are modeled in this process in steps 5 and 7, respectively. Hypothesis two states that both qualitative and quantitative information should be used in decision making. This hypothesis is more difficult to link directly into the process; however, the modeling and simulation steps are tailored to receive both quantitative and qualitative input, and the risk analysis is set up to be completed qualitatively, as numerical probabilities will be difficult to determine at this stage of design. Hypothesis three can be explicitly linked to the process in step 4 and throughout the modeling and simulation steps.

The base for this process comes from the generic risk analysis process laid out earlier. Risk identification is the first step. In the developed process, because this analysis takes place early in the design process, steps 1 through 3 in the problem setup take place before risk identification. In more traditional systems engineering processes, steps 1 and 3 can be referred to as the problem and solution concept identification steps (Dieter 2000). As with systems engineering, these steps include understanding the customer requirements and developing solution concepts that map to those customer requirements.

Step 2 in the process is unique in engineering risk analysis processes. Scenario development, in this case, means creating a set of plausible future scenarios to use for the examination of the assumptions determined in the previous step. Since these assumptions are good for a limited number of futures, they should be examined over a broad set of possible futures to determine the risk associated with not meeting them. The scenario development step was not found in the traditional engineering risk analyses examined.

The risk identification step seen in traditional risk analysis processes here is similar to step 4 of the process: uncertainty and risk identification. While risk identification usually involves only trying to identify potential risks, this step involves identifying the assumptions that engineers, managers, and board of directors have about this design, and then the uncertainties in those assumptions. While in traditional risk analysis the question is “What can go wrong?,” the question here is “What do we assume will happen? And what happens if those assumptions are incorrect?” The tracing of assumptions about future political, social, economic, and employment situations is not found in traditional risk analysis processes; however, analyzing these risks is similar to the creation of a functional hazard assessment for a safety and/or reliability analysis. In an FHA, the system is broken down into functions and a determination is made about what could go wrong with each function (“ARP 4761” 1996). A similar process is completed in step 4: assumptions about the system functions are identified and potential problems in the form of uncertainties associated with those assumptions are also identified.

For the modeling and simulation focus area, these steps are generally correlated with the risk analysis and mitigation steps in other risk analysis and mitigation plans. The solution modeling step is most closely related to systems engineering concept modeling steps, but also part of risk analysis, since there can be no risk analysis without a concept model. The risk modeling and assessment steps are equivalent to the risk analysis step in the traditional plan. The risk modeling step, unlike traditional risk modeling steps, determines how each uncertainty will affect the variables being used to model the systems. The risk assessment step contains a risk calculation that is different from the traditional calculations: it is more intuitive to human thinking and weights high-consequence outcomes more heavily than low-consequence outcomes. Using a more intuitive scale allows for more realistic tradeoffs and, is not found in engineering analyses. The risk mitigation step, step eight, is equivalent to the risk mitigation planning step in the traditional process. The final step in the new risk analysis plan is the decision support setup. Decision support will take the form of an interactive interface that allows for risk mitigation tradeoffs to be made on-the-fly. An environment that supports risk mitigation and analysis tradeoffs and allows for examination of assumptions in real-time is unusual and is not present in other risk analyses. Another unique aspect of this risk analysis is that it is designed to be completed quickly and updated equally quickly for use during conceptual design as plans rapidly evolve.

5.3.1 Problem Setup

The first focus area for the proposed risk analysis and mitigation process is the problem setup area, illustrated in Figure 23. This focus area involves four steps, from establishing the need for a new system through uncertainty and risk identification. These steps will be described in greater detail in the next four sub-sections; the purpose of this section is to understand how these steps are inter-related. These four steps are lumped into the area of problem setup due to the iteration between them and they are all related to setting up the problem for the modeling and simulation focus area, to be described in Section 5.3.2, below.

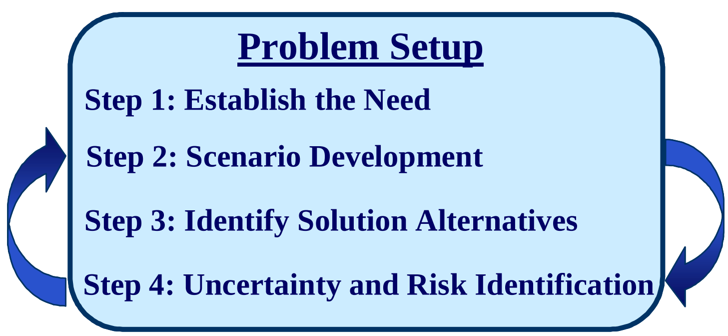

Figure 23: Problem Setup Process

The first step in the problem setup is establishing the need for a new system. This step is very important and often takes the longest time of all the steps, since it involves gathering and collating information from a variety of sources, A good understanding of the problem allows for potential design solutions to be easily generated and for those solutions to fit into the context of the problem. There is a weak feedback loop between steps one, two, and three: as new information becomes available, new scenarios can be generated, new problem solutions can be created and old ones can be discarded as necessary.

After a market need and high level requirements for a new system have been established, future scenarios are developed, solution alternatives are identified and potential risks are identified. There is extensive feedback between these three steps, as the scenarios will drive the solution alternatives and risk identification, but the risk identification may identify some deficiencies in the scenarios.

As the first focus area for the risk analysis process, the outputs of the problem setup process become the inputs into focus area two, the modeling and simulation process. The outputs of the problem setup include the potential design solutions to be examined, a list of assumptions and risks for each design solution, and a set of scenarios to be modeled for completion of the risk analysis.

5.3.1.1 Establish the Need

Establishing the need is the first step in the risk analysis and mitigation process, and also the first step in the problem setup focus area. While it is listed as the first step in most design processes, in reality, establishing the need, including defining and understanding the problem, weaves its way throughout the entire design process, from conceptual design to detailed design, and then continues throughout manufacturing and operations and support. Therefore, while it is not disingenuous have problem understanding as part of the first step of the design process, it is more correct to consider it as the first, middle, and last step of the design process.

Establishing the need for a new system includes learning everything possible about a problem. Generally, this process is begun with the identification of a problem, need for change, etc. Sometimes a customer identifies a problem or shortcoming with an existing system and requests a new or updated system to correct said problem. Other times, the problem or shortcoming is identified by an end-user and brought to the attention of the product manufacturer. Sometimes, the problem is identified by the manufacturer himself, and solved internally.

Problem identification can take many forms. For some systems, it is relatively straightforward with specific performance parameters. For example, an airframer and group of airlines determine that there is a market for a new commercial aircraft that fits into the current airport and air traffic control systems, will meet near-future (approximately 20 year time-span) noise and emissions standards, and is less costly to operate than existing aircraft, but carries a large number of people and can travel 10,000 nmi nonstop. Such a system may be difficult to design and build; however, the performance envelope is well-defined. For a military system, specific performance goals may be determined based on intelligence about foreign systems. For example, there may be a requirement for a new military system to travel faster or have a smaller turning radius than a foreign system which could be a potential threat. The performance goals for this system are defined, but the solution space is more open-ended than for the previous example of the commercial aircraft, since, although both systems must fit into existing infrastructure, there are fewer regulatory requirements to satisfy for military systems.

In some instances, problem identification does not come with specific performance goals attached to it. Sometimes the problem is as simple, and as complicated, as a customer wanting a better system. In this case, and very possibly in the cases cited in the previous paragraph, there will need to be some requirements elicitation and translation in order to gain a better understanding of the problem. There are tools that can aid in this process and will be very useful in the endeavor to translate fuzzy requirements like into performance and economic metrics.

While the system requirements, or needs, are defined, the system wants should be defined also. While the customer or end-user will have a list of requirements, there will probably also be some desirements, or wants, also. These will be metrics or functions that the customer would like to see in the system, but would be willing to forego or trade off.

It is very important to note that requirements and desirements will change as a project moves forward in time and along the design schedule. It is important to keep up with these changes and to continually update any tools or processes in use to reflect these changes. Changes to this stage of the risk analysis process also need to be moved downstream: if any changes are made here in step one, steps 2 through 8 should be carefully gone over to make sure that no changes need to be made there, also.

One way to anticipate changing requirements is to understand not only the problem itself, but also the background relating to the problem. Understanding the context in which the problem was first identified and the context in which the system will ultimately perform will help the system designer to better anticipate the requirements and desirements changes that are bound to occur. Understanding the context can involve a large amount of background research. It includes understanding what is currently happening in the industry that the system is to be developed for as well as what direction the industry is likely to go in the future. For complex, costly systems, it also includes understanding current and predicting future economic conditions of the customer, the industry, and any other major players or suppliers, as well as the general economic condition of major world powers.

Learning about an industry and the direction it's going should be relatively easy for a designer who works in a specific industry. Reading industry-specific journals and/or professional society newsletters should inform the designer what different industry experts believe the future of the industry will be. Predictions about specific companies are also easy to come by for some industries, particularly those like the aerospace industry where there are only a few major companies. Learning about the general economic state of the world is more challenging. Popular newspapers and magazines, are a good source of general news about the state of the US economy and important national and international developments. International news magazine and newspapers should also be read. For purely economic news and future predictions, publications such as *The Wall Street Journal* and *The Economist* can give global perspectives on economic news. Publications such as these also provide experts' predictions of the state of different economies and industries for the future.

In general, the problem understanding step of the risk analysis process is analogous to the problem definition of most conceptual design processes, with a few additional requirements. It is a time-consuming process that needs to be initially completed before any design work is done and then continually updated as new information becomes available throughout the design process.

5.3.1.2 Scenario Development

The second step in the process is scenario development. While this is listed as the second step in this risk analysis process, there is significant iteration between steps two, three, and four, and these steps will not be completed serially.

The scenario development step involves creating or generating different plausible future scenarios. A limited number of scenarios are generated: a minimum of three is probably required to effectively bound uncertainty, but two can be used if sufficiently different (Ringland 1998); more can be generated depending on the need. Since the future is unpredictable, the purpose of this step is to bound the future uncertainty, not to determine precisely what will happen in ten, fifteen, or twenty years. Scenarios can be as detailed as necessary, but should leave room for some interpretation. The scenarios can be as mundane or as exciting as necessary, but shouldn't all predict future calamities or future prosperity for everyone. A good rule of thumb is to do a "best case"—prosperity for all, world peace, great scientific breakthroughs enable worldwide sustainable development, etc—along with a "worst case" and several more likely scenarios that fall somewhere in between (Ahmed 2003, Fahey and Randall 1998). These scenarios are not intended to be fully specified; variable specification will take place in the second focus area of the process.

The question, of course, is how to determine what the future scenarios should be like. This is a complicated question without a unique right answer, and will be left up to the judgment of the decision maker. There are several ways to determine future scenarios, some of which were discussed in Section 4.2.1. One way to create scenarios, and the easiest way to defend the created scenarios, is to use expert opinions. Finding these opinions involves either talking to the experts or doing background research and understanding of how the opinions were generated. One would need to understand not only the politics, economics, and technology development native to his field, but also those at the local, national, and global scale. It can also take time to determine who the experts are in many different fields and to explain their work to those less knowledgeable.

Since the goal of this process is that one doesn't need to be a finance or marketing manager to complete it, requiring months of research to rely entirely on expert opinion for scenario creation will be difficult to implement. Another way to create scenarios is to poll local experts, that is, creation by committee, either with each committee member creating his own scenario or with the entire committee creating a set of scenarios. The advantage of having a committee create scenarios over an individual is that in a committee, no one person's opinions should dominate the scenario creation process.

For traditional scenario creation with one best case, one worst case, and several more likely cases, decision makers should agree in substance on the best and worst case scenarios and should agree in spirit on what constitutes a plausible future; however, different people will create different scenarios. To gather information for plausible future scenarios, the creators should have a good knowledge of the recent history of the aerospace industry in particular and the economy in general. The creators should be keeping up with the current events and what other politicians and economists predict for the future. The scenario(s) should reflect a variety of potential futures and be based on the current state of things and the recent past. Given that much design is completed by committee, scenarios will probably be generated by committee as well. In this case, the committee can agree on what aspects of the future each scenario should address, and then each member of the design committee can create his/her own plausible future scenario. When each committee member has created a scenario, the committee can then generate a best and a worst case scenario, and determine the scenario likelihoods of occurrence. In general, the best and worst case scenarios have a low likelihood of occurrence, while the scenarios generated by each committee member will have a higher likelihood.

There are methods available to aid in scenario creation, some of which were explained in Chapter 5. The six-step process listed in Section 5.2.1 is a good outline to follow since many scenario creation processes are similar. Almost all scenario creation processes involve determining which aspects of the future one wants to examine. One way to determine the factors to examine is through a brainstorming session. After the brainstorming session, those factors can be put into a matrix and that matrix, with some external logic applied to it, can be used to specify scenarios. External logic can take the form of committee or expert opinions or an impact matrix that determines the interactions between the factors in the matrix.

An example matrix of alternatives for scenario creation is illustrated in Figure 24. This matrix of alternatives takes into account the economy, employment, transportation, government, international relations, the environment, housing, education, and leisure. The matrix of alternatives can be created based on any factors that the decision makers think are important to specify for the future. The matrix of alternatives does not, by itself, specify future scenarios; however, it does allow the scenario creators to see whether their scenarios are different enough to take into account many plausible futures. As illustrated in Figure 24, the combinatorial space for future scenario creation is almost unlimited; this matrix has $7.3*10^{22}$ possibilities.

Other scenario generation tools are available. A smaller matrix of alternatives can be created that examines only the major factors in a scenario, and then the scenarios are wound around a few overriding factors instead of trying to specify everything about a future. For example, major drivers that affect commercial aviation include the cost of fuel, the number of leisure and business travelers, and governmental and airport regulations, so future scenarios should specify these factors. This technique allows for the examination of a set of plausible futures and also makes certain that the major factors in each scenario are clearly delineated. Again, determination of the major factors for scenario creation can be completed by expert committee or by polling industry experts, if possible.

Another way to create scenarios is completely freeform. Each scenario generation committee member creates a scenario or set of scenarios without input from the committee, or with minimal committee input. Scenarios created in this manner will likely be more disparate than scenarios created in other manners, since different people will think different aspects of the future are important.

Economy	Interest Rates	very low	low	average	high	very high
	Stock Market Returns	negative	zero	low	average	high
	Unemployment Rate	low	average	high	sector-specific	
Jobs	Wages	decreasing	steady	increasing slightly	increasing quickly	
	Sectors Doing Well	pharmaceuticals	aerospace	entertaintment	IT	energy
	Sectors Doing Poorly	energy	entertainment	aerospace	IT	
	Where Located	urban	suburban	coasts	interior	
	Where Working	central office	satellite office	home		
Transportation	Type of Fuel	hydrocarbon	hybrid (HC and electric)	electric	other	
	Cost of Fuel	low	medium	high	very high	
	Other Travel Costs	low	medium	high	very high	
	Traveling Not Advised	Middle East	Southeast Asia	North Africa	Sub-Sahara	Latin America
	Who Can Travel (regs)	little international	need ID			
	Availibility of Public Transportation	Little	good in cities	cities and suburbs	everywhere	
Government	Energy Regulation	little regulation	heavily regulated	same as today		
	Transportation Security	very secure	some sectors secure	lax security	privately funded	
	Illegal Immigration	major, intervention	major, no intervention	minor, intervention	minor, no intervention	
	Deficit Spending	very high	high	average	low	surplus
	Revenues	high	average	low		
	Tax Rates	high	average	low		
	Tax Structure	regressive	progressive	income	sales	
International Relations	Getting along with neighbors	well	some problems	many problems	war	
	Borders	open borders	no immigration problems	fortified borders		
Environment	Global Warming	big problem	worry	not a worry		
	Regulations	very stringent	industry-specific	somewhat lax	very lax	
Housing	Cost	very high	high in pockets	affordable		
	Where Available	coasts	interior	south	midwest	
	Who is Buying	established professionals	young professionals	older people	everyone	
	Renting/Buying Cost	lower than average	average	high		
	Mortgage Rates	low	average	high		
	Utilities Costs	low	average	high	area dependent	utility dependent
Education	Cost of Primary Education	government funded	privately funded	low	high	
	Where Primary Ed. Takes Place	home	private school	local public school	large public school	
	Cost of Secondary Education	low	medium	high		
	How Educated is Workforce	mostly educated	mostly uneducated	only elite educated	only wealthy educated	
Leisure	How Much Money Available	little	some	lot		
	How Much Time	little	some	lot		
	Where Spent	near home	travel in US	travel abroad	stay home	
Other	Disease	epidemic	outbreak	outbreak threat	no threat	
	Terrorism	not a worry	small worry	abroad worry	worry at home	

Figure 24: Interactive Matrix of Alternatives for Scenario Creation

5.3.1.3 Alternative Solution Development

After the problem has been researched and defined as thoroughly as possible given time and personnel constraints, potential solution alternatives should be identified. There are various ways to identify potential solutions, but the most popular begins with brainstorming. A brainstorming session or sessions can be done in a group or individually. Individual brainstorming sessions often are completed more quickly than group brainstorming sessions; however, a group session may generate more ideas, resulting in a larger solution space. Having a group instead of an individual complete the brainstorming phase of solution development can also prevent one person's thoughts from dominating the identified solution space, since as much of the solutions space as possible should be examined.

When brainstorming, it is important to understand the problem, as outlined in the previous section. While developing and understanding of the problem, it is also important to know whether this problem has been identified before, and, if so, what solutions were identified previously and why did those solutions fail.

During brainstorming, it is important that as many solutions as possible, no matter how unusual or outlandish, be identified. Practical brainstorming limits will depend on the time and number of participants available. After all ideas are generated, each idea should be discussed and evaluated qualitatively, or quantitatively, if time is available, for feasibility and viability purposes. If ideas were generated by a group or team, this process can take place in a group discussion. Project timescale and potential technology development should be taken into account when discussing the feasibility and viability of potential solutions. It is important that all members in the discussion group be offered time to air an opinion on the matter of feasibility and viability for each solution; the person who has the strongest will shouldn't be allowed to dominate the conversation or have his opinion better represented than others. However, the person who knows the most about the idea (most likely the person who generated it) should be given the chance to explain the solution idea and discuss any criticisms.

Feasibility and viability determination is a judgment on the part of the group making the downselection decisions. In a qualitative sense, which is generally how this step will be completed, feasibility is determined by committee consensus. In general, evolutionary solutions will likely be feasible, while revolutionary solutions will require more thought to determine feasibility. Product feasibility includes the ability to design, build, and maintain the system in the timeframe available. This is a judgment on the part of the design committee, but this committee should contain engineering designers and manufacturing experts who are able to make this determination. Therefore, if a new solution alternative must be working in seven years, but the technology required to create that alternative is 10-12 years away, that is an infeasible alternative. If there is some question as to whether a solution will be feasible, it may be best to not discard that solution, but to save it for further examination.

Viability can be more difficult for an engineering design committee to determine. If possible, a business or marketing expert can help make this determination based on projections of the number of units sold, manufacturing and maintenance costs. If that is not possible, a best guess approach using a number of experts in the field can help to accurately determine viability.

After infeasible and non-viable solutions are rejected, the number of solutions left must be taken into account. If there are few enough solutions to examine given the time constraints for a particular project, no other downselection must be completed. If, however, there are more solutions than can be examined in the given time allotted, then another set of downselections must take place. Other methods of solution downselection are not as cut and dry as the use of feasibility and viability. These methods also involve judgment and such judgment can be more difficult to document than that involved in feasibility and viability determination.

One method that can be used for downselection involves the elimination of out-of-the-box design solutions. Since most people are risk averse (Slovic 2000), and more likely to use a solution based upon existing concepts, eliminating revolutionary solutions in favor of evolutionally ones is a valid downselection process. Unfortunately, no revolutionary solutions would ever emerge if everyone chose this method of downselection. Another method of downselection, is to determine feasibility and viability on a sliding scale and eliminate solutions until there are few enough to examine. This method can produce the same results as the previous method; however, it is easier to track assumptions through this method, and easier to resurrect potential solutions at a later date if necessary.

There is a feedback loop between this step, the previous one, and the following one. As alternative solutions are generated, it may be discovered that some parts of the scenarios need to be better specified; afterward, the solution space my need to be updated and more or different potential solutions may need to be examined.

5.3.1.4 Risk Identification

Once it has been decided which solutions to examine in further detail, the next step is the risk identification step. This step entails explicitly listing the assumptions inherent in each solution and then listing any risks that are present if those assumptions are not met and any other risks that can be identified.

The purpose of this step in the analysis process is to identify assumptions about the future and uncertainties associated with meeting, or not meeting, those assumptions. These uncertainties, if there are consequences to not meeting the assumptions, lead to risk. Listing out assumptions about what the future will constitute is difficult, since many of these assumptions are taken for granted. Generally, when the solutions are first devised, a rosy future is assumed: everything will go according to plan. All necessary technologies will be available at the right time and will have the desired impact, any necessary aid from a government source will be available at the right time with the necessary money, the projected market will be, if anything, an underestimate, etc.

This step can be completed in several different ways. The assumptions can be listed in the order they are though of or, in some cases, talked about in the previous step. It is also possible to complete this step in a more methodical way: to list assumptions falling in categories, rather than completing a long list. There are many different sets of categories for examining risk, such as those provided by Haimes (2004) and Porter and Hewitson (2005). A set of five categories, listed below, is chosen based on recommendations by Schwartz (2004): "[C]orporate decision making has an economic component, a social component, and a personality component." Based on his assertion, and the knowledge that technology development plays a significant role in the aerospace industry, the five categories were chosen to overlap these components.

- Technology
- Government
- Employment
- Economy
- Culture

These assumption categories are not exhaustive but serve as a representation of where the majority of assumptions will fall for each solution.

Technological assumptions can affect both feasibility and viability. Representative technological assumptions would include those associated with performance, schedule and cost. Performance assumptions includes the assumption that the system will perform according to specifications laid out before the system is designed. There are assumptions associated with the project schedule, including deadlines and certification plan timelines, while cost assumptions include falling within budgetary guidelines and being able to deliver the promised performance for a promised cost.

Technological assumptions can be collated and assessed for each technology individually or collectively, but are analyzed only at a high level in this risk analysis process.

Assumptions about government and politics, like technical assumptions, are associated with both feasibility and viability. Assumptions covering government and politics can refer to any of local, state, and federal governments along with national and international industry-governing bodies. Governmental assumptions include things such as health and safety regulations, which can manifest themselves at the local, state or national level and assumptions associated with creating, certifying and maintaining facilities, that manifest themselves predominantly at the local and state levels. Some of these assumptions will involve local and state community and political relations. State and local governments are often receptive to job creation and facilities building; however, there are still a myriad of regulations to consider, particularly if a company plans on using hazardous materials or running a plant for two or three shifts. These are generally viability concerns, but hazardous materials procurement and use may pose a feasibility concern also.

On the federal and international level, there are certifications and regulations that need to be met before the aircraft can fly. Assumptions associated with both aircraft certifications and other regulations will include timeline and other requirements for certification and meeting regulations. Not meeting the requirements can be a feasibility problem, while the manifestations of not meeting the requirements or timelines are impacts to viability since the aircraft is not in service for the projected amount of time. These requirements and timelines are generally set very early in the design process, so small changes to them can have large impacts. Since certification requirements and timelines are usually known before the design is launched, a simple brainstorming session should be able to determine many of governmental and political assumptions.

Assumptions about employment are more difficult to identify and analyze, and they generally impact viability. These assumptions can include the availability and cost of labor, as well as the possibility of long-term work interruptions. Worker availability is often taken for granted; however, if specially skilled workers are needed and those workers are close to retirement age, finding new skilled employees can be a challenge, and a shortage of workers will drive up labor costs. Other factors that affect worker cost include overhead and benefits. Healthcare benefits have become more expensive in recent years, and a future spike in benefits could increase employee costs. Along with worker availability and cost, companies must worry about work interruptions created by employees. Long-term work disruptions cost a company a great deal of money, both in legal costs and lost opportunity costs. Long-term work interruptions instigated by employees are rare but are a risk nonetheless. These and other employment risks are difficult to identify and even more difficult to analyze. Brainstorming is an acceptable way to identify these assumptions, but it may not identify any event that hasn't happened yet, so identifying all employment assumptions can be difficult.

There are many assumptions about the economy in general that are built into each solution. Economic assumptions impact viability. Economic assumptions include meeting sales goals or having an anticipated borrowing power or sunk cost. Many economic factors are assumed and most of these factors are difficult to predict. While many assumptions, such as interest rates, are apparent to even lay economists, it is more difficult to accurately predict how these factors will change in the future. For example, aircraft manufacturers today complete 20 year market outlooks; predicting how each of these factors will change in the next 20 years is very difficult. Technological, governmental, and employment assumptions can often be predicted beforehand and their risks possibly mitigated, economic catastrophes, such as stock market crashes, can happen almost overnight and, due to the long recovery time for these events, have long-term consequences on a company creating a product with a twenty year or longer lifespan. Because economic changes manifest themselves so quickly, it is very important to choose a solution that will be robust to changes in these factors. If such a solution is not found, it is important to understand the conditions that will create a non-viable product so a company will be able to decrease its losses.

The final source of assumptions from the list above are cultural assumptions, or, more generally, the assumptions associated with the fact that one must appeal to a group of people who are going to use product. Cultural assumptions include the things such as people continuing to travel and the rate of travel continuing to grow; however, there is potential for both involuntary and voluntary travel reductions in the future. Such travel interruptions are a concern for aerospace companies creating commercial aircraft since much of their revenue is derived, albeit indirectly, from the traveling public. Other concerns centering on the traveling public include the possibility of aircraft purchasing interruptions. Other cultural considerations include the assumptions associated with doing business in foreign countries. These companies will also need to understand the dynamics of negotiating with foreign governments and employing foreign workers in their home country.

Once the assumptions are identified the risks associated with not meeting these assumptions should be identified. For technological assumptions, technology evaluation tools such as Technology Impact Forecasting (TIF) and Technology Identification, Evaluation and Selection (TIES) can be used to help identify technological risk if enough information is available for the technologies and programs (Kirby 2002). If too little information is available to use TIES or TIF, more qualitative methods must be used to identify any other areas of risk. For other assumptions, those related to governmental or political practices, cultural practices, employment, or the economy, those risks can be identified by examining the assumptions in each category.

These risk areas are meant to represent different potential and possible risks that aerospace companies will encounter when designing for large-scale, long time-length projects. The use of these risk categories, and any others that are pertinent, should help to increase the decision maker’s understanding of many areas of programmatic risk and help align decision makers with engineers, economists and marketing experts. Obviously, the future that is envisioned will have some bearing on what assumptions are buried in each solution. This problem is addressed by having a feedback loop.

Steps two through four of the risk analysis and mitigation process require iteration. While creating future scenarios, a decision maker may discover new assumptions, risks, or potential feasibility and viability problems he didn’t realize before. This iteration allows the decision maker to work through these two steps until he is satisfied that the problem is captured to the extent that he is comfortable. In reality, this iteration will probably be more messy and convoluted than is illustrated, but it is an important part of the process. The iteration step helps to make this process dynamic and the product easily modified when new information arises. It also helps enable the process to be completed at differing levels of fidelity.

5.3.2 Modeling and Simulation

The second focus area of this process is the modeling and simulation area. Like the problem setup focus area, it also contains four steps: solution modeling, risk modeling, risk assessment, and risk mitigation, shown in Figure 25. The modeling and simulation steps take information from the problem setup steps and deliver information that can be used in the decision support step of this process.

Modeling and Simulation

Step 5: Alternative Solution Modeling

Step 6: Uncertainty Quantification

Step 7: Risk Assessment

Step 8: Risk Mitigation

Figure 25: Modeling and Simulation Focus Area

The information necessary from the previous step includes the potential solution options, the list of risks and assumptions, the specified scenarios, and the information gathered about the problem. The first step in the modeling and simulation focus area is the alternative solution modeling step. In this step, each solution is modeled by the decision maker. Many modeling codes exist throughout the aerospace industry that allow aircraft to be modeled.

The solution modeling step requires information about the solution from step two. Since the same solution model will also be used for the risk modeling and risk assessment steps, the list of assumptions and their associated risks as well as the list of scenarios and their specifications are also necessary. The uncertainty quantification and risk assessment steps use the same solution models created in the solution modeling step; however, in this step more information is applied to model and then assess each risk over the developed scenarios.

5.3.2.1 Alternative Solution Modeling

The fifth step of the method is variable selection and scenario modeling. This is an involved and important step that can be easily divided into four parts: the first part is the determination of metrics of interest, the second part is the solution modeling procedure, the third part of this step is the variable selection process, while the fourth part is the scenario modeling process. Variable selection involves choosing the number and type of variables to model while solution modeling involves using analysis tool to model each solution and then building surrogate models of important parameters for each solution.

The first thing one needs to understand about the solution modeling process is that it will depend on the tools available. Understanding the design tools available can be a time-consuming task; fortunately, there are often experts available to help with this process. In order to determine the metrics of interest, the designer or decision maker needs to understand what the design tool has the ability to model. While the same set of metrics will not be used for every problem, it is likely that the necessary metrics will include performance metrics, such as takeoff and landing field lengths, noise and emissions parameters, and fuel consumptions. Economic metrics can include a manufacturer and customer cashflow and/or net present value.

The designer or decision maker needs to understand the fidelity of the modeling tools, particularly if different tools are required to model different solutions. The designer should understand which parts of the created solution model will be very trustworthy and which parts will still be very uncertain. The designer needs to understand which modules in the model are applicable to his problem and the fidelity of any extremely important modules that will be involved in solution comparison. The designer and decision maker must also understand differences between any modeling tools that will be used to model different solutions. If modeling tools have differing fidelity and/or different strengths and weaknesses, decision makers will need to be aware of the differences when comparing results between tools. Expert users of the design tool can provide significant insight into the best way to model each solution alternative. Each solution alternative model should be run deterministically and the results should be understood and then verified to the extent that is possible before completing the rest of this process.

While each solution model can be created deterministically, a probabilistic model is created to assess the solutions across scenarios. Variable selection is very important for not only solution modeling, but also later for risk modeling and assessment. Variable selection involves choosing which variables are needed in order accurately assess the system and still be able to calculate the risk for each scenario. Variable selection involves a mapping process between the scenarios as they are written and the risks as they are listed. Once the variables are identified, it can be completed in the form of a matrix, with the list of risks on one axis and the list of variables on the other, as illustrated in Figure 26.

	Variable 1	Variable 2	Variable 3	Variable 4	Variable 5	Variable 6
Risk 1						
Risk 2						
Risk 3						
Risk 4						
Risk 5						
Risk 6						
Risk 7						
Risk 8						
Risk 9						
Risk 10						
Risk 11						
Risk 12						
Risk 13						
Risk 14						
Risk 15						
Risk 16						

Figure 26: Risk and Variable Mapping Matrix

It is important to determine what variables are available for use that are specified in each scenario and affect the risks listed. The answer to this question depends on a variety of factors, including the analysis tools available and what variables they contain. If the decision maker had the ability to model everything, the list of variables would be almost endless. As it is, the decision maker must understand the analysis tools available to him and what variables those tools can understand. In general, the decision maker will want analysis tools that can handle and understand both technical and economic variables and be able to model additional technologies and general economics. While the decision maker may not have tools available that can model everything he wants, he may be able to modify his tools or post-process his results in such a fashion that he can model the solutions and risks he is interested in.

While there is no universal list of variables that will model every risk one can determine, there are some variables that can model different types of risk. For technical risk, technology variables can include weight reduction factors on materials or systems that can potentially be updated in the new design, or performance increase factors, such as drag reduction technology. The cost factors associated with using this new technology can also be included. Economic variables can include labor and materials costs, production rates, and the number of aircraft sold, as well as more global economic variables including interest and inflation rates and the cost of fuel.

Choosing variables for models created using different analysis tools presents a more complex set of problems. Ideally, all of the tools used would have the same set of variables to choose from for modeling purposes. Unfortunately, this is seldom the case. Sometimes different analysis tools present similar variable choices, so variables can be worked out between the tools so each solution model can be created from a similar set of variables. When this is not possible, or when analysis tools have differing levels of fidelity, variable selection may differ between solution options. This case is not ideal, since it means that direct comparison between solution options becomes much more difficult.

Scenario modeling, like variable selection, also requires knowledge of the analysis tool to be used. The first step in the scenario modeling process is to map each scenario to the variables being modeled. For example, Scenario 1 will have the same (or very similar) variables as Scenario 2, but those variables will have different ranges that reflect the differences between the two scenarios. Each scenario will have its own set of variable ranges and each problem solution will have its own model.

When the variable ranges are determined for each scenario for each model, the scenarios can be combined into one range for each variable for each model. The minimum and maximum of each variable across all scenarios becomes the variable minimum and maximum for modeling purposes. In Table III, the range for variable 1 would be 1.4 to 2.6 and the range for variable 2 would be 4 to 12.

Table III: Variable Range Determination

	Variable 1		Variable 2	
	min	max	min	max
Scenario 1	1.4	1.8	4	6
Scenario 2	2.2	2.6	9	12
Scenario 3	1.3	1.6	4	7
Scenario 4	1.8	2.4	6	10
Scenario 5	1.7	2.0	5	9

Creating only one model for each solution instead of one model for each scenario for each solution will decrease modeling and simulation time and necessary computing power. If there are five potential solutions and four scenarios for each solution, it is much quicker to run five potential solutions rather than twenty solutions. Having all the scenarios rolled up into one set of variables also makes the risk analysis and mitigation process less time-consuming, and as time is valuable in conceptual design, there is potential for more solutions to be examined with this process.

Modeling each solution over the set of variables can be done in several different ways. This author recommends a design of experiments (DoE) as a modeling tool, since it can be set up to use with surrogate models. DoEs come in many forms; one of the most often recommended forms is one set up for a linear, second order parametric regression equation, such as a face-centered central composite design. This type of DoE can be used for many applications. Most statistical software packages have some such DoEs built-in, and others can be created or purchased. When the DoE is created, a set of extra, possibly random, points should also be created in addition to the base points. These points will be used for verifying that the surrogate model is accurately representing the created model.

Post processing will probably be necessary to gather the data into some useful form and create a sense of time-dependence in the model for each solution. Creating time-dependent models can be a problem as many analysis codes do not contain time-dependent variables. One way to get around this problem is to specify variables at a specific point in time. For example, an analysis tool may be set up where the production schedule is an input and so a production schedule, per year, can be input into the tool to give the illusion of time-dependence. Or, potentially, post-processing may allow variables to be changed with time; as an example, a created cashflow may allow the user to have the ability to change inflation rate or increase or decrease wage rates over a period of time.

Surrogate models for important metrics for each solution are built after the solution is modeled. Important metrics are those necessary for comparison between solutions and will include both performance and economic parameters. These models can be created using any surrogate modeling technique desired; however, there are some techniques that are more popular than others for parametric models. Appendix A explains two such techniques: response surface modeling and neural networks. These models should be validated against the random data added to the end of the DoE used for scenario modeling. The surrogate model will go across all scenarios and can potentially be used even if the solution is later updated.

The output of the solution modeling step is the surrogate models of each solution over the set of scenarios. These models will be used in the following steps to model and assess the list of risks created in step three.

This type of scenario modeling is not often undertaken. Scenario modeling in literature treats scenarios as discrete events, not stochastic events. The addition of variables to the scenario building and modeling steps is unusual.

5.3.2.2 Uncertainty Quantification

Step 6: Uncertainty Quantification, is the next step to complete after all of the solutions have been modeled. The goal of the uncertainty quantification step is to map each potential risk to the set of variables that are used to model each potential solution. After that, it is to determine the severity of the impact that each risk could have on the solution, and then use the created scenarios to determine the probability of occurrence of every potential risk. Thus, this step deals with both the probability of each occurrence of each potential risk and the consequence if such and outcome occurs.

The first step in the uncertainty quantification process is to determine what to use as the baseline for every potential solution model. The baseline model is the model that meets all the initial assumptions that are identified, i.e. what the designers expect to happen. For example, when designing a new commercial aircraft, Boeing has an assumption of how many of that aircraft will be sold and at what price they will be sold. If the number of aircraft to be sold and aircraft price are two of the variables, than the baseline for those variables would be the initial assumed number of aircraft sold and the price of the aircraft. If those variables are correlated, correlation logic should be built into the baseline numbers and the risk modeling and assessment steps; Some Monte Carlo analysis computer programs allow for variable correlation.

Once the model baseline is determined, the second step is to map the consequences of each potential risk to the variables used to model the solution. Since the variables used to model the solution were decided upon with the list of assumptions and risk available, this process should be doable without adding new variables. That is, every risk should have consequences that map to at lest one variable. The easiest way to complete this process is to create a matrix mapping the assumptions and their uncertainties to the variables. The matrix can be filled in by hand or, potentially, automatically, although an automatic process proved too difficult for this author to implement.

The matrix can be filled in either quantitatively or qualitatively. To fill in the matrix quantitatively, much information must be known about the risk and the variable. To use the example from the previous paragraph, to fill out the matrix quantitatively it must be known that a certain risk will decrease the average price of the aircraft by $10,000,000 and 120 fewer aircraft will be sold. Early in conceptual design this information is rarely known and is often still uncertain; therefore, the risk modeling matrix is generally better filled out qualitatively. The scale used to fill out the matrix can be whatever is deemed appropriate by the decision makers. Eventually, in step seven of this process, the scale will be mapped from qualitative or generic quantitative inputs to specific quantitative inputs. An example of such a risk matrix is illustrated in Figure 27.

			Variable 1	Variable 2	Variable 3	Variable 4	Variable 5
Employment							
	Assumption 1	Uncertainty 1	-1			-1	
		Uncertainty 2			-3		
		Uncertainty 3	-3	-2		1	
		Uncertainty 4		-1			
		Uncertainty 5	2				-2
	Assumption 2	Uncertainty 6			-3	3	
		Uncertainty 7	-2				1
		Uncertainty 8		3	-1		
	Assumption 3	Uncertainty 9	-1				
		Uncertainty 10	1			-2	-1
		Uncertainty 11			1		
		Uncertainty 12	-3				
	Assumption 4	Uncertainty 13			-2		-3
	Assumption 5	Uncertainty 14	3	-2			
		Uncertainty 15					
		Uncertainty 16		1	-2		-1
	Assumption 6	Uncertainty 17	-1			-1	
		Uncertainty 18	-1				3
		Uncertainty 19			2		
		Uncertainty 20				-2	

Figure 27: Risk Modeling Spreadsheet Example

While the qualitative scale can be anything the decision maker chooses, there are some common scales exist. There is a monotonic, linear scale, such as 1-3, 1-5, or 1-10. These scales are very common in many applications, and have the advantage of simplicity. They work well for applications where the decision maker knows little about the consequences associated with a risk. To use such a scale, the consequences of each potential risk would be mapped to each variable such that a small degradation from baseline performance would be mapped as a one while a large degradation from baseline performance would be mapped as the maximum on the scale. One of the problems with this type of scale is that human perception of consequences in a risk assessment is non-linear, as explained in previously. One way to get around this problem is to assign a non-linear scale, such as 1 to 3 to 9, in place of a linear scale of 1-3. The advantage of such a move is that it conforms better to human perception of consequence, and, therefore, can potentially achieve more accurate results. A problem with both of these scales is that they only allow for degradation in the variable performance. In real life, a potential risk may positively impact one or two variables but negatively impact several others, thus leading to a potential overall negative impact. Similarly, it also assumes that there is a definite direction of improvement or degradation in each variable, while some variables may have a nominal value and movement to either side is a degradation in performance. Variables that impact schedule are examples of this type of variable: either a speed up or a slow down of schedule increases cost (Augustine 1997). A way to get around this problem, and the method that this author chose to use, is to use a scale that is both positive and negative such as -3 to 3. Using this type of scale allows for both increases and decreases in each variable from the baseline value. It also allows for better examination of variables, such as technology factors, that may improve performance but have additional cost.

While different scenarios should be taken into account while completing the risk model mapping process, it is not always necessary to determine consequences over each scenario. Often, the same assumption and potential risk will have the same set of consequences across all scenarios, although the probability of occurrence will change between scenarios. If this is the case, and many times it will be, there is no need to create one risk model for each scenario; instead, one risk model can be created for each potential solution or the same risk model can be used for multiple potential solutions if the solutions are sufficiently similar.

Inputs for the risk modeling step are the created scenarios, the list of assumptions and risks for each potential solution, and the variables that were used to create each solution model. Outputs from this step are the risk model matrix for each model or an overall risk matrix for the set of solutions. These outputs will be fed into the next step: risk assessment.

5.3.2.3 Risk Assessment

Since this process involves a scenario-based risk analysis, the use of scenarios should come into play when determining the likelihood of each potential risk actually happening. While the consequences of each potential risk actually coming to pass may be the same, or at least very similar, no matter what scenario or set of scenarios are used, the probability of any particular thing going wrong will change depending on the scenario. Therefore, the probability of each potential risk associated with an assumption must be separately assessed over each scenario.

Probability assessment can also be done qualitatively or quantitatively. Early in conceptual design, a qualitative assessment is often a better choice than a quantitative assessment. It is easier for the human decision maker to judge whether the probability of a specific event is unlikely or likely vs. whether that event has a 25% or a 35% chance of happening. At this point in conceptual design, there is so much uncertainty in how likely an event is to take place in the future that assigning it a numerical probability is too difficult for the decision maker and disingenuous to anyone who later peruses the risk assessment: the decision maker doesn't have that much confidence in his probability to provide that precise a number.

Qualitative probability assessment can assess probabilities either using language or on a scale. Assessment using language is familiar to people who speak almost any language. It requires a scale of event likeliness such as low probability, medium probability, or high probability. A risk analysis involves the analysis of both probabilities and consequences and then the combining of those two analyses into a full risk assessment. This process lays out separate assessments of probabilities and consequences and then combines them, instead of having just one assessment. This author chose to use a qualitative scale to assess probabilities of occurrence for each potential risk over each scenario because at this stage of design determining numerical probabilities is a very uncertain process.

1. extremely unlikely
2. very unlikely
3. unlikely
4. somewhat likely
5. very likely

Many risk assessment methodologies, such as the probabilistic risk assessment technique used by NASA ("Probabilistic Risk Assessment…" 2004) and others throughout the aerospace industry rely on scales similar to the one given above. The scale itself can be modified to fit whatever problem the decision maker is trying to solve; however, the same scale should be used to assess all potential risks over all scenarios over all solutions. Also note, the scale above can easily map to a numerical 1-5 scale for risk calculation purposes.

Sometimes the probability of occurrence for each potential risk can be assessed once and be valid for all solutions, other times each solution must be assessed individually. If the solutions are sufficiently similar, it is possible to complete a probability assessment once for all potential solutions; there may also be times when two or more solutions can share a probability assessment while another probability assessment must be completed for other solutions. Completing this process by hand, as this author chose to do, is time-consuming; however, it is a difficult process to automate since it requires decision making capabilities.

Once the probability of occurrence of each potential risk is assessed over each scenario, a cumulative probability can be assessed across all scenarios. This can be done by assigning a likelihood for each scenario and then summing the probability times the likelihood of each scenario for each potential risk. For example, if there are five scenarios, best case, worst case, and three more likely, the best and worse case scenarios are less likely to occur than the three middle ones, so they can be assigned a small probability of occurrence, such as 5%, while the more likely scenarios can be assigned a larger probability of occurrence, such as 30%. This procedure gives a weighted average probability of occurrence for each potential risk, as illustrated in Figure 28. A numerical scale was chosen for this project; the scale is one to five, with one meaning extremely unlikely to occur and five meaning likely to occur. A likelihood of occurrence for each assumption and uncertainty must be completed for every scenario. For example, in Figure

28, the probability of occurrence of Risk 1 in the first scenario is listed as a four, or somewhat likely.

			Cumulative Probability	Scenarios Probability 1	2	3	4	5
Employment								
	Assumption 1	Uncertainty 1	1.3	4	4	1	1	1
		Uncertainty 2	1.75	4	1	3	1	1
		Uncertainty 3	2.25	2	1	4	2	1
		Uncertainty 4	2.05	4	1	3	1	2
		Uncertainty 5	1.15	1	4	1	1	1
	Assumption 2	Uncertainty 6	3.2	3	1	5	2	3
		Uncertainty 7	1.7	2	2	1	1	3
		Uncertainty 8	2	1	3	2	3	1
	Assumption 3	Uncertainty 9	1.1	1	3	1	1	1
		Uncertainty 10	2.35	4	1	3	1	3
		Uncertainty 11	2.25	1	2	4	2	1
		Uncertainty 12	1.95	2	1	1	3	2
	Assumption 4	Uncertainty 13	2.25	2	1	1	3	3
	Assumption 5	Uncertainty 14	1.9	1	1	3	2	1
		Uncertainty 15	1.65	2	1	2	2	1
		Uncertainty 16	2.75	5	2	5	1	2
	Assumption 6	Uncertainty 17	1.65	2	1	1	1	3
		Uncertainty 18	1.95	2	1	1	3	2
		Uncertainty 19	2	3	1	3	2	1
		Uncertainty 20	2.65	1	4	4	3	1

Figure 28: Cumulative Probability of Occurrence

The cumulative probability takes into account the probabilities for all scenarios, weighted by the probability of the scenario's occurrence. In the Figure above, scenarios one and two have a probability of occurrence of 0.05 (the best and worst case scenarios) while scenarios three through five have a probability of occurrence of 0.3. Thus, each potential risk has a cumulative probability of occurrence associated with it, calculated using Equation 6.

$$CumulativeProbability = \sum_{i-1}^{\#Scenarios} ScenarioProbability_i * UncertaintyProbability_i \quad (6)$$

Once the probability of occurrence for each potential risk is calculated, the consequence associated with each potential risk can be calculated. In reality, these steps are interchangeable; either one can be completed first.

Assessing the consequences of each potential risk is a multi-step process. The first thing to be done is to completely map the risk model to the set of variables for each potential solution. Since the risk model used a qualitative -3 to 3 scale while the variables each have a quantitative range, the mapping process must translate between these two pieces of information. Using the example from the previous section, if the variable is the number of aircraft produced, the baseline is 1000 aircraft, and the variable range is 600 to 1200 aircraft, one potential map could be as listed in Table IV.

This scale is linear, but any scale will work as long as it is consistently linear or non-linear across all the potential solutions. For the scale below, it is linear on the lower end and non-linear on the upper end, and it has different slopes for good and poor outcomes. This is because decision makers are likely to assume the future will go well (Lovallo and Kahneman 2003) and set a baseline accordingly; the actual value is more likely to fall below than above the baseline. Notice that it is not necessary to use the entire variable range for each solution model; if the range is accurate, the entire range will be utilities across all solution models. This process must be completed for all variables for each solution model. Some variables, such as the price of fuel, will have the same map for all solutions, while others, such as product cost, will be different across solutions.

Table IV: Risk Model to Variable Mapping

Risk Model Result	Variable Result
-3	700
-2	800
-1	900
0	1000
1	1050
2	1100
3	1200

This scale is linear, but any scale will work as long as it is consistently linear or non across all the potential solutions. For the above scale, it is linear on the lower end and linear on the upper end, but it has different slopes for good and poor outcomes. This is because human decision makers are more likely to make the initial baseline a generous estimate; the actual value is more likely to fall below than above the baseline. Notice that it is not necessary to use the entire variable range for each solution model; if the range is accurate, the entire range will be utilities across all solution models. This process must be completed for all variables for each solution model. Some variables, such as the price of fuel, will have the same map for all solutions, while others, such as product cost, will be different across solutions.

Once the mapping is completed, then each potential risk must be input into each surrogate model to see the consequences on the whole system if the event does occur. The goal is to see the effect of each potential risk on the technical and economic outputs modeled in step four. To determine the consequences of each potential risk, the technical and economic outputs must be examined and a determination must be made as to how severe is the consequence should the event occur.

The consequences assessment, like the probability assessment, can also be completed qualitatively or quantitatively. For the same reasons as mentioned above in the probability assessment, this author has chosen to complete the consequence assessment qualitatively using the scale below.

1. very small
2. small
3. medium
4. high
5. catastrophic

The determination of exactly what delineates a very small consequence from a small consequence, etc, is left to the decision maker completing the risk analysis step. Some guidelines that this author chose to use were the difference in the amount of time to break even and the final profit between the baseline and the assessed event, the degradation in performance, especially if one of the performance goals was not met, and degradation in emissions between the baseline and the assessed event. Since this analysis is completed by a human decision maker, it is possible that two different decision makers would assign different consequence ratings for the same event. This is to be expected; however, the differences should be small and consistent across all solutions. One decision maker should not have assigned a consequence of five to an event while another decision maker assigned a consequence of two to the same event. If many decision makers are working on different parts of the risk analysis portion of this procedure, they should lay out guidelines for consequence severity before assessing the different potential risks. It may be possible to determine a set of rules for consequence and automate this process, but this author did not choose that route, instead, this author completed this process by hand.

After the consequences are determined for each potential risk for each assumption, the actual risk is calculated in order to determine whether each potential risk has an actual risk associated with it. There are several formulas to calculate risk when given a set of probabilities and consequences. One of the traditional ways to calculate risk is to use the expected value formula given in Equation 5 in Section 3.3.3, repeated again here.

$$E(X) = \sum_i p_i x_i \tag{5}$$

This method has the advantage of simplicity, since a single multiplication is required and also has the advantage of a single, deterministic number for risk ranking purposes. However, it has the problem of not conforming particularly well to human perception of risk.

One of the ways to get around the problem of human risk perception not corresponding to the strict definition of risk calculation is to weight the consequences part of the risk equation more than the probability part of the risk equation. This weighting can take different forms; it can be a linear multiplier or an exponential function. This author chose an exponential function to use for the consequences side of the equation because this author believes it more closely corresponds to human risk perception than a linear or other multiplier. This author chose a base of two for the exponential function to approximate consequences while still achieving the desired effect; however, any base could be chosen. The base of two was chosen because it weighs consequences highly when the consequence is large, but more closely approximates the traditional risk calculation when the consequence is small. The new risk analysis equation used by this author to compute risk with a given qualitative probability and consequence is as follows:

$$R(x) = p_x * 2^{C_x} \quad (7)$$

R(x) is the risk associated with the uncertainty, p_x is the cumulative probability of not meeting the assumption, and C is the consequence of not meeting the assumption.

This new equation allowed for the calculation of risk for each solution over all scenarios. This calculation can be completed automatically in tabular form, as listed in Table V. In that Table, the cumulative probability of each risk associated with each assumption is calculated. Then, consequences for each potential solution a re determined using the one to five scale explained above. The risk is calculated using Equation 7.

Table V: Risk Table

			Cumulative	Scenarios Probability					Consequence		Risk	
			Probability	1	2	3	4	5	Solution 1	Solution 2	Solution 1	Solution 2
Employment												
	Assumption 1	Risk 1	1.3	4	4	1	1	1	3	3	10.40	32.00
		Risk 2	1.75	4	1	3	1	1	4	5	28.00	128.00
		Risk 3	2.25	2	1	4	2	1	3	4	18.00	32.00
		Risk 4	2.05	4	1	3	1	2	1	1	4.10	8.00
		Risk 5	1.15	1	4	1	1	1	0.5	1	1.63	2.00
	Assumption 2	Risk 6	3.2	3	1	5	2	3	1	2	6.40	12.00
		Risk 7	1.7	2	2	1	1	3	3	5	13.60	64.00
		Risk 8	2	1	3	2	3	1	0	0	2.00	1.00
	Assumption 3	Risk 9	1.1	1	3	1	1	1	1	3	2.20	8.00
		Risk 10	2.35	4	1	3	1	3	1	1	4.70	8.00
		Risk 11	2.25	1	2	4	2	1	1	2	4.50	4.00
		Risk 12	1.95	2	1	1	3	2	1	1	3.90	4.00
	Assumption 4	Risk 13	2.25	2	1	1	3	3	0.5	1	3.18	4.00
	Assumption 5	Risk 14	1.9	1	1	3	2	1	0	0	1.90	1.00
		Risk 15	1.65	2	1	2	2	1	0.5	0	2.33	2.00
		Risk 16	2.75	5	2	5	1	2	0	2	2.75	20.00
	Assumption 6	Risk 17	1.65	2	1	1	1	3	1	1	3.30	4.00
		Risk 18	1.95	2	1	1	3	2	0.5	1	2.76	4.00
		Risk 19	2	3	1	3	2	1	1	-2	4.00	0.75
		Risk 20	2.65	1	4	4	3	1	2	1	10.60	2.00

The method outlined in this section was set up to meet this goal: create a process that allows for the examination, for the purpose of decision making, of technical and economic objectives, as well as programmatic risk and risk control and mitigation strategies. It was also designed to be used by engineers at the conceptual design level. After some background investigation on what makes people want to follow a process to complete an assignment, a more comprehensive lest of requirements for the risk analysis process was created. This list is not intended to be all-inclusive; however, it should highlight some important aspects of creating a methodology that others will understand and choose to follow.

The risk assessment step in this process seeks to assess the severity of each potential risk and assign a severity ranking to each potential risk. The goal of this step is to see which of the list of the potential risks should be considered a serious risk and which members of the list need not be worried about. This step is important to take the time to complete correctly. It can be time-consuming to complete by hand and also time-consuming to write a program to complete automatically. Unfortunately, it is important to identify the members of the list of potential risks that pose the greatest hazard to the program and each solution; therefore, this step must be completed as accurately as possible.

Once each potential risk has an actual calculated risk, a risk analysis and ranking can take place. Each risk can be ranked, either qualitatively or quantitatively. A quantitative ranking can be made based on the calculated risk; however, this ranking may not mean very much when calculated risks are very close in number. When one calculated risk has is 10.33 while another calculated risk is 10.5, there may be very little difference in the ranking and evaluation of such risks. A better way to rank such risks is to rank them qualitatively in groups. Risks can be ranked based on probability and consequences, with low probability and low consequences meaning low risk and high probability and high consequences meaning very high risk. There are many such ranking schemes, one of which is illustrated in Figure 29. Since this ranking scheme takes into account the increased weight of consequences over probability, particularly at high consequence outcomes, it was chosen by this author to illustrate a qualitative ranking and compartmentalization of risk.

After risk analysis takes place, the next step is to complete a risk mitigation process as outlined in the next section. The risk mitigation process takes information from this step, including the risk calculation and risk rankings, as well as the performance and cost characteristics of each potential solution. Inputs for the risk analysis step include the list of assumptions and potential risks, the risk model matrix, and the set of scenarios. Outputs are a qualitative ranking and numerical representation of risk for each alternative over the set of future scenarios. This representation of risk will be used as an input for both the risk mitigation step and the decision support step that will follow.

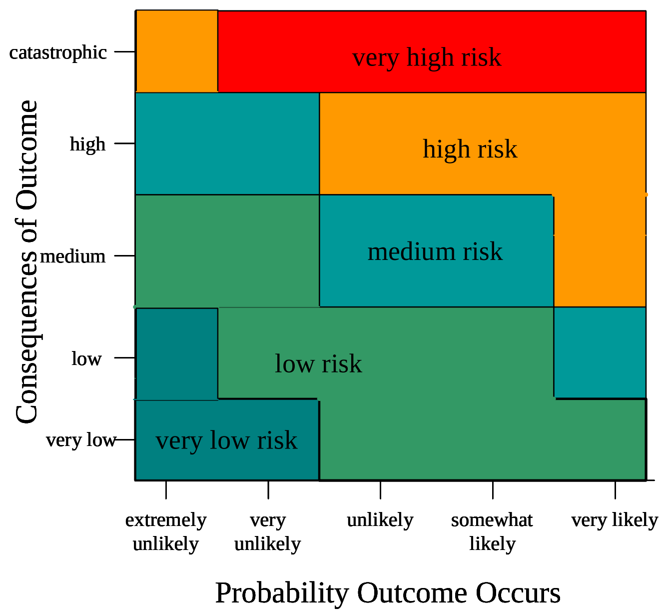

Figure 29: Risk Analysis Chart (Modified from Haimes 2004)

<u>5.3.2.4 Risk Mitigation</u>

The purpose of the risk mitigation step is to see the effect of partially or totally taking steps to mitigate the larger risks identified in the previous step. Risk mitigation is an important part of any risk analysis process; while finding out which parts of a system cause the most risk is important, it is equally important to know what steps can be taken to mitigate risk.

Determining how to mitigate risk is difficult. For technical risks, it can mean having a backup plan for the use of new technologies if said technologies do not come to fruition and provide the necessary results in the necessary timeframe at the necessary cost. For economic risks, mitigation processes can include planning to spend more money earlier in the design phases in order to decrease the chances of an economic disaster later in the design process. While these ideas sound good in theory, in a real design project these decisions are difficult to make. It can be difficult to determine how to put in place a mitigation plan for a technical risk when future technology performance is uncertain: should the mitigation plan include using the technology even if its performance goals are not met, or should the mitigation plan include the use of older, established technologies even if they will provide sub-optimal performance? There are also cases in which a new technology or technology suite is necessary for system performance goals to be met and in these cases the technological risk mitigation plan cannot include any backoffs in technology and so must include decreases in performance capability.

Economic risk is also difficult to mitigate in real projects. There may not be any additional money to spend up front on decreasing economic risks, or, if there is money available, it is a limited amount. Tradeoffs must be made among which risks to mitigate and which risks or types of risk provide the biggest bang-for-the-buck, or lowest cost/benefit ratio. Since there is never an unlimited amount of money to spend, and there are always risks that cannot be mitigated, any risk mitigation process, technical or economic, is difficult to implement. Other concerns for both technical and economic risk mitigation include the timeframe in which these risks must be dealt with. For risks that are near-term, mitigation plans or processes may be seen as more urgent, even over potentially programmatically catastrophic risks. Since the human decision maker will perceive immediate risks as more important than long-term risks, this problem is a human nature problem, not a risk analysis problem and, as such, must be worked around as well as possible.

While all of the above problems with completing a risk analysis process are present at all phases of design, they are magnified during conceptual design since all information is very uncertain and time scales are long. Risk mitigation processes during early conceptual design are generally focused on one or two areas of risk. For example, NASA's risk planning and mitigation process focuses on technological risks in terms of cost, schedule, and performance. It does not deal with other types of economic risk such as those associated with changes in political administrations, cultural changes, or employment problems. A process that allows for the examination of potential mitigation of all types of risk is, as far as this author understands, unique.

The first step to completing the risk mitigation process is to determine, through use of the list of assumptions and risks, which risks can be mitigated and which cannot. Some risks will affect all potential solutions and cannot be mitigated through any action by the corporation creating the product or the user. These risks include such things as pandemics and changes in global political alliances. Other risks, such as those associated with demographic changes in population and employees (present and future) can, and should, be prepared for. In general, technical risks are more likely to be able to be mitigated than economic risks; however, one exception is the unforeseen invention of an industry-altering technology. While such an occurrence is rare, it should nonetheless be included in the risk analysis.

The next step in the risk mitigation process is to determine the performance and economic effects of mitigating each of the risks that can be mitigated. This is the complicated element of the risk mitigation process.

For technical risks, the goal is to see the performance and economic impact of not having new technologies achieve the projected performance. Since the technologies that are being examined have already been modeled, it is easy to change the technology parameters and see the performance and economic impacts of changing technologies. Now that the impacts of changing technologies can be seen, it is necessary to choose fallback positions for each technology or technology suite. These fallback positions should be chosen with the aid of the person or group of people developing the technology. For example, if a new technology will decrease the weight of the avionics system by 15%, there may be two fallback positions if the 15% is too far a reach: 10% and 0%, which is existing technology. The 10% fallback position will impact performance parameters and may have a slightly lower projected cost as the initial position, while using existing technology will generally have a lower cost, for the manufacturer, than using new technology. This type of analysis can be completed for each technology variable or set of parameters and can be easily coded into almost any program. Investigating mitigating the risk associated with new technologies means seeing and measuring the impacts associated with moving to technology fallback positions and measuring the economic risk associated with those new positions. So not only does the impact of changing technology impacts need to be calculated, but this impact also needs to be mapped to changes in the risk associated with the technology. This mapping is done by first performing the same risk assessment on the fallback position as was performed on the initial technology and then decreasing the risk linearly in proportion to the cost difference between the baseline technology value and the new technology fallback position, as illustrated in Equation 8:

$$\%ChangeinRisk = \frac{BaselineRisk - NewRisk}{BaselineRisk} * 100 \tag{8}$$

This risk then decreases as one moves from the use of new technology to the use of existing technology. The cost associated with this move can be positive or negative, depending on whose costs are being measured. The costs for the end user will probably increase as one moves from using newer technology to using existing technology; however, the costs for the manufacturer will generally increase with the use of new technology.

While it is complicated to see the effects of mitigating technical risk, economic risk is even more difficult. The economic risk mitigation analysis involves planning to spend more money up front in order to have less risk later on in the design process.

Mitigating economic risks involves seeing how variable changes impact the program's cost and then mapping variable changes to risk reduction. In order to map variable changes to risk reduction, since each risk can be mapped to several variables, involves seeing how each change in a variable from the baseline to a new position (-3 to 3, from above) impacts different aspects of project cost. While this is easy to do when variable impacts are monotonic and cross-terms between variables do not exist (or are very small), the complication increases greatly as variable impacts on economic responses are non-monotonic and cross-terms become larger. For the best case, when variable impacts on responses are monotonic and cross-terms are small, the decision maker can create a table of how each variable impacts each economic response of interest. For example, if the economic variables of interest are the ones that make up a cashflow, then the impact of each variable for each solution for each level, -3 to 3, as it differs from the baseline must be calculated. If first unit cost is one of the responses of interest and the cost of engineering labor was one of the variables, then the impact of increasing and decreasing engineering labor cost to a given rate is calculated, as per Table VI below.

Table VI: Variable Change Map

Variable Change	Variable Value	First Unit Cost
3	120	138.0
2	100	135.2
1	80	132.5
0	60	130.0
-1	50	127.5
-2	40	125.1
-3	30	122.6

As the first unit cost impacts the product's cashflow, it can be seen that planning to spend more money on labor costs correlates to planning for an increased first unit cost and an increased manufacturing cost as part of the cashflow. While this change means planning to spend more money than the original assumption called for, it also reduces economic risk since there will be a decreased chance of overrunning the new predicted set of costs. Whether it makes sense to plan to spend this money or to plan that the original assumption is true depends on the amount of money available and the risk tolerance of the decision making team.

When functions are non-monotonic, this process can be completed the same way, but the results are more difficult to interpret. Non-monotonic functions are usually, but not always, schedule dependent: both speeding up and extending a schedule causes an increase in cost. Cost functions that are best at a nominal value can make it difficult to see whether it is beneficial to reduce risk, since the cost increases whether the variable is increased or decreased. In some of these cases, any deviation in the initial assumption increases risk, which can mean, if there is a high probability that the assumption will not be met, that the initial assumption should be changed before any risk mitigation is undertaken.

When cross-terms impact the economic and performance metrics of interest, it becomes more difficult to determine the impacts of each variable change. Some logic must be created to accurately see the impact of changing a variable such that it no longer conforms with the initial assumption. This logic needs to be specific to each metric for each proposed solution and created as necessary. While this is a time-consuming step, many times the cross-terms are of small enough impact that it is unnecessary to complete, or, if it is necessary, there are only a few terms that are important.

Seeing the effects of mitigating economic risk is similar to seeing the effects of technical risk. Equation 8, from above, is used to determine the impact of mitigation of economic risk also. As the risk is reduced per Equation 8, the impact of the reduction is seen on the economic parameters through the changes in variables. To continue to use the example from Table VI, if the uncertainty associated with an assumption has a labor rate variable value of three, meaning that labor rates are likely to increase in the future, than the first unit cost is also likely to be higher than the initial assumption. Decreasing this risk means that the new assumed value for the labor rates approaches the potential value as outlined by the particular risk in question. Using Equation 8, the new value of the risk is changed to be lower than the initial value. As this value decreases, the potential economic consequences decrease linearly. However, the costs associated with this decrease in risk are added into the cashflow or other economic metric of interest: as the risk decreases, the first unit cost goes from a value of 130 to a value of 138, or approximately a 6% increase in first unit cost.

Inputs to the risk mitigation step of this process include the list of assumptions and risks, the risk model, and the metrics of interest for each solution. The output for this step shows which risks can be mitigated and the potential impact, performance and economic, of mitigating different risks. The risk mitigation process to be laid out here is intended to illustrate the zero-order economic and performance effects of mitigating certain risks. It is not intended to determine whether such a risk mitigation procedure is possible; however, that would be a useful addition to this process.

5.3.3 Decision Support

The last focus area of this process is decision support. Now that all of the information generated in the previous eight steps is available, it must be presented in such a way that it is useful for a human decision maker. Human decision makers are only able to take in and process a limited amount of information at a time, so too much information and too many tradeoffs should be avoided. At the same time, enough information should be available to allow the decision maker to make good decisions and back up those decisions with available data.

The data availability and visualization is an important part of decision support. As this is a risk mitigation process, much of the decision support interface will center around risk analysis and mitigation visualization. A good decision support interface should provide all information necessary to make a decision and allow for tradeoffs within the environment, especially for a risk analysis and mitigation process.

While such an interface will be different for every product, there are some must-haves for this particular process. For this process, it is important to know what the assumptions and risks are, so those should be listed for examination. There also needs to be some way to differentiate between risks that can be mitigated and those that cannot. It would also be useful to have the ability to compare risk across the different solutions and have the ability to mitigate different risks across the different solutions while being able to see the overall impact of different types of risk. This part of the interface can be completed in a list form, such as the one illustrated in Figure 30 below. That interface is built in MS Excel and contains a list of assumptions, a list of uncertainties (potential risks) associated with the assumptions, and the initial baseline calculated risk for each of the uncertainties for each potential solution, a differentiation between risks that can be mitigated and those that cannot, and a set of slide bars for illustrating the effects of mitigating risks. While this is a long list of information, it is presented in a concise list and so it is easy to understand.

Assumptions	List of Potential Risks Due to not Meeting Assumptions	Twin-Engine Aggregate Risk Changes	BL
Travel will increase at 4%/year	Increase in telecommunications causes decrease in travel	10.40	10.40
Can sell twin for overseas use	Customers uncomfortable on overseas flights on twin	3.20	3.20
More travel & wealth within China	Leveling off of Chinese population	3.40	3.40
China opening to west	Tension between China and Britain/US over Hong Kong	4.60	4.60
Little travel to SE Asia	Opening of SE Asia	6.80	6.80
There is no change in cultural preferences for American/ European a/c	Asian preference for American aircraft	30.40	30.40
	Japanese preference for American aircraft	7.20	7.20
	Middle Eastern preference for American aircraft	4.00	4.00
	General preference for status quo	2.00	2.00
America comes into line about government aid	American companies boycott European airframers	22.40	22.40
	American consumers boycott European airframers	6.60	6.60
No regional/global epidemics	Epidemic decreases flying public	9.20	9.20
	Epidemic cuts off S.Asia	5.40	5.40
	Epidemic cuts off Africa	5.10	5.10
Rule of law prevails, in general	Civil unrest in China	4.20	4.20
	Fear of flying due to terrorist incidents	10.20	10.20
	Civil unrest in Eastern Europe	8.70	8.70

Figure 30: Risk Mitigation Interactive Process

Other parts of the decision support interface include those associated with the airframer's economic metrics of interest, as illustrated in Figure 31, those associated with the aircraft's performance, in Figure 33, and those associated with the airline's economic metrics of interest, in Figure 32. For the example given in Figure 31, the airframer's economic metrics are a cashflow for each potential solution and a comparison of the aggregate risk for each potential solution. This information is gathered during the aircraft modeling step. As changes are made to the risks shown in Figure 30 (the slide bars are moved), differences between the baseline cashflow calculation and the new cashflow calculation can be observed for each potential solution. Other examples of economic metrics of interest, which are not chosen here, are an NPV calculation or just a maximum sunk cost or breakeven point. All of this information is contained in the cashflow diagram, but can be broken down further to ease comparison.

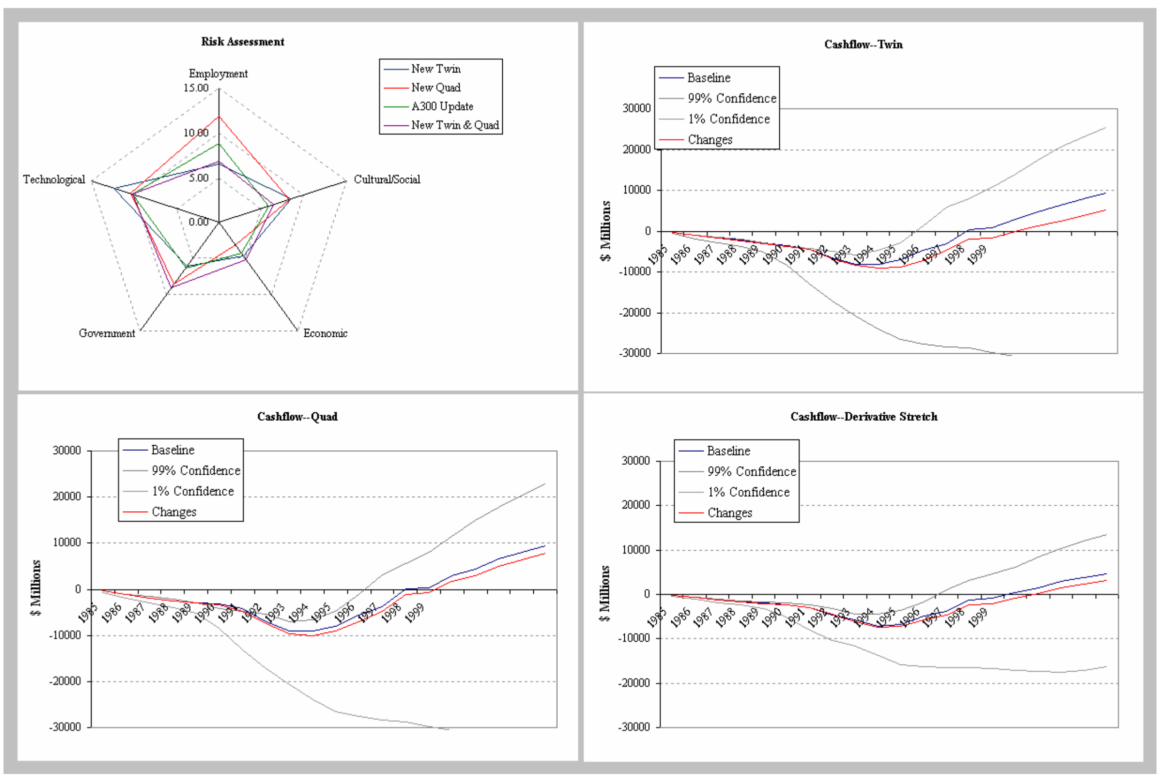

Figure 31: Risk and Cashflow Comparison

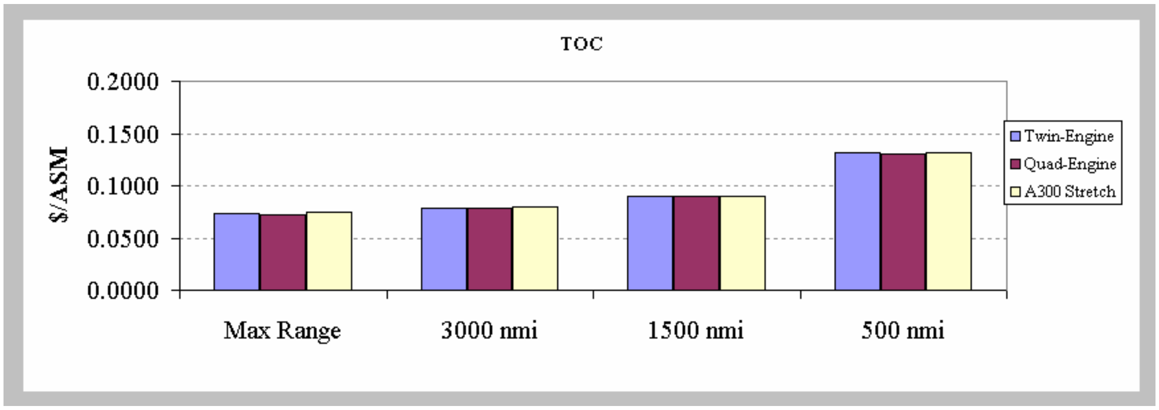

Figure 32: Airline Economic Metrics of Interest

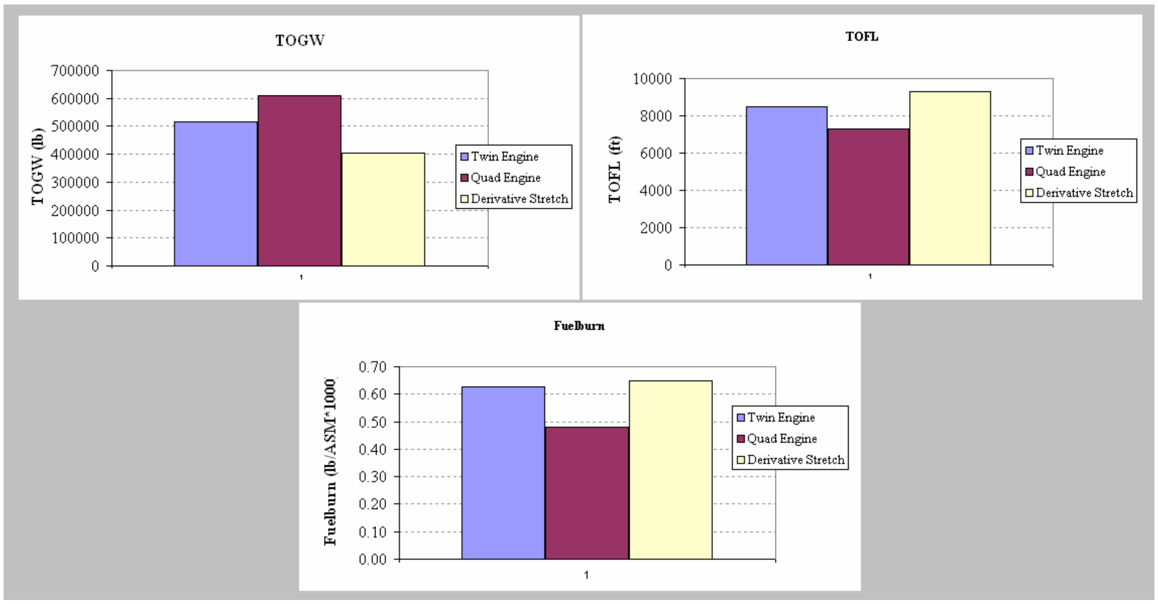

Figure 33: Performance Metrics of Interest

Performance metrics will, obviously, differ from product to product. For a commercial transport, takeoff gross weight (TOGW), takeoff field length (TOFL), and Nitrogen Oxide emissions (NO_X), fuelburn and noise are some of the important performance metrics. These three are listed below because they are of interest to both the airline and the manufacturer. Like the manufacturer, the airline also has economic metrics of interest; one of them is the required yield. It is important to be able to make tradeoffs between what is best for the manufacturer and what is best for the customer, which is why customer economic metrics and performance metrics of interest to the customer are also available for a risk comparison.

Having performance as well as economic characteristics for both the manufacturer and the customer available provides information that can be used for trade studies and comparison by a human decision maker. While this may seem like an overwhelming amount of information, much of the decision making will center around the manufacturer's cashflow or other economic metrics and the list of assumptions. Other metrics become necessary to examine only in certain situations: the airline metrics should be examined if there is a significant change in any of them. The performance metrics will be examined when technical risk is mitigated, but generally the economic impacts on performance metrics are small.

While having all of this data is very useful for trade studies, it can still be made more useful for decision making by implementing one of the MADM techniques explained earlier. TOPSIS was the chosen technique to implement here due to its simplicity and adaptability. An interactive TOPSIS, illustrated in Figure 34, was created to aid in the decision making process. All games that can be played on the decision support framework outlined above have results that can be seen here on this TOPSIS. The attributes used to rank different alternatives are listed down the left side of the diagram. Those attributes can be anything the decision maker is interested in examining. The relative importance of each of those attributes can be changed, as different decision makers may have differing rankings for those attributes. Changing the relative importance of each attribute can change the rankings of the potential solutions; however, the ability to play games and complete tradeoffs with the TOPSIS model outweighs the need for simplicity and a single solution.

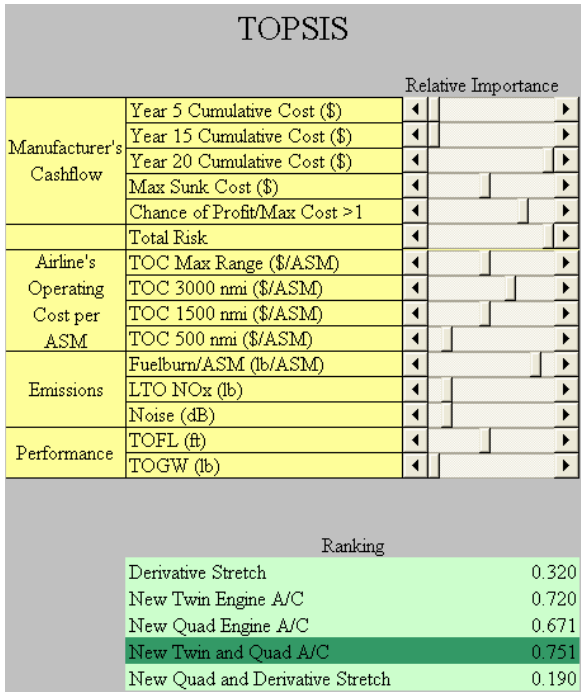

Figure 34: TOPSIS for Decision Support

Decision support plays an important role in the risk analysis and decision making processes. Decision support interfaces will be very different from project to project, but they should all have some of the same components: examination of assumptions, uncertainties in those assumptions, manufacturer's economic metrics, performance metrics, and how risk mitigation will affect the economic and performance metrics. They may also include some decision-making techniques for comparing the different solutions; the technique used here was TOPSIS. These techniques do not substitute for a human decision maker in the loop; however, they may add information or at least provide more rationale behind decision making.

5.4 Hypotheses Tests

As stated above, the hypotheses laid out in Section 5.2 should be testable. The demonstration problem will include a section on hypothesis testing, in order to demonstrate that the hypotheses are valid. Valid hypotheses are necessary for a demonstration of the scientific methodology used to create the risk analysis and mitigation process. Invalid hypotheses will be a sign that the process doesn't work as intended, and should be amended at such time, while valid hypotheses are a good initial demonstration that the process does work as intended, and more tests should be done to continue to demonstrate whether that is true. It is hoped that the hypotheses generated here for the creation of this process will be valid.

Hypothesis 1: A risk analysis along with the outcome analysis will allow consequences and uncertainty to permeate the business case and increase information available for decision making without overwhelming the decision maker. This hypothesis can be tested by skipping steps six through eight in the proposed process and determining whether there is still enough information to support decision making. Without the risk analysis, there is only a benefit, or outcome, comparison across scenarios and potential solutions. A (monetary) outcome-only comparison does not take into account risks in the form of future uncertainty and decision consequences, so the choice of configurations will be limited to the one with the highest payout. With the introduction of consequences, the decisions can be based on both outcomes and risk and better outcome decisions can trade off with lower risk decisions. Decisions can change when risk is taken into account along with outcomes. Steps six through eight will show the decision maker whether the addition of a risk analysis and risk mitigation process will change the decision and add information to the decision making process.

Hypothesis 2: Both qualitative and quantitative information are available and can be used in decision making; the ability to use both types of information increases the number of applications for a risk-benefit analysis without overwhelming a human decision maker. This hypothesis can be tested by limiting the amount of information available to the decision maker. If the process is artificially limited to have quantitative inputs only, are any configurations unable to be analyzed? What information is lost in the analysis process? Is it more difficult to complete a risk analysis? Does the quality of the risk analysis suffer? Does the decision maker feel that less information enables him to make better decisions? Is there too little information to complete the process and make a decision during the early phases of conceptual design? And on the other side of the spectrum, if the process is limited to qualitative inputs only, is its usefulness limited as more information becomes available? If either of these conditions limit the use of the risk analysis process, then increasing the types of input data will increase the applicability of this process.

Hypothesis 3: Too much uncertainty can render a risk analysis meaningless; the use of future scenarios can bound uncertainty and tie it to specific circumstances. Testing hypothesis three can involve the creation of an "anti-scenario" just like all the other scenarios; however, this scenario has full uncertainty ranges just like a traditional probabilistic analysis. The probabilistic analysis can be run and data measured and collected just like the other scenarios. When the risk analysis and decision making time comes, the probabilistic analysis is analyzed exactly the same ways as the scenario based analysis. If the uncertainty in this analysis overwhelms decision making capabilities, then the use of scenarios is shown to be more effective at understanding and using future uncertainty. Even if the uncertainty in this analysis does not overwhelm the decision making capabilities by making solutions indistinguishable, the use of scenarios can still add a layer of traceability to the decision making process. To test whether this is true, explain how the variable distributions were derived for the scenario based analysis and then compare to the probabilistic analysis. If there is more information about how to create distributions from the scenario based analysis, then there is more traceability in that process.

CHAPTER 6

DEMONSTRATION PROBLEM

While the last Chapter outlined a risk assessment method to be used in the earliest part of conceptual design, a demonstration problem is intended show that the method will work and can be completed as outlined. It is not the intention of this chapter to prove that this method is the only way to complete a risk assessment; there are many risk assessment methodologies. However, it is the intention of this chapter to demonstrate that the hypothesized risk assessment process has some superiority over currently existing conceptual design phase risk assessment processes in that is examines risks that are not well-examined by current engineering risk analysis processes. Much of this demonstration will take place at the end of this chapter, in Section 6.4 when the hypotheses listed in Chapter 5 are tested and it is determined whether these hypotheses are met. The hypotheses are met if the demonstration problem shows their plausibility.

Since this process prominently involves a human decision maker and a model of the future, it was difficult to determine whether to use a current or historical example for this demonstration problem. Using a current example would allow the problem to be completed from the perspective of not knowing the future; however, any validation of the problem results would take many years. Therefore, since a current or future demonstration problem could not be used, a past problem was chosen. While a past problem allows for comparison of predicted values and scenarios with real-life values and scenarios, it also has the disadvantage of the decision maker knowing what happened. It can be difficult to create scenarios, examine options, and create problem solutions accurate to the time period when the outcome is already known. Even with these difficulties, a past problem was chosen, as it was felt that hypothesis testing and comparison to the actual outcome of events was an important part of the demonstration problem

Choosing a demonstration problem is difficult even though it is already known to be a historical example. The problem should be contained within the aerospace industry, and should be a design problem, since that is one of the initial assumptions for this process to work. The demonstration problem could be either commercial or military. Military problems have the advantage of generally having more and very different potential solutions for a given set of requirements; however, it can be very difficult to model any out-of-the-box solutions accurately and to acquire accurate, unclassified requirements data for comparison purposes. Commercial problems have the advantage of possessing generally straight-forward requirements and goals; however, commercial transports are all very similar so it could be difficult to distinguish between solutions enough to demonstrate that this process works.

Timeframe is also another consideration. While the further back one goes in time the more future comparison information would be available, as one goes further back in time it is more difficult to find information regarding the decision makers' thought processes and more difficult to determine the impacts of local, state, and world events. In light of these problems, this author prefers to use a relatively modern demonstration problem, such as one from the 1980s.

6.1 Problem Setup

The problem chosen for this demonstration is the development of a commercial aircraft in the 1985 timeframe. The problem is inspired by Airbus Industrie's development of the A330 and A340, but is not meant to exactly mimic that design problem.

In this case, setting up the problem requires learning as much as possible about the time period in question. Major players in the industry, motives, competition strategies, and so on should be understood as well as possible. National and international concerns also need to be reviewed and understood, especially as related to the design and manufacture of a new commercial aircraft. All of this information is gathered during step 1 of the process. Once step 1 is completed as thoroughly as possible, steps 2 through 4 are competed. These steps are easy to complete—after all, the decision maker knows what happened—but more difficult to justify. Therefore, it is very important to understand not only what was happening both within the aerospace industry and around the world, it is also important to be able to demonstrate that solutions generated are accurate to the time period in question.

6.1.1 Step 1: Establish the Need

The first step toward looking for a solution to any problem is to identify the problem. In this case, the problem is that it is 1984 and a notional airframer would like to break into the long-range air transportation market. While at this time the airframer already has a medium-range widebody fleet and a short-range, narrowbody fleet, it currently does not have a wide-body, long range aircraft in production.

6.1.1.1 Existing Wide-Body Aircraft

At this time, existing wide body aircraft include Lockheed's L1011, Douglas' DC-10, Airbus' A300/A310, and Boeing's 747 and 767. Of these aircraft, only the Boeing 767 and 747 and the Douglas DC-10 are true long-range aircraft, with ranges greater than 5000 nmi, and the Boeing aircraft are dominating this market. The DC-10 is an older trijet aircraft, launched in 1968, and is considered unreliable due to a number of accidents in the previous decade ("The McDonnell Douglas DC-10" 2003). There is potential for a DC-10 update or replacement toward the end of the decade, but that may not happen unless the company's financial prognosis improves. The Boeing 767 is a medium to long range, twin-engine wide body aircraft that was first flown in 1981 as the 767-200, with the 767-200ER, extended range, flown in 1984. It was developed in conjunction with the 757, with which it shares a common cockpit ("Boeing 767-200"

1998). A stretch version, the 767-300 and -300ER are scheduled to be flown in 1986 (“Boeing 767-200” 1998). Boeing’s 747 is a long range, wide body four-engine aircraft. It was first launched in 1970, with an updated 747-300, with upper deck, first flown in 1980 and another potential update projected for the latter part of this decade (“Boeing 747-300” 1998).

The other existing wide body aircraft of the time, the Lockheed L1011 and the current Airbus A300/A310, are not considered competing aircraft for the 747, 767, and DC-10, since they do not have as long a range. As the airframer strives to design and build a new long range wide-body aircraft, the major competition will be Boeing’s 767 and 747; the DC-10 and any additional updates to it are currently, and projected to be in the future, a minor player in the long-range market.

6.1.1.2 National and International Events

In the mid 1980s there were many changes taking place in the world. One of the big ongoing news pieces in the early 1980s was the changing of the USSR. Between 1980 and 1985, there were four General Secretaries of the Communist Party. The first is Leonid Brezhnev, who is remembered for the war in Afghanistan and giving increased powers to the KGB. Yuri Andropov took over for Brezhnev in 1982. He tried to reduce corruption and increase productivity in the USSR and elsewhere in Eastern Europe. He tried to reach out to the leaders of Western Europe and the United States; however, he was largely unsuccessful. While he wanted to reform the USSR, he died before he was able to accomplish significant reforms. He was succeeded by Konstantin Chernenko, who only lasted 13 months. Mikhail Gorbachev, who succeeded Chernenko and was groomed by Andropov, proved to me a more open Soviet leader than those before him. He cultivated a policy of increasing freedom of speech and the press in the Soviet Union in the 1980s. He took control of the USSR in March 1985, and reached out to the West. When he took office in 1985, he tried to accelerate economic reforms, including incentives for increased production. He continued talks with the United States and Western European countries for a reduction in medium-range nuclear weapons.

With the changes taking place in the USSR, some other Eastern European countries are also becoming more open. The solidarity movement in Poland, an anti-communist movement that began in 1980, was still going in 1985. Although the Polish government, with the backing of the Soviet Union, violently tried to put down the revolution, the movement slowly gained momentum as an attempt for the workers to have more say in their government. This movement is one example of the growing discontent among the working population in Eastern Europe. An increasing black market for western goods and ideas was one result of these nationalistic movements, as was an increasing demand for education and freer travel.

While the previous two paragraphs describe the political situation in Eastern Europe, the economic situation should also be understood. From the mid 1970s through the early 1980s, the Soviet economy stagnated. Production, agricultural and otherwise, was flat, even as the population continued to grow. With this problem, shortages of food and other goods became widespread, leading to the populace's discontent with their government. During this time, the government tried to keep the status quo and make few, if any, necessary reforms. When Gorbachev took over in 1985, he instituted labor reforms to try to increase productivity.

Western Europe was also making changes during this time. In France and Britain there were representative governments, headed by François Mitterrand elected in 1981 and Margaret Thatcher elected in 1979, respectively. Politically, these governments were very stable in the 1980s.

Thatcher politically survived the Falklands war in 1982 and a coal miner's strike in 1984. She was a proponent of a free-market, entrepreneurial economy and sold off pieces of state-owned businesses to workers. Thatcher, like Ronald Regan, supported using deterrence against the Soviet Union and supported nuclear disarmament talks with Gorbachev.

Mitterrand was the first socialist president of France, elected in 1981. He passed a wealth tax to try to prevent an economic crisis. While he was a socialist at a time when other world powers, including Thatcher and Regan, were conservative, he still supported close Western European collaboration between France and Germany, Spain, Portugal, and Great Britain. While he was less popular with the United States government than those in Western Europe, he still aligned his government with the United States and Great Britain against the Soviet Union.

Economically, Western Europe was doing better than Eastern Europe in the early 1980s; however, there were also economic problems in this area of the world. In Britain, the unemployment rate increased from 6.2% in 1980 to 11.9% in 1983 before leveling off at 11.3% in 1985. In France and other countries in continental Europe, the trend is similar but less dramatic, as illustrated in Figure 35. This rising unemployment rate was of concern to both the government of these countries and their population. High unemployment led to decreased job security, decreased economic growth, and stagnant wages, illustrated in Figure 36 for Germany. Western European leaders at this time were trying to combat the increase in unemployment and flat wages. While gross domestic product (GDP) growth was higher for Western Europe than Eastern Europe at this time, Western European GDP growth was still lower in the 1980s than in the 1950s and 60s. One reason for this was the recession in the United States in 1982-1983.

Another problem facing Western Europe that also faced the United States was high inflation. As illustrated below in Figure 37, inflation increased an average of 7% per year in the United States, 9% per year in France, and 11% per year in Great Britain between 1980 and 1985. At the same time, in 1984, the FTSE 100, a British stock index similar to the S&P 500, decreased 15% (“FTSE (^FTSE) 100” 2006).

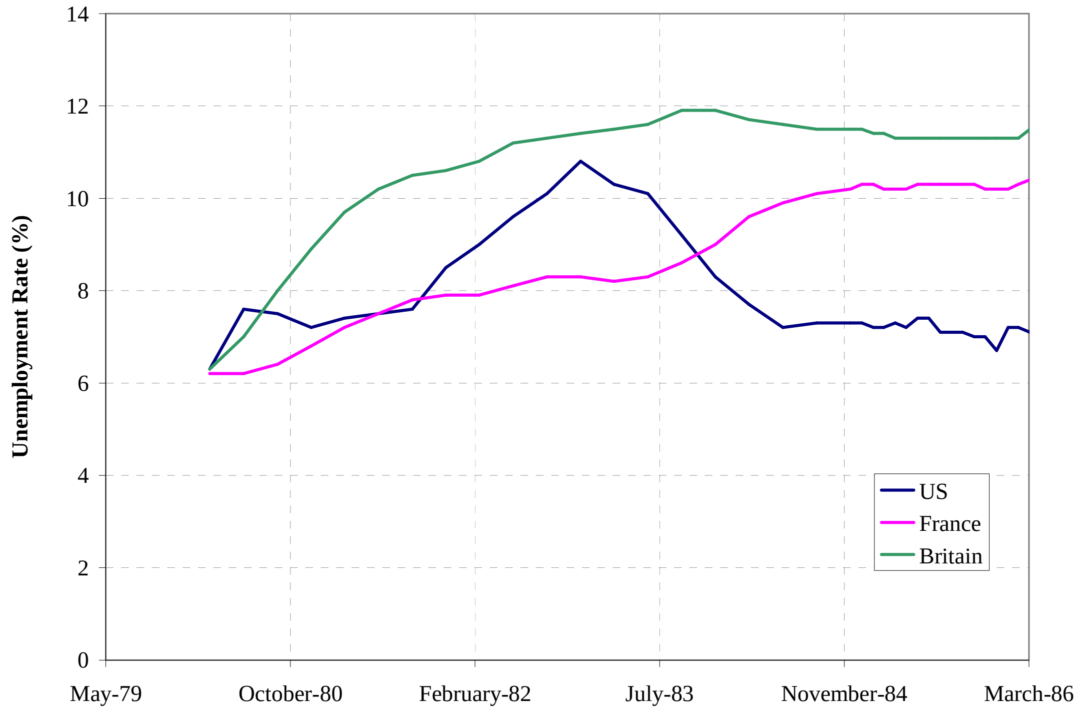

Figure 35: US, Britain, France Unemployment ("Historical Unemployment Rates" 2006, "Taux de chômage." 2005, Lindsay 2005)

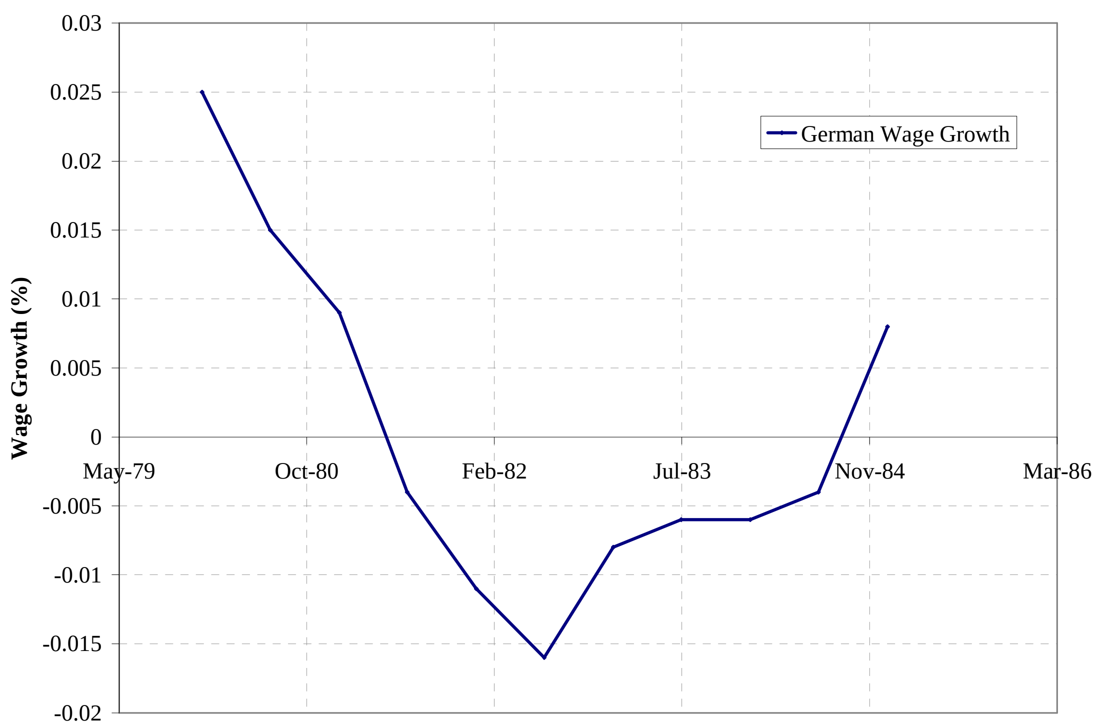

Figure 36: German Wage Growth (Lange 2007)

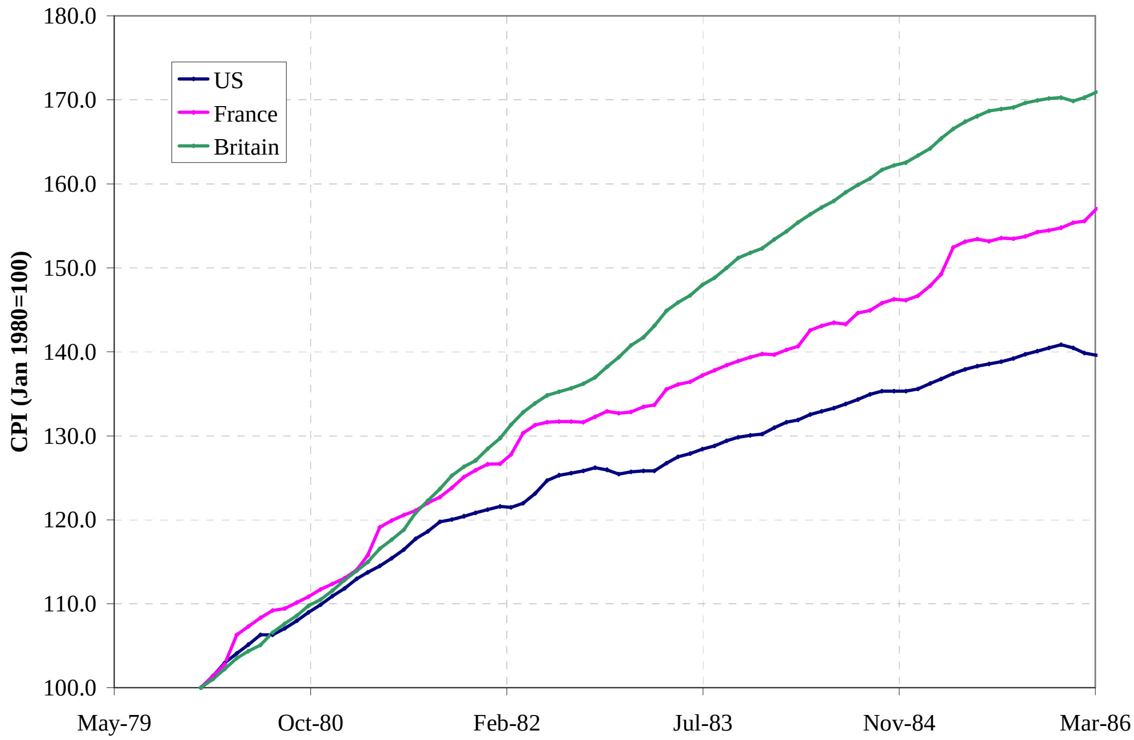

Figure 37: US, Britain, France CPI ("Consumer Price Index" 2006, "Retail Price Index…" 2006, "Indice Mensuel…" 2005)

In the early 1980s, the United States was faring as well as Western Europe, both politically and economically. Ronald Reagan was elected president in 1980 and then re-elected in 1984. Like Thatcher, he was a capitalist and proponent of the free market. He was able to drop the marginal tax rate for the highest tax brackets by almost 50% and also decreased the tax rate for businesses ("Ronald Reagan" 2006) in an effort to help boost the economy. He was unpopular during 1982-1983, when US unemployment topped 10% (see Figure 35) and the Dow Jones Industrial Average (DJIA) dropped below its 1981 high, as depicted in Figure 38, before rebounding in 1983. Much of his economic policy, called Reaganomics, was focused on decreasing tax rates and creating jobs as a way of lifting the US out of the early 1980s recession. While the recession ended, tax revenue dropped and government spending continued, resulting in a large increase in the national debt.

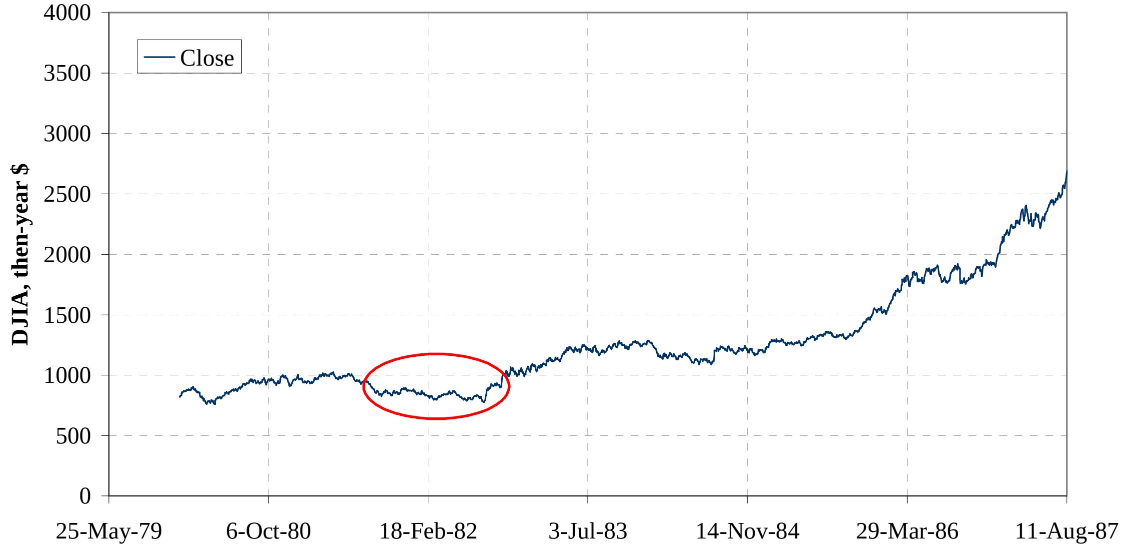

Figure 38: DJIA ("Dow Jones…" 2006)

Reagan also negotiated with other countries abroad. He declared himself against communism, but opened talks with Gorbachev for the purposes of arms reduction and increased trade. He also increased trade with China and Japan during his two terms in office. He recognized that both the Republic of China, on Taiwan, and the People's Republic of China, the mainland, were important trading and political partners, and sought to negotiate with both.

The People's Republic of China (China) was in the midst of a cultural and political revolution in the 1980s. Under the leadership of Deng Xiaoping, a new constitution was adopted in 1982. This new constitution gave more rights to the general populace in terms of freedom of religion, speech, and press than were available before. It also disbanded the communes that had been prevalent in the farming areas of the country and gave the land to the workers. As more than half of China's population lived in poverty in 1980 ("People's Republic of China" 2006), these reforms were well-received.

During this time period, China was also seeking to increase productivity, worker output, and worker's standards of living. The goal was to industrialize the country as quickly as possible. At that time, Chinese labor was very cheap so goods could be made cheaply. While there were some criticisms directed at the Chinese government for how political and social dissents are handled, China has a rising GDP and a decreasing number of people living in poverty.

Also during this time period, other Asian cities like Taiwan, Hong Kong, and Singapore are also modernizing. Hong Kong, Singapore, and South Korea increased exports and productivity while raising the standard of living for their own population in the 1970s and early 1980s ("East Asian Tigers" 2006). Increased trade with Europe, the United States, and Japan and a well-educated, hardworking populace were characteristics of these countries in the 1970s and 80s.

Japan, which industrialized itself just after World War II ended, was an important economic force in the mid 1980s. Its people had the highest standard of living in Asia at that time. The population was well-educated, unemployment was low (Alexander 1985), and a brisk trade business had developed between Japan and the United States, and, to a lesser extent, with Western Europe. Japan was known for cheaply creating and exporting technologically advanced goods such as automobiles and electronics that were of high quality. The economy was doing very well, as evidenced by the Nikkei 225, a stock index similar to the S&P 500, gaining 16% annually in 1985 and 1986, as illustrated in Figure 39. Politically, Japan was a US ally with US military bases on its soil but reluctant to get too involved in international disputes, particularly with China.

While the world's economic power is, or will soon be, concentrated in Europe, Eastern Asia, and the United States, other parts of the world are still important. For Central and South America, the early 1980s are marked politically by coups. The United States government is generally supportive of conservative and military governments while some European countries are more supportive of the country's general population. While cocaine use was becoming a problem in the US by 1985, Central and South American countries were generally not world economic powers.

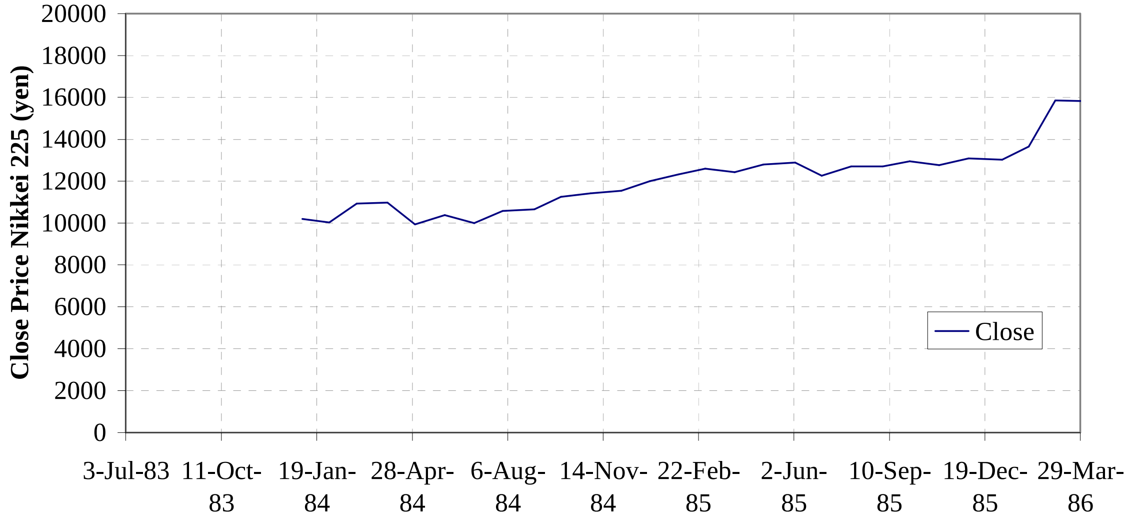

Figure 39: Nikkei 225 ("Nikkei 225 (^N225) 2006)

The continent of Africa also had some economic problems. The northeast and north central part of the continent experienced a severe drought in the 1980s; there was much suffering and malnutrition even with international aid. South Africa had internal problems, the most severe of which was apartheid, which would eventually fall in the 1990s. Much of the continent was had problems of poverty and corruption, along with the newly identified AIDS virus, which appeared to quickly kill those who caught it. In Egypt, the war and tensions with Israel are over.

In the Middle East, the United States and, to a lesser extent, Western Europe, were supporting Israel over other countries. Since the end of the war with Egypt, the south of Israel had been militarily quiet. However, Lebanon was politically and militarily unstable at the time, so military power was being concentrated on the north border. With Lebanon's instability was the fear that Jordan and Syria would also fall victim to revolutions, attempted coups, or militarists. As the western world had significant interest in a safe and secure Middle East, the United States tried to work with Middle Eastern governments to stabilize the region. At that time, Israel was a firm ally and Iran was a firm enemy, since the Islamic government had taken over the country in 1979. Saudi Arabia, Egypt, and Iraq were softer allies at that time, as was the rest of the Arabian

Peninsula to insure the continued flow of oil; this is especially important as the price per barrel of oil had been dropping since 1980, from $37.42/barrel to $26.92/barrel in 1985 ("Historical Crude Oil Prices" 2004).

In Central Asia, there is little unrest, but the biggest countries were India and Pakistan, who are historically enemies. India developed nuclear capabilities in the 1970s, but, like China, spend much of the early 1980s beginning to modernize the country. Indira Gandhi was prime minister, and the government at that time was trying to decrease malnutrition and increase educational opportunities for rural children. While India was a democracy, Pakistan was a state ruled by the military. In Pakistan, the 1980s are characterized by a return to Islamic law and a military regime. While there is historical animosity between Pakistan and India, the border was peaceful during the early 1980s.

6.1.1.3 The Aerospace Industry

The historical perspective shown in the previous section has an impact on the aerospace industry. While the aerospace industry is often linked to the defense industry, here it refers only to the commercial sector of the industry. At this time, the industry is composed of older, propeller transport aircraft that are being slowly phased out to make room for more of the newer jets, as well as narrow and wide body jet aircraft.

In 1985, major aircraft manufacturers in the market in the western world were Boeing Corporation, Lockheed Corporation, McDonnell Douglas Corporation, and Airbus Industrie. At this time an airframer looking to expand market share has decided that the long-range, wide body market will increase in the coming years (Lenorovitz 1986). With the increase in globalization predicted in the coming decades, an increase in the long-range, wide body market makes sense. As cities such as Singapore, Seoul, Hong Kong, and Taiwan increase in size, industrial production strength, and monetary value, there will be more travel to and from these places. Also, as large, populous countries like China and India become more industrialized and wealthy, there will be a larger demand for travel both to and from them and also within their borders. With the potential opening of the Soviet Union to more foreigners, there will also likely be more demand for travel to and from Moscow. All of these markets will be well-served by a high-capacity, long-range, fuel-efficient commercial aircraft. There are also the issues of air traffic, runway, and ground traffic congestion. Busy airports are already increasing landing fees as a way of pushing more airlines into using larger aircraft, thus decreasing runway congestion (Lenorovitz1987).

All of the considerations outlined above translate into a need for a new aircraft for the long-range, wide-body market. This new aircraft should include new technologies that are available or will be available over the next few years. It must have a low per-seat-mile operating cost in order to be competitive and must also be compatible with existing airport, runway, and air traffic control infrastructure.

Different companies have had different responses to these potential world changes. Lockheed, back in the late 1970s, created an updated version of the L-1011. While this updated version was supposed to be a competitor in the long-range market, it proved to be inferior to the 767, and production was halted in 1983 ("Lockheed L-1011 TriStar 500" 2002). As a commercial airliner, the L-1011 has been so far generally unsuccessful; however, the Royal Air Force (RAF) purchased several and is planning to convert them to tankers. McDonnell Douglas, maker of another trijet, is researching updates for the DC-10. Such updates will include a stretch version of the DC-10 to accommodate more passengers, a newer, more electronic flight deck, and wing updates to decrease drag ("McDonnell Douglas MD-11" 2001). These changes will hopefully increase McDonnell Douglas' market share in the long-range, wide body aircraft market.

Boeing Corporation, which currently has the largest market share of long-range, wide body aircraft, is also looking to upgrade its fleet. Boeing is looking to upgrade and stretch the current 767 to create an aircraft between the 767 and the 747 in size. The new aircraft, as a 767 upgrade (currently dubbed the 767-X), will be a long-range twin. It will be able to serve the current 767 markets and, hopefully, will someday serve even longer-range oversea markets with the creation of a new Extended-range Twin-engine Operations (ETOPS) rating.

From the perspective of a notional airframer, Boeing and the 767 and 747 are the main competition in this market. The goal is to create a more cost-effective competitor for the 767 fleet currently in existence. This new aircraft should be less expensive to operate than the current 767s and the projected 767 replacement. The new solution should have higher capacity and longer range than the current 767, and should have lower per seat mile operating costs, while still incorporating new technologies that will allow the aircraft to remain competitive longer (Lenorovitz 1986).

There is also potential to try to gain a market advantage by using more American sub-contractors for aircraft parts (Lenorovitz 1988). Such changes, along with projected increases in the long-range, wide-body market could increase aircraft sales and also increase profit for the airframer.

Since the goal of this design is to create a product that is superior not only to existing products but also to newly developing products, it is important to know what technological advances are to be expected over the next five years. Some expected technological advances include lighter avionics systems, newer lightweight aluminum alloys, and newer uses for carbon-fiber/epoxy materials (Lenorovitz 1987). New avionics developments include the ability to use a standard cockpit for the new aircraft under development, thus decreasing pilot training time as well as avionics system weight reductions. There is also potential for a newer, fly-by-wire system that is lighter than existing systems. Lighter-weight aluminum alloys have been developed over the past 15 years, which have the potential to save a fraction of the aircraft’s weight. The carbon-fiber/epoxy materials used to build the tail of current widebody aircraft should be extendable to a larger aircraft. Other technological advances include the use of winglets to reduce drag.

6.1.2 Step 2: Scenario Development

Scenario development is an important step in the risk analysis process. Several processes to create scenarios have been discussed. The scenarios used in this example have the disadvantage of being created by a single decision maker, instead of a committee or group of industry experts. However, the process used to create the scenarios was similar to one that would be used if the scenarios had been created by committee.

To begin scenario creation, the decision maker determined what aspects of the future to examine to bound the scope of the problem and current events, variables, or drivers could potentially have a significant impact on the future of commercial aviation. In this case, the aspects of the future that need to be specified are employment, culture, politics, economics, and technology as these factors will affect the commercial aerospace industry. These categories were chosen for continuity: the potential future risks will be identified in these categories, and it is the purpose of this process to address these risks.

Given the state of the industry and the world in 1985, there are some important variables for the scenarios to address. From a macro-environmental standpoint, the future of Eastern Europe and the Soviet Union will affect the global economy and, by extension, global air travel. Currently, Eastern European society is becoming more open; that trend could continue or change. Changing population demographics in Asia, particularly China, India, Japan, and South Korea will also affect the global economy. These populations could continue to become wealthier, or not. From a micro-environmental standpoint, variables that will have a significant effect on the industry include the price of fuel. Fuel is a significant part of an aircraft's total operating costs, so fluctuations in fuel price can cause large changes in revenue for an airline. These three variables will have a great influence on the commercial aerospace industry for the near future.

Other variables will also influence the future. The potential for air travel disruptions should also be examined. Terrorist events had not significantly disrupted travel in the 1980s; however, there were three aircraft hijackings and two airport attacks attributed to terrorists in 1985, so the terrorist threat appeared to be increasing. Another threat that may be increasing is the threat of disease. Several new viruses were identified in the 1970s and early 1980s, and travel has the potential to increase the speed at which disease spreads. Terrorism and disease, while not necessarily driving forces for the commercial aerospace industry, have the potential to cause disruptive futures.

Now that three main variables and two disruptive forces have been identified, the scenarios should be created to mix and match the variables. Five scenarios were created: one particularly good picture for the future, one particularly bad picture for the future, and three very different middle of the road scenarios. One of the ways to help insure that the scenarios were different was to create a matrix of alternatives. The created matrix is illustrated in Figure 40. It consists of ten main categories each with two or more sub-categories that have at least two options each. Having this many categories and options means that the user can specify the future in a myriad of different ways. The main categories consist of economy, jobs, transportation, government, international relations, environment, housing, education, leisure, and other. These categories were chosen because they are important pieces of society and important to specify for a particular future in order to address the variable and disruptive forces mentioned above. The scenarios, rather than being deterministic, the way engineers usually think about scenario-based analysis, are open-ended, so they can be used in a probabilistic analysis just like traditional variable distributions.

The IRMA tool was used to aid in the specification of scenarios for this problem. For the first scenario specified, the best-case scenario, the IRMA is illustrated in Figure 41. In this IRMA, the green boxes were the chosen scenario attributes.

Economy	Interest Rates	very low	low	average	high	very high
	Stock Market Returns	negative	zero	low	average	high
	Unemployment Rate	low	average	high	sector-specific	
Jobs	Wages	decreasing	steady	increasing slightly	increasing quickly	
	Sectors Doing Well	pharmaceuticals	aerospace	entertaintment	IT	energy
	Sectors Doing Poorly	energy	entertainment	aerospace	IT	
	Where Located	urban	suburban	coasts	interior	
	Where Working	central office	satellite office	home		
Transportation	Type of Fuel	hydrocarbon	hybrid (HC and electric)	electricc	other	
	Cost of Fuel	low	medium	high	very high	
	Other Travel Costs	low	medium	high	very high	
	Traveling Not Advised	Middle East	Southeast Asia	North Africa	Sub-Sahara	Latin America
	Who Can Travel (regs)	little international	need ID			
	Availibility of Public Transportation	Little	good in cities	cities and suburbs	everywhere	
Government	Energy Regulation	little regulation	heavily regulated	same as today		
	Transportation Security	very secure	some sectors secure	lax security	privately funded	
	Illegal Immigration	major, intervention	major, no intervention	minor, intervention	minor, no interventior	
	Deficit Spending	very high	high	average	low	surplus
	Revenues	high	average	low		
	Tax Rates	high	average	low		
	Tax Structure	regressive	progressive	income	sales	
International Relations	Getting along with neighbors	well	some problems	many problems	war	
	Borders	open borders	no immigration problems	fortified borders		
Environment	Global Warming	big problem	worry	not a worry		
	Regulations	very stringent	industry-specific	somewhat lax	very lax	
Housing	Cost	very high	high in pockets	affordable		
	Where Available	coasts	interior	south	midwest	
	Who is Buying	established professionals	young professionals	older people	everyone	
	Renting/Buying Cost	lower than average	average	high		
	Mortgage Rates	low	average	high		
	Utilities Costs	low	average	high	area dependent	utility dependent
Education	Cost of Primary Education	government funded	privately funded	low	high	
	Where Primary Ed. Takes Place	home	private school	local public school	large public school	
	Cost of Secondary Education	low	medium	high		
	How Educated is Workforce	mostly educated	mostly uneducated	only elite educated	only wealthy educatec	
Leisure	How Much Money Available	little	some	lot		
	How Much Time	little	some	lot		
	Where Spent	near home	travel in US	travel abroad	stay home	
Other	Disease	epidemic	outbreak	outbreak threat	no threat	
	Terrorism	not a worry	small worry	abroad worry	worry at home	

Figure 40: Scenario Creation IRMA

Economy	Interest Rates	very low		low	Yes	average		high		very high	
	Stock Market Returns	negative		zero		low		average		high	Yes
	Unemployment Rate	low	Yes	average		high		sector-specific			
Jobs	Wages	decreasing		steady		increasing slightly		increasing quickly	Yes		
	Sectors Doing Well	pharmaceuticals		aerospace		entertaintment		IT		energy	
	Sectors Doing Poorly	energy		entertainment		aerospace		IT			
	Where Located	urban		suburban		coasts		interior			
	Where Working	central office		satellite office		home					
Transportation	Type of Fuel	hydrocarbon	Yes	hybrid (HC and electric)		electricc		other			
	Cost of Fuel	low		medium	Yes	high		very high			
	Other Travel Costs	low		medium	Yes	high		very high			
	Traveling Not Advised	Middle East		Southeast Asia		North Africa		Sub-Sahara		Latin America	
	Who Can Travel (regs)	little international		need ID							
	Availibility of Public Transportation	Little		good in cities	Yes	cities and suburbs		everywhere			
Government	Energy Regulation	little regulation		heavily regulated	Yes	same as today					
	Transportation Security	very secure	Yes	some sectors secure		lax security		privately funded			
	Illegal Immigration	major, intervention		major, no intervention		minor, intervention		minor, no interventior	Yes		
	Deficit Spending	very high		high		average		low		surplus	Yes
	Revenues	high	Yes	average		low					
	Tax Rates	high		average	Yes	low					
	Tax Structure	regressive		progressive	Yes	income		sales			
International Relations	Getting along with neighbors	well	Yes	some problems		many problems		war			
	Borders	open borders	Yes	no immigration problems		fortified borders					
Environment	Global Warming	big problem		worry	Yes	not a worry					
	Regulations	very stringent		industry-specific		somewhat lax	Yes	very lax			
Housing	Cost	very high		high in pockets	Yes	affordable					
	Where Available	coasts		interior		south		midwest			
	Who is Buying	established professionals		young professionals		older people		everyone	Yes		
	Renting/Buying Cost	lower than average		average	Yes	high					
	Mortgage Rates	low	Yes	average		high					
	Utilities Costs	low		average	Yes	high		area dependent		utility dependent	
Education	Cost of Primary Education	government funded	Yes	privately funded		low		high			
	Where Primary Ed. Takes Place	home		private school		local public school		large public school			
	Cost of Secondary Education	low		medium	Yes	high					
	How Educated is Workforce	mostly educated	Yes	mostly uneducated		only elite educated		pnly wealthy educatec			
Leisure	How Much Money Available	little		some		lot	Yes				
	How Much Time	little		some	Yes	lot					
	Where Spent	near home		travel in US		travel abroad		stay home			
Other	Disease	epidemic		outbreak		outbreak threat		no threat	Yes		
	Terrorism	not a worry		small worry	Yes	abroad worry		worry at home			

Figure 41: Best-case Scenario IRMA

This scenario is the global prosperity scenario. It represents this author's view of the best thing that could have happened globally between 1985 and 2004. In this scenario, interest and borrowing rates were low, higher education was achievable for all who want it, fuel costs are relatively low, and jobs are plentiful. The global characterization of this scenario is that the USSR becomes a democratic society through peaceful revolution, either in total or each member state. East/West relations improve, and Eastern Europe becomes economically comparable to Western Europe by 2004. On the whole, a united, wealthy Europe has emerged from the cold war.

In Asia, China also becomes a democratic society and becomes an economically powerful force. China is on its way to becoming a first-world society, and its population has leveled off. Japan has been at the heart of many technical advances over the years in electronics and is keeping up the trend. The country is very wealthy, and has the highest standard of living in the world. Asia's other large democracy, India, also has a growing middle class, and is solving its rural poor problem through government efforts to increase educational opportunities to poor children.

In the Middle East, there has been a peaceful revolution in Iran. Iran and Iraq have signed a peace treaty and are leaving the area near their border clear of military forces. Since the oil industry is booming as world consumption increases, most of the Middle East is growing wealthy. Israel is stable and is having no problems with its neighbors. In Africa, AIDS has been controlled through anti-viral medication and a vaccine that has become commonplace in most of the world. There are still factions of disenfranchised people in the Middle East, Africa, and South America, but they are small and are causing few worries about terrorist incidents.

The second scenario, the worst-case scenario, is almost the opposite of the previous scenario. In this scenario, the United States and Western European economies never really recover from the recession of 1982-83 and the high oil prices of earlier this decade. Instead of recovering, the economies begin sagging again in the late 80s. This time, the problems are global. In the United States, many companies bought out their older, more expensive workforce, so the number of workers compared to the number of retirees is small. In both the US and Western Europe, it is very difficult for the young workers to get ahead, since much of their paychecks are going to taxes to support an older generation. Socially, there is much opposition to new technologies since the nuclear accident in Alabama in 1987. While the accident was small-scale and there were few deaths (and few projected deaths), for the public it still underscored the need for careful examination of new technologies.

Seeing the downward spiral of the Western European and American economies causes Eastern Europe to close its borders. The USSR isn't threatening to the west, but they continue to be a closed economy, with little global interaction. With the decrease in request for Chinese goods in the late 1980s and 1990s, Chinese modernization comes to a screeching halt. China closes its doors to westerners, and more and more Chinese live in poverty. The Chinese government roughly puts down any hint of rebellion, but there is still low-level unrest, particularly among young people, who are chronically unemployed.

The situation in the Middle East is similar to China, with repressive governments clamping down on free speech. Unfortunately, there is also some low-level, unorganized terrorism in the Middle East and Africa. With international aid drying up, poorer countries are having to grapple with disease and hunger problems, but there are no global pandemics. In general, there is some civil unrest, particularly among young people with poor job prospects; however, none reach the level of a serious movement. There are also some border skirmishes and more-or-less bloodless coups in various parts of the world, but again, no all-out war.

Scenarios number three, four, and five are different from the first two. These scenarios don't portray either the best or worse future outcome. Instead, they portray outcomes that seem to be more plausible. None of these scenarios is meant to portray an accurate future, just a potential one.

The third scenario highlights what could happen if the AIDS virus becomes a global pandemic. In this situation, much of the world's governments' resources are being taken up to fight this disease, either directly or by supporting AIDS research. In the United States, most people are healthy and taking precautions to prevent infection. The biomedical field is very large and heavily subsidized by the government. Travel is discouraged to and from countries with significant infections, but not banned. However, most people travel only in countries with low rates of infection. In Western Europe, the situation is similar to the United States. Countries are cooperating to try to find a cure or better treatment for AIDS. Eastern Europe and China have stopped the AIDS epidemic by closing their borders to foreigners and not allowing their citizens to travel. Japan has become a world leader in the biomedical research field, and its population is very wealthy. In the Middle East, cultural pressures have kept the AIDS virus to a minimum, and thus there is a renewed vow to follow Islamic law. There is much travel between countries that are working on AIDS research, but little to countries where there are many infections, including much of Southeast Asia, Sub-Saharan Africa, India, and Indonesia. The economies in these countries are struggling, since many of their young workers have been struck down by AIDS. There is a renewed call for traditional religious values all over the world, as it is seen as one way to help combat the spread of AIDS.

The fourth scenario centers on an on-going Middle East conflict, which started over the increased price of oil and has exploded into a world conflict. In 1987, the OPEC countries decide to cut production to increase the price of a barrel of oil. As some countries agree to cut production and some do not, the conflict in the Middle East starts internally. The countries that do not agree to cut production were invaded, and the rest of the world, which is relying on the oil-producing countries, steps in to help sort out the conflict.

In the United States, the war in the Middle East changes much about society and is compared to Vietnam. Society has become economically polarized, with the wealthy and well-educated having more educational and job opportunities for their children, while the less-advantaged children end up working in service jobs or for the military. Blue-collar workers are losing purchasing power, especially with the rising fuel prices. The defense industry is booming, and there is much emphasis on alternative fuels. In Western Europe, life is similar to America. There is an economic gap in educational and employment opportunities, with the poor losing purchasing power. Lack of oil from the Middle East has forced America and Western Europe to find alternative fuel sources, one of which is the USSR. Newfound wealth in the USSR leads to a peaceful revolution, and society there is much more open. Oil is also being imported from South America, particularly Venezuela, where the US is helping a friendly government stay in power. In Asia, Japan is still the world leader in the micro-electronics field. The Chinese economy, however, is very depressed. It is dependent on foreign oil and exports to fund its modernization process, and when the exports decrease and oil prices increase, the economy dipped and has never recovered. India, on the other hand, is receiving significant support from North America and Europe. Due to its proximity to the conflict in the Middle East, European and North American troops are stationed there and are using parts of the country as a base of operations.

In the Middle East, North American and European allies are the secular governments in Israel and Iraq. Small countries, including Lebanon and Kuwait, are caught in the middle and have been annexed by other powers. Syria, Iran, and Saudi Arabia are the main powers. Radical Islam has made a comeback in these countries due to the war.

Travel to and from the Middle East is totally curtailed, except for military travel. Travel between North America and Europe and, to a lesser extent, Asia, is common. International travel security is very high, and security lines to enter and leave countries are long.

The final scenario describes a technology explosion during the 1990s. All over the globe, new electro-mechanical devices are being developed. In the United States, there is a definite distinction between the wealthy, the middle class, and the poor. There are many high-tech jobs for the wealthy and well-educated, and also many blue-collar jobs that pay well for the middle-class. For the poor, the service sector jobs are disappearing as technology takes over. Open college positions in the United States, particularly in technology driven areas, are filled with students from other countries. Western European countries have been taking advantage of the new technologies more than North American countries. Due to their increasingly urban populations, these countries need more and better mass transportation and work at home options, which new technologies are providing.

Eastern Europe has been mostly left out of the technology explosion. These countries are mostly closed and are still operating as if it is 1985. Due to the nature of the governments in these countries, it is difficult for westerners to discover what is happening there. Asia has been a big part of the technology revolution. While the United States is still educating many of the world's students, many new technologies are being developed in China and India, and Japan is a source of continuing innovation. The standard of living in India, China, and most of the rest of Southeast Asia is rising rapidly. These cultures still value hard work and education, but are also becoming consumer cultures like the United States. Even the Islamic world has not been immune to the technology explosion. Hand-held small electronics are common in the Middle East and North Africa. Oil-producing countries are prosperous with more people joining the consumer revolution, even as advances into alternative energy increase.

In this scenario, there is much demand for long-range and international travel. Vacations for the wealthy and business travel make up most of the international travel, and short-range domestic travel by air has declined as advances in rail transportation have made it more viable.

6.1.3 Step 3: Alternative Solution Development

Now that the problem and potential futures have been identified, potential solutions, or families of solutions, must also be identified. Since this is a large sunk cost, long timeframe project, it is assumed that each generated solution will eventually become a family of solutions. Therefore, it is assumed that, if the aircraft proves to be viable, not only will the original solution be designed and built, but there is also potential for stretch, extended range, and other versions of this aircraft.

There are several ways to determine what the potential solutions are and which ones should be investigated. Since most commercial aircraft, with the exception of the Concorde, look very similar, configuration options are rather limited. Since this aircraft must fit into existing airport infrastructure, traditional aircraft configurations will be weighted more heavily than out-of-the-box configuration options. Unless it proves to be an infeasible or non-viable configuration, the aircraft will have one fuselage, one wing, and one tail. Since it has never been commercially done before, the development and certification costs for a non-conventional aircraft will likely be much larger than those for a conventional aircraft and, because it would have such a different appearance, it may be difficult to sell. It could be difficult to find a willing population to fly on such an aircraft even if it could be sold to an airline. On the other hand, since most people are familiar with a conventional aircraft configuration, new technologies that do not change the appearance require no additional work to convince the flying public of their safety as long as there are no accidents.

Since the choice here is limited to a conventional configuration aircraft, there are a few physical and functional characteristics to be concerned about when choosing a baseline configuration for a family of aircraft. One possible way to downselect between the possible alternatives is with a very simplified matrix of alternatives, as illustrate in Figure 42.

This matrix of alternatives is small; at this point in decision making there is little information available for decision making, and, as long as the aircraft meets the physical boundary constraints imposed by existing airports and runways, the aircraft's physical size can be determined at a later date. It is much the same for functional characteristics. The aircraft needs a lower per seat mile operating cost than existing aircraft and must meet plausible future noise and emissions requirements. Since it is a conventional configuration and must fit into conventional airports and flight patterns, more precise performance characteristics can be determined at a later date.

Physical	Type of Tail	conventional	T-tail	
	Number of Engines	two	three	four
	Main Engine Placement	wing	near tail	
Economic	Number of Passengers	250	275	300
		325	350	
	Max Range (nmi)	5000	5500	6000
		6500	7000	>7000

Figure 42: Aircraft Configuration Matrix of Alternatives

Three conventional configurations were chosen from the matrix of alternatives presented in Figure 42; if none of these prove feasible and viable, other configurations will be chosen at a later date. The configurations were chosen based on the airframer's preferences: be able to add enough new technology to produce the lowest per-seat-mile costs in the market, as low a development cost as is reasonable, and to cover the entire widebody, medium and long range market.

The first, illustrated in Figure 43, is a derivative of an existing aircraft. The derivative is a stretched version of an existing widebody, medium-range aircraft with two engines placed under the wings and a conventional tail. It would be able to carry more passengers than the current version of the aircraft: around 300 in a two-class layout. While this aircraft would be less costly to design and build, since a version already exists, it has the disadvantage of having a shorter range and not covering the entire market. The engines, wings, and fuel tanks were designed for a smaller aircraft, with a current range of 4100 nmi, and a stretch version would likely have an even smaller range. While in a performance-based world these deficiencies would disqualify it from consideration, a derivative aircraft has some attraction since its development cost is so low. If it could be designed and updated with new technologies and the operating cost was comparable to other newly developed aircraft, it will still be a contender. If it has a common cockpit with existing aircraft, it would also save airline's money on training costs and the parts' suppliers money on replacement costs.

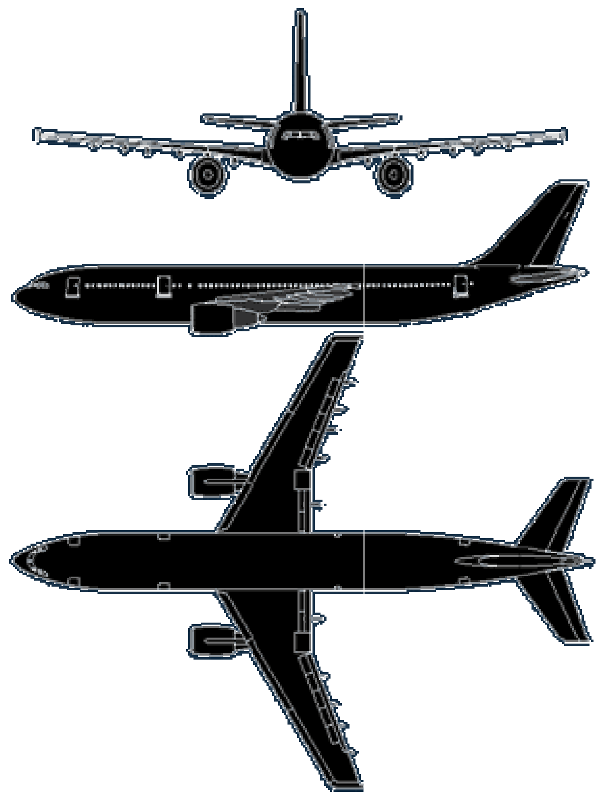

Figure 43: New Derivative Aircraft (modified from "Airbus A300-600" 1998)

Another aircraft configuration to be examined is a new twin-engine under-wing mounted aircraft with a conventional tail. A notional graphic of a new twin-engine aircraft is given in Figure 44. This aircraft will transport approximately 325-350 passengers and likely have a max range of approximately 5500 nmi.

While a new twin-engine aircraft will be more costly to develop than a derivative aircraft, developing an aircraft from scratch can lead to lower operating costs and, in this case, more flexibility later on to create derivatives. It could also be easier to integrate new technology into a new aircraft than to retrofit an existing aircraft with new technology.

Some of the disadvantages of creating a new twin-engine are the low max range and long takeoff field lengths as compared to a tri- or a quad- engine aircraft. A twin-engine aircraft also needs to be Extended-range Twin Operations (ETOPS) certified before it can fly over large bodies of water, while a tri- or quad-engine aircraft does not. Needing an ETOPS certification can add time and cost to aircraft development, and some passengers could become fearful on overseas flights on a twin-engine aircraft. A twin-engine aircraft also has a takeoff disadvantage at high altitude and on hot days, when takeoff is difficult. On the other hand, a twin-engine aircraft has the potential to have lower operating costs than one with more engines.

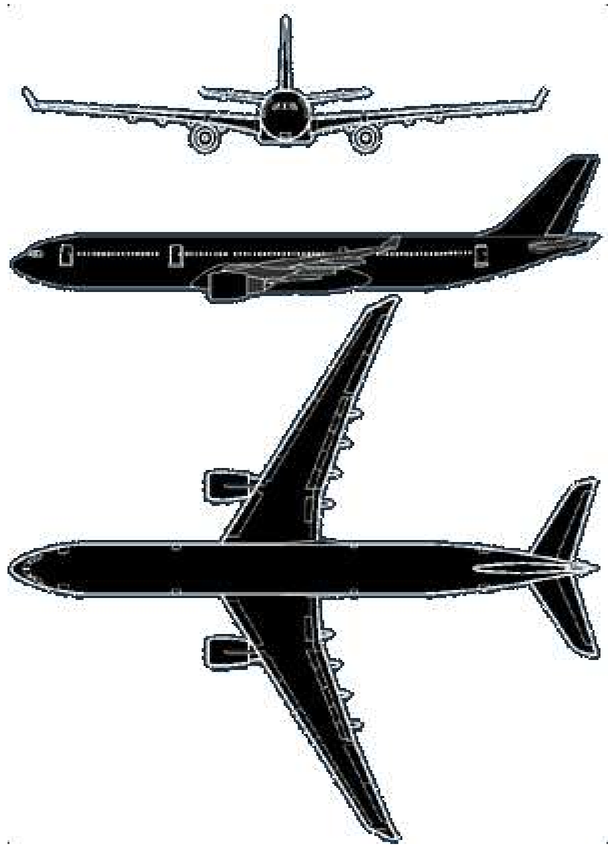

Figure 44: New Twin Engine Aircraft ("Airbus A330-300" 1998)

Since a twin-engine aircraft has some potential problems as a long-range, overseas aircraft, it also makes sense to examine a three or four engine aircraft. A three engine aircraft generally has two under-wing engines and one engine in the vertical stabilizer. Having the third engine below the tail and above the fuselage creates additional structural requirements for the aft end of the fuselage, and a carbon-fiber/epoxy tail has never been tried with a trijet. For these reasons, the three-engine aircraft idea was discarded.

A new four-engine aircraft has all the advantages over an existing aircraft derivative as a new twin-engine aircraft. It compares to a new twin-engine aircraft as explained above: can fly longer routes, doesn't need an ETOPS certification, has better "hot-high" takeoff characteristics, and the flying public is potentially more comfortable in it. However, it can have a higher per seat mile operating cost than a twin-engine aircraft, depending on engine characteristics.

The characteristics of the four-engine aircraft to be examined include four under-wing engines, and a conventional tail. It should carry approximately 275-300 people for 7000 or more nmi. A notional four-engine aircraft is depicted in Figure 45. This aircraft needs to be smaller than a 747, since it is supposed to compete with the 767-200ER.

There are also some other aircraft options that include two or more of the above aircraft. One of these options is to create a new twin-engine aircraft and a new four-engine aircraft. This family of aircraft would capture both the medium- and long-range segments of the market, and segmenting the market may prove to be more cost-effective than trying to create one aircraft to cover the entire medium- and long-range widebody market. One way this would be cost-effective is to create one fuselage and landing gear system with one basic wing and tail for two engines and one modified wing and tail for four engines. Both wings would need to have the same fuselage interface for this idea to work. Designing a new twin-engine aircraft and a derivative four-engine aircraft will be more expensive than just designing a new twin-engine aircraft; however, if the two aircraft can be created as one aircraft platform and one derivative, the cost will be significantly less than the design of two separate aircraft. While this type of aircraft development has not been done before, it is thought to be no more complicated than the creation of a new wing and tail system for a derivative aircraft.

Figure 45: New Four Engine Aircraft ("Airbus A330-300" 2002)

However, this option also requires the use and potential development or updating of two different classes of engines. While it can be expensive to create two new classes of engines instead of one, it may be possible to modify existing engines to fit the needs of this aircraft. Since long-range twin-engine aircraft already exist, the correct engine class for this aircraft also exists. Potential engine choices for a long-range twin-engine aircraft include the GE's CF6 class and Pratt and Whitney's PW4000 class of engines. Instead of the creation of an entirely new engine family, it may be possible to create a derivative engine family that reduces development time and cost, but still allows the use of new, more advanced engine technology.

For a four-engine aircraft, engine development may be more complicated. The existing widebody four-engine aircraft, the 747, is significantly larger than the proposed four-engine aircraft solution. Engines needed for the proposed four-engine aircraft would need to be approximately half the thrust as those proposed for the twin-engine aircraft since the aircraft will be so similar. This puts the proposed engine thrust in the 30,000 lb thrust class. There are existing engines in this thrust class, most notably the CFM-56, that could be used or modified for use with a new four-engine, long-range, widebody aircraft.

The advantages of the creation of two new aircraft over a single new aircraft are that it could capture more of the long-range, widebody market. If the development costs can be kept low and the aircraft markets are sufficiently different that creating two aircraft allows for significantly increased sales, than two aircraft may be a more economically viable solution than a single aircraft of any configuration. The danger in creating two aircraft on the same platform is that the platform is a compromise solution and so is optimal for no one. If this case occurred, it could decrease aircraft sales, not increase them. However, both aircraft are appealing to the same market, so there is less danger of a non-optimal, too-compromised solution. These two aircraft should appeal to different segments of the long-range, widebody market, and so development should increase, not decrease sales.

Another solution that calls for development of two different aircraft is the development of a new four-engine aircraft along with a larger, updated derivative discussed previously. The development costs of designing a derivative and designing a new four-engine aircraft are less than the creation of two totally new aircraft; however, these costs may be greater than the cost of parallel development of a new twin and new quad on the same platform. Updating and stretching a current aircraft can be a costly process. Many of the systems on that aircraft were initially developed more than ten years ago. These systems need updating to tomorrow’s standards, not just today’s standards. There is also the problem that growing an aircraft reduces its range; however, there may still be a market for a medium-range widebody that can carry 300+ passengers, particularly as countries like China increase their demand for air travel.

Creating a new four-engine aircraft in addition to updating the an existing aircraft can increase the company’s market share. As a new four-engine aircraft would be longer-range than an updated derivative, it will compete in a different segment of the market. These two aircraft fill complimentary roles; however, they will probably be expensive to develop in parallel. Another advantage to stretching an existing aircraft is that, as a derivative, its development time is shorter than a new aircraft. It would be out in the market competing with the 767 before a totally new aircraft could be fully developed, which could be an economic advantage for the company.

There are five options listed above as potential solutions for this problem:

1. Updated, stretched derivative aircraft
2. New twin-engine aircraft
3. New four-engine aircraft
4. New twin- and four-engine aircraft built on one platform
5. New four-engine aircraft and updated, stretched derivative aircraft

Each of these five solutions could have been under consideration in the mid 1980s for a 767 competitor.

6.1.4 Step 4: Uncertainty and Risk Identification

Now that five potential solutions have been identified, it is time to begin examining them. The first step to examining the solutions from a risk analysis perspective is to examine the assumptions made about each solution. The assumptions to be examined fall into five categories: employment, culture, general economy, politics and government, and technology. Since the ultimate goal of this process is to create a product that helps illuminate to engineers how managers make decisions, the categories are chosen to be facets of risk that manager decision makers care about.

The first category of assumptions to be examined is employment. These assumptions have to do with finding the correct workers to complete the job, being able to pay them competing wages, and being able to communicate with them. The list of employment assumptions and their corresponding uncertainties is depicted in Table VII.

Table VII: Employment Assumptions and Risks

Assumption	Risk
Will have, or be able to hire, enough workers to meet demand	Not having enough qualified design engineers
	Not having enough manufacturers--early
	Not having enough manufacturers--late
Accurately anticipate workers costs	Higher turnover rate
	Can't afford to keep workers on during cyclic work cycle
	Workers labor costs increase
	Union boycotts (early in manufacturing cycle)
No language barriers	Workers difficulty communicating between countries
Pay workers competing wages in different countries	Inability to pay workers competing wages in different countries
	Loss of workforce to American companies
	Worker benefits' cost increases
No cultural problems between workers	Difficulties working between European countries
	Difficulties working with immigrant labor
	Inability to import unskilled labor
	Difficulty with communications with outsourced labor
Minimal business losses	Loss due to working with outsourced labor markets
Training costs are low compared to productivity	Increased time/cost to effectively training workers in new technology
	Increased time/cost to effectively skill unskilled workers
Mobile workforce	Inability to move worker locations as necessary
Stable workforce	Work interruptions due to extenuating circumstances

The first assumption about the workforce is that there will be enough workers to meet future demand. Risks in this assumption include the potential to not have enough engineers or manufacturers. Along with the assumption that there will be enough workers is the assumption that the employer can accurately anticipate the cost of those workers. Risks there include whether the turnover rate is larger than anticipated, whether worker costs, either wages or benefits, increase, and whether the company can afford to keep workers occupied if the work becomes cyclic. All of these risks have the potential to increase the cost of workers.

Another potentially problematic assumption stems from the knowledge that these workers are likely to be working in different countries and there are likely to be a significant number of foreign workers for some jobs. The initial assumption is that having workers in foreign countries and foreign workers in the home country will not cause any cultural conflicts or loss of workforce stability. Risks in these assumptions include potential problems with language barriers, whether it is possible to pay workers differently in different countries, whether or not workers from different countries actually get along, and that there are no unanticipated costs from doing business in other countries. A more global airframer can also make the assumption that the company can move its workers around if necessary; however, if the employees do not wish to do this, it can be challenging to create a mobile workforce.

The second category of assumptions to be examined is cultural and social assumptions. These assumptions have to do with culture, where people travel, and the potential for future service disruptions. The list of cultural/social assumptions is depicted in Table VIII.

Table VIII: Cultural/Social Assumptions and Risks

Assumption	Risk
Can sell twin for overseas use	Customers uncomfortable on overseas flights on twin
More travel & wealth within China	Leveling off of Chinese population
China opening to west	Tension between China and Britain/US over Hong Kong
Little travel to SE Asia	Political opening of SE Asia
There is no change in cultural preferences for American/ European a/c	Asian preference for American aircraft
	Japanese preference for American aircraft
	Middle Eastern preference for American aircraft
	General preference for status quo
America allows government aid for development	American companies boycott European airframers
	American consumers boycott European airframers
No regional/global epidemics	Epidemic decreases flying public
	Epidemic cuts off S.Asia
	Epidemic cuts off Africa
Social stability	Civil unrest in China
	Fear of flying due to terrorist incidents
	Civil unrest in Eastern Europe

The first assumption is that consumers will be comfortable flying over water on a twin-engine aircraft. The risk associated with that assumption is that, due to some incident on a flight, passengers show a preference for three or four-engine aircraft. Other assumptions related to that include that there are no major wars or epidemics that cause a decrease in travel, and that travel to China will increase in the future. Risks in these assumptions include the possibility of wars and epidemics and the potential for a closed China. Other cultural assumptions deal with issues surrounding aircraft preferences. The assumption is that there will be no inherent bias for American aircraft and that there is no overwhelming preference for a four-engine aircraft over a two-engine one. Risks in these assumptions include the potential for preference for American aircraft and a preference, particularly in Asia, for four-engine aircraft for overseas flights.

There are also a number of general economic assumptions that need to be examined. These assumptions are assumptions about general economic conditions in the future and include such things as interest rates, stock market returns, and borrowing power. The assumptions for this problem are listed in Table IX.

Table IX: Economic Assumptions and Risks

Assumption	Risk
Good global economic conditions	Aircraft financing interest rate rises
	European recession
	Asian recession
	American recession
Stable fuel costs	Cost of fuel increase
New security prevents terrorist attacks	Increase in security costs due to terrorist attacks
4% growth in travel	Business travel decreases
	Leisure travel decrease
Steady unemployment	Unemployment increases
American economy stay strong	Economic growth slows in US
	Lower-than-expected growth projections (for reasons not listed above)
European tax structure and subsidies remains same	Decrease in British tax revenues (for reasons not listed above)
	Decrease in French tax revenues (for reasons not listed above)
	Increase in British tax payouts
	Increase in French tax payouts
	Need outside financing for some development
Derivatives are also viable	Derivatives compete with initial for sales

The first assumption, and the most important assumption, is that good global economic conditions will prevail over the next 20 years or so. This means that there will be no recessions in major aircraft markets such as North America, Western Europe, or Asia. It also means that travel will continue to increase throughout these regions, and implies that there will be continued money available for leisure spending of the general population. This increased travel is also seen in the assumption that travel will continue to increase at the rate of 4% annually; however, economic conditions that cause a decrease in business or leisure travel can prevail, making this assumption less than accurate.

The assumption that the American economy remains strong has uncertainty that the country may still be in recovery from the last recession in 1981. On a similar note, the assumption that there will not be widespread unemployment and the problems that go with it is also made. The risk in this assumption is whether or not unemployment can remain stable and relatively low in the world's aircraft markets. With the potential opening of Eastern Europe, there is some fear of poorly educated Eastern Europeans flooding into wealthier Western Europe and increasing unemployment, as well as causing a host of other economic problems. There are other assumptions that also impact the flying public's purchasing of tickets. Some of these assumptions include the continued prevention of terrorist attacks and stable fuel prices. Both of these conditions have much uncertainty, particularly since there is nothing an aircraft manufacturer can do about either of them: Airbus is incapable of lowering fuel prices or stopping terrorist attacks.

The assumption of continued economic support in the form of subsidies and low-interest loans form European governments is also uncertain. The final economic assumption involves the eventual creation of derivatives. It is assumed that the derivatives will be viable at the time of creation and that it will make sense to keep designing aircraft in this family. As it is uncertain whether this will be true, it is difficult to determine the accuracy of this assumption at this time.

The next set of assumptions are those involving government or politics. This includes the local, national, and international levels of government. It includes assumptions about international relationships and their uncertainties, as well as local problems with building, purchasing, or maintaining facilities. It also involves assumptions about certification times and difficulties, both with certification in Europe and North America and with international certifications such as ETOPS. These assumptions are listed in Table X.

The first assumption listed above is that American and European governing bodies will have common emissions and noise regulations. It is likely that this assumption is valid; however, there is still uncertainty since the European is higher than American and, in the future, European airports may have more stringent noise regulations. The next two assumptions involve the assumption of political stability in Southeast Asia and the Middle East, along with a similar mention of South America further down the list. The risk here is whether this will be the case in the future.

Table X: Political Assumptions and Risks

Assumption	Risk
Future emissions and noise regulations are as predicted	Differences in American/European noise regulations
	Differences in American/European emissions regulations
Middle East stays politically stable	War in the Middle East
	Governmental instability in Middle East
SE Asia is politically stable	Governmental instability in SE Asia
Continued warming of relations between eastern and western Europe	Cooling of relations between East and West
	Eastern Europe closes its borders
US/China relations get better	Tensions in emerging relations between US and China
Britain/India relations stay good	Cooling of India/Britain relations
Nuclear powers keep treaties	Nuclear war/proliferation threat
South American political problems stop	Governmental instability in Latin America
US Government has no political concerns with European a/c	US will allow American companies to subcontract on this a/c
	US doesn't leave Airbus alone over government subsidizing of aircraft
	US will easily allow American airlines to buy European aircraft
	Boeing will allow American companies to work sub-contract on this aircraft
Can develop a/c w/o borrowing excessive money	Cannot get all wanted French funding for a/c
	Cannot get all wanted British funding for this a/c
	Cannot get enough French funding for this a/c
	Cannot get enough British funding for this a/c
Can get everything certified on schedule	Time/cost to get 2 similar a/c certified at same time (widebody only)
	Time/cost get ETOPS certification before put in service (twin only)
Will be able to make a/c	Cannot build new factory in Toulouse

The next three assumptions involve continuing good relations between different countries: the United States and China, India and Britain, and the continued warming of relations between Eastern and Western Europe. There is uncertainty in whether these themes will continue over the next several years. Only recently have Chinese/American relations become better and Eastern/Western European relations are only just starting to warm after many years of Cold War. There is still the potential for these relationships to go back to the way they were ten years ago. Along with increased international friendliness is the assumption that the world's nuclear powers will continue to abide by their treaties and that there will be no nuclear threat. While this assumption has proven valid for the last 40 years and will probably continue to be valid for the next 20, it is still an assumption with some risk about whether it can be met.

The next assumption deals with whether the United States government will allow American carriers to purchase European-made aircraft with little interference. There are several risks in this assumption about the American government. Since the American government is unhappy with the idea of European subsidies for aircraft development and manufacturing, one risk is whether or not these subsidies will become a major problem, or just a complaint. Another risk is whether or not the American government will allow US-based companies to be major subcontractors or, potentially, development partners on this aircraft.

Another, very important, assumption is that the airframer will be able to finance the development of this aircraft, either through low-interest government loans or government subsidies. The risks in this assumption include uncertainties in the amount of money available in the form of government loans and the amount of money to be pledged in the form of subsidies from, particularly, the British and French governments but also from the German and Spanish governments. There is uncertainty both in the amount of money available for development and whether or not it will be enough to develop a new aircraft family. The last assumption on the list goes along with this assumption: that the manufacturer will be able to create a facility to build this aircraft. There is uncertainty as to whether it will be possible to build a new factory large enough to put together this aircraft.

The final assumption on the list is that everything about the aircraft will be certified on the schedule laid out early in design. While this shouldn't be a problem for most certification plans, two of the solution options call for designing two aircraft at the same time, and certification for two aircraft will be more time-consuming than certification for one. So one of the uncertainties is the time and cost necessary to certify two aircraft at the same time. The other uncertainty in the certification process is the time and cost necessary to get an ETOPS certification as soon as possible for a twin-engine aircraft.

The last set of assumptions to be listed are the technological assumptions. These assumptions are associated with the use of new technologies or the extension of existing technologies to this aircraft. These assumptions are listed in Table XI.

Table XI: Technological Assumptions and Risks

Assumption	Risk
Can create larger, composite tail piece	Increasing time/cost to create larger, composite tail piece
Will be able to use more Composites	Unable to use more composites for non-structural parts
Can easily integrate a/c parts	Inability to integrate a/c parts from multiple manufacturers
Can use A300 cross-section	Inability to use existing aircraft cross-section
Can meet 6000 nmi range	Cannot meet 6000 nmi range wanted
New lightweight AL can be used	Cannot use lightweight aluminum alloys
Can create carbon-fiber tail	Cannot use carbon-fiber for tail
	Cannot add passengers in lower berth--cargo displacement
Easy-load cargo pellets	Cannot design configuration to easily load cargo pallets
Competitor's a/c has no significant advantage	Competitor aircraft more fuel efficient than anticipated
	Competitor aircraft/engine less costly
Can create best aircraft in industry	Time/cost to create most fuel-efficient a/c in industry
	Time/cost to create lowest per-seat-mile cost in industry
	Cannot use winglet drag reduction technology
One a/c platform for twin and quad	Cannot create one a/c body to support both twin and quad (widebody only)
Can use common cockpit with A320 and all updates	Cannot create electronic fly-by-wire system
	Inability to use more digital display in cockpit
	Inability to create a common-cockpit with A320 for larger aircraft
No industry-altering technology	Competitor's industry-altering technology
Derivatives can be created	Cannot create derivatives using same technology

The first two assumptions have to do with the use of more composite materials on this aircraft. The assumptions are that a new, larger composite tail can be created and that more composite materials will be able to be used for other parts of the aircraft. The risks in these assumptions include the increased time and cost to design and test a larger composite tail and whether composite materials are developed for use in other aircraft parts. Since a composite tail has been used on previous aircraft, it is likely that it can be extended to a larger aircraft. Along with the assumption that there will be more composite materials used in this aircraft is another materials assumption: there will be lighter-weight aluminum alloys used in this aircraft than in previous aircraft. The uncertainty in this assumption is whether or not these newer, lighter-weight alloys can be used in place of older alloys.

Other assumptions deal with design and part integration. These assumptions include the assumption that the aircraft will be designed well enough that parts from different manufacturers are easily integrated into the finished product. There is uncertainty in how much communication will take place between different suppliers, so integration may not go as smoothly as planned. There are also some design assumptions that have uncertainty about them. The first is that this aircraft can be designed using either the same or a similar cross-section to existing widebody aircraft. Since these aircraft will be larger and more modern there is uncertainty as to whether the exisiting cross-section is the correct platform to use. It is also assumed that the newly designed aircraft will meet the 6000nmi range that the 767 possesses in order to compete with it. However, it is uncertain whether a new twin-engine aircraft can meet this range. This aircraft is also supposed to be designed for easy-load cargo, in order to increase cargo capacity and decrease turn-around time on the ground. However, the ability to easily load cargo depends on the design of the cargo trucks and the aircraft configuration, both of which are uncertain. The main design assumption for this new aircraft for some potential solutions is that a twin- and four-engine aircraft can be created on the same platform. Since this has never been done before, it is not certain whether it is possible to do or not.

The other technological assumptions involving this aircraft take into account the entire industry. These assumptions are that the competitor’s aircraft will not have a significant advantage over this aircraft family, the airframer can create an aircraft with the lowest per-seat-mile cost in the industry, no industry-altering technologies will be discovered, and that derivatives can be created on the same platform as the original. For the assumption that the competitor’s aircraft will not have a significant advantage over the new aircraft, there is uncertainty about what the competitor’s aircraft will be, so there is no way to tell for sure whether it will be better or worse. The same reasoning applies to the assumption that this new aircraft will have the lowest per-seat-mile cost in the industry. The assumption that an industry altering technology will not be created is probably a valid assumption; however, there is always a small chance that such a technology will happen in the near future.

This section lists and explains some of the assumptions that could have been made in 1985 before the decision for an airframer to launch a new aircraft. The list is not all-inclusive. However, listing the assumptions and risks associated with those assumptions is one step in helping engineers create a product that is robust to risks in the external environment.

6.2 Modeling and Simulation

The second focus area of this process is the modeling and simulation area. In this focus area, the solution model is created and then a DoE is run using variables that will enable the risks to also be modeled. Then the risks are assessed and the risk mitigation model is created. The risk analysis and mitigation models, as well as the outputs from the solution models all come together to create the decision support environment.

6.2.1 Step 5: Alternative Solution Modeling

In Step 5, models for each of the potential problem solutions are created, then variables are chosen to model the set of assumptions and their uncertainties, then these variables are put into a DoE and the DoE is run. Finally, the data for metrics of interest are gathered for each DoE case and the metrics are regressed using the chosen variables.

For this problem, the creation of a new widebody, long range aircraft, potential solution options have been chosen. These options include a stretch version of an existing aircraft, a new twin-engine aircraft, a new four-engine aircraft, and some combinations of those three. Therefore, for this exercise, three baseline aircraft will need to be created: a new twin-engine, a new four-engine, and a derivative of an existing twin-engine aircraft. With these new aircraft, new engines must also be modeled, since new engines will be more fuel-efficient than existing ones.

The modeling environment chosen for this project was NASA’s Flight Optimization Software (FLOPS) (McCullers 2001) and Aircraft Life Cycle Cost Analysis

(ALCCA) (Garcia et al. 2001). Both of these pieces of software existed in the 1980s, so it is not a stretch to declare that FLOPS/ALCCA, or something similar to it, could have been used by Airbus engineers to model these aircraft. FLOPS is a semi-empirical modeling tool that can be used to size commercial and military aircraft. Given information about the aircraft, including the number of passengers, the distance it should fly, what it is made out of, and any technological updates, and it will provide sizing and performance characteristics about the aircraft for a specified set of missions. It will provide takeoff, climb, cruise, descent, and landing performance, as well as weights and physical sizes for the aircraft. ALCCA is an empirical cost-estimating tool for both commercial and military aircraft. It takes in information about the cost and complexity of the aircraft's materials, the cost of manpower, the cost and complexity of subsystems, and any technology that can help reduce cost or manpower and builds a manufacturer's cashflow. It also takes in information about the cost of fuel, manpower, and the number of flights and load factor for the aircraft and will also output an airline's cashflow.

Understanding the inputs and outputs allows the designer to determine the variables and metrics of interest. The metrics of interest are often easier to determine than the variables. These metrics include aircraft cost and performance metrics, as well as airline costs metrics. Airframer's cost data can be in the form of a cashflow, so metrics that make up a cashflow should be recorded. For this case, the cashflow can be divided into cost and revenue metrics. Cost metrics include the first unit cost, the number of aircraft manufactured to date, the sustaining costs, and the research, development, testing, and evaluation (RDT&E) costs, so all of these metrics should be included. While the cost metrics were easy to determine, the revenue metrics are more difficult, since they are market driven and cannot be set. Revenue metrics include the pay schedule for the aircraft and the aircraft price.

Aside from cashflow metrics of interest, there are also performance metrics of interest to record. The takeoff gross weight (TOGW), takeoff field length (TOFL), landing field length (LdgFL), and the approach speed (Vapp), are all metrics to record, as are the NO_x emissions and any other weights that are deemed necessary, such as the operating empty weight. (OEW).

Airline metrics are the airline's cashflow metrics, which are not used in this example, and the airline's operating costs. In ALCCA, one of the outputs is the airline's total operating cost (TOC), per aircraft-seat-mile (ASM). This is also an important metric for the aircraft manufacturer, since it is a metric that compares well across manufacturers as long as the route length is the same and the number of seats is comparable.

So now that the metrics of interest are known and can be recorded, it is time to determine the variables and create the models. Determining the variables can be very difficult; it is more an art than a science. The list of assumptions and their uncertainties are given in Section 6.1.4, and those uncertainties are what this author needs to model. There are several common themes throughout the list of assumptions. Many of the assumptions involve decreasing the number of aircraft sold, increasing the labor rates, decreasing production rates, increasing materials cost, and increasing RDT&E time. Other variables needed are those associated with the technology, including the composite tail, the avionics equipment, and the decreased weight of aluminum. The final list of variables is as follows:

1. Number of years of RDT&E
2. Production number (number of aircraft sold)
3. Inflation
4. K-factor on the cost of Aluminum (materials cost)
5. Engineering labor rate
6. Manufacturing labor rate
7. Airline's borrowing interest rate
8. First year production rate (per month)
9. Second year production rate (per month)

10. Fourth year production rate (per month)
11. Fifth year production rate (per month)
12. Ninth year production rate (per month)
13. K-factor on the weight of Aluminum
14. Cost of jet fuel
15. Percent of tail made out of composite materials
16. Avionics system weight

Variables eight through twelve need more explanation. FLOPS is a static computer code; there is no way to complete a time-dependent analysis without specifying many different variables. These variables are meant to model increases and decreases in production through time. These sixteen variables are used to model all of the assumptions that are listed in the previous section.

Now that the variables have been specified, it is time to create the aircraft models. Three baseline models need to be created, but slightly different outputs are required for each model. The three models are created in FLOPS using a 300pax model that was available for a baseline. The 300pax model was then updated with the new information for the new aircraft.

The first aircraft created was the new twin-engine aircraft. It was created using information gathered about the A330 from the Airbus website ("A330-300 Specifications" 2006) and the Airliners.net website ("Airbus A330-300" 1998). All information that could be found about the aircraft and an engine, in this case a notional CF6-80, replaced the initial baseline information. The goal was to create a model of an aircraft that was close to an A330. The aircraft was created using A330 dimensions including tail height, tail areas, geometric characteristics such as sweep and taper, tail airfoil characteristics, wing area, geometric characteristics, and airfoil characteristics, and fuselage characteristics. Other data, including wing, tail and fuselage materials as well as engine characteristics such as weights, dimensions, and an engine deck, were also needed. The engine deck was generated using NPSS and WATE and resembles a CF6-80.

A330 dimensions and weights were used as initial guesses; FLOPS sized the aircraft to the required range, in this case 5600 nmi. Sizing the aircraft to the range was difficult. Initially, the aircraft was sized for a 6000 nmi range; however, this range required more fuel and a heavier structure than could be reasonably put on the aircraft without decreasing payload volume. So the range was decreased to 5600 nmi in order to more accurately represent the aircraft's performance as it was built. This exercise was a good sanity check; the actual aircraft doesn't have a range of 6000 nmi, so the model shouldn't either.

The four-engine aircraft was built in a similar fashion to the two-engine aircraft. Information was gathered about the A340 from the Airbus and Airliners.net websites ("A340-300 Specifications" 2006) and ("Airbus A340-300" 1998). Like the previous aircraft, this aircraft was created using A340 dimensions including tail height, tail areas, geometric characteristics such as sweep and taper, tail airfoil characteristics, wing area, geometric characteristics, and airfoil characteristics, and fuselage characteristics. Other data, including wing, tail and fuselage materials as well as engine characteristics such as weights, dimensions, and an engine deck, were also needed. The engine model in this case was a notional CFM56-5C, also created in NPSS and WATE. The initial aircraft FLOPS model was the same for both aircraft: still a notional 300pax model.

Again, all dimensions were kept the same but the aircraft was sized for the max range by FLOPS. In this case, the max range was set to 7500 nmi, which would make it part of the very long-range market. In 1985, that market had only Boeing aircraft, so creating a long-range aircraft would add an element of competition to the market that a European airframer may be able to capitalize on.

Making a derivative aircraft was more difficult than creating notional aircraft for the new twin- and four-engine configurations. An A300-600 created with non-propriety data was used as part of the baseline; the 300pax aircraft was also used to help create this aircraft's baseline. After that, the aircraft was stretched—the fuselage length and number of passengers increased. A300 dimensions were used, including tail height, tail areas, geometric characteristics such as sweep and taper, tail airfoil characteristics, wing area, geometric characteristics, and airfoil characteristics, and fuselage characteristics. The materials were changed to reflect the increased technology developed in the last ten years. The engine used was also a CF6-80 model.

This aircraft model initially had some modeling problems in FLOPS. The wing size needed to be increased for takeoff field length to be less than 9000 ft. Once the wing size was increased (aspect ratio remained the same) then the aircraft was sized for a 4000 nmi mission. While this range is approximately the range of the A300-600, and the aircraft has been stretched, with the larger wing the model was able to carry enough fuel to make 4000 nmi.

Now that the aircraft have been modeled and the variables selected, it is time to set up the variable ranges for the DoE. There are sixteen variables listed, and all need to have ranges attached to them. These ranges will be the same across all the model aircraft, since the variables are technological or monetary. The ranges are as follows, with all dollars in 1985 dollars:

1. Number of years of RDT&E [6, 9] Six years to nine years falls into the normal range of what one would expect for aircraft development time, from conceptual design to the first delivery.
2. Production number (number of aircraft sold) [600, 1200] The prediction for the number of aircraft sold will depend on the aircraft configuration, so this range is very wide. It also represents the number of aircraft sold over a 20-year timeframe.
3. Inflation [2.5%, 8%] This range accounts for average inflation over a 20-year timeframe. Even if inflation during individual years is higher, it is likely that over a 20-year span the inflation will average between 2.5% and 8%.

4. Scale-factor on the cost of Aluminum (materials cost) [0.9, 1.1] This variable is an exponential factor on the cost of Aluminum, which makes up most of the structural materials on the aircraft. Increasing or decreasing it 10% allows for changes in the cost of materials.
5. Engineering labor rate [$60, $120] This labor rate is the cost of engineers per man-hour. The labor rate times 1.25 is the cost of engineering management per hour. It also covers the cost of benefits.
6. Manufacturing labor rate [$30, $60] The manufacturing labor rate is the cost of manufacturing labor per man-hour. Like the engineering labor rate, the manufacturing floor foreman's rate is 1.25 times the normal rate; this number includes benefits.
7. Airline's borrowing interest rate [2%, 12%] This is the rate that the airline's use to borrow money to finance aircraft. While it is a wide range, this range covers the differences in creditworthiness between different airlines, as well as the different potential futures with different inflation and borrowing rates.
8. First year production rate per month [0.05, 1.5] During the first year, the production will be lower than later in the process. Depending on whether the aircraft production gets off to a fast or slow start, the production rate could be at either end of the spectrum. Also, if there are any problems with the manufacture in the beginning, the production rate will be low.
9. Second year production rate per month [0.1, 2.5] The second year of production is similar to the first. The production rate should be increasing over the first year; however, there is still the potential for problems in manufacturing which will decrease the production rate.
10. Fourth year production rate per month [0.5, 6] The fourth year production rate is meant to symbolize a mid-timeframe production rate. The maximum production rate for the existing facilities is approximately five per month. If new technologies

are put in place, the rate may increase to six aircraft per month. The low end of the production rate would be reached if there were any production interruptions or a decrease in aircraft orders.

11. Fifth year production rate per month [0.5, 6] The fifth year production rate is similar to the fourth year production rate
12. Ninth year production rate per month [0.5, 6] The ninth year production rate is also similar to the earlier production rates, except that the ninth year is meant to represent a year toward the end of the manufacturing cycle.
13. K-factor on the weight of Aluminum [.95, 1] Advancements in technology have led to the creation of lighter-weight aluminum alloys. The baseline value of the weight of aluminum is 1, with a 5% decrease as the maximum potential k-factor. A 5% decrease in aluminum density seems small; however, this is still a significant weight reduction.
14. Cost of jet fuel [$0.40, $2.00] The average cost of fuel is widely variable. Having boundaries as wide as possible, from $0.40/gal to $2.00/gal, seems to be the best way to cover the entire range of possibilities.
15. Percent of tail made out of composite materials [0%, 100%] One of the technological goals in the creation of a new aircraft is that the composite tail that is currently used on the A300 can be extended to a larger aircraft. If the technology can be extended, the percentage will be near 100%; however, there is also the possibility that the technology cannot be extended to a larger aircraft, or cannot be extended completely, so the percentage of the tail made up of composites would be lower.
16. Avionics system weight scalar [0.9, 1.25] Advances in technology have led to the potential decrease in avionics system weight. In this case, the new aircraft baseline avionics weight multiplier is set to 1, so further decreases in the weight

cause the avionics weight decrease the multiplier, while inability to use the new technologies as planned increases the avionics weight multiplier.

Now that the variable ranges have been set and the modeling and simulation environment has been decided upon, it is time to set up the DoE to run the cases. With sixteen variables, a 290 case central composite DoE was chosen. This DoE was then augmented with 200 additional points, randomly distributed. The first 100 of these points will be used in the model fitting to help fit the models in between the central composite points, while the last 100 points will be used to check the model fit. All of the cases were run in a modeling and simulation environment.

The outputs from the modeling environment are the same for the first three potential solutions, new twin-engine, new quad-engine, and A300 stretch. In these cases, the outputs from FLOPS/ALCCA that are tracked are the performance metrics of TOGW, TOFL, Vapp, OEW, NOx, and LdgFL. These outputs are common to all aircraft, and they do not change depending on whether one aircraft or two will be designed. Cost outputs from FLOPS/ALCCA that are common to all aircraft are the first unit cost, acquisition price (Acq), the total RDT&E cost, the RDT&E cost from year one to year ten, the annual delivery rate from year six to year twenty, and the sustaining cost from year six to year twenty. For the solutions that require more than one aircraft, some of these outputs change.

For the creation of both a new twin- and a new four-engine aircraft, the new twin-engine aircraft was used as a baseline. The RDT&E costs was gathered for a new wing for the four-engine aircraft for each DoE case and then added to the twin-engine RDT&E cost per year. For the new derivative and four-engine aircraft, it is assumed that a stretch version of an aircraft with a new wing while updating much of the technology will have an RDT&E cost of approximately 50% of the creation of a new aircraft. This assumption is based on the FLOPS outputs: creating a new wing and adding newer, larger engines accounts for approximately 30% of the aircraft RDT&E cost; the additional technology and certification requirements were assumed to account for the last 20%. First unit cost was also discounted accordingly. Since sustaining cost is based on the number of aircraft produced, it was not necessary to gather more information about sustaining costs for each aircraft.

The next step is to build a cashflow for each solution option, and then create surrogate models of all necessary outputs with the inputs. Building a cashflow with the available outputs is relatively simple. On the cost side, there is the RDT&E cost and the sustaining cost, which are directly available as outputs, and the manufacturing cost, which is calculated using a learning curve and the first unit cost. The manufacturing cost was calculated using a learning curve of 85% off the first unit cost, the first unit cost, and the number of units that are manufactured. The revenue side is simpler to calculate but more complicated to put in place. On the revenue side, it is assumed that there is an average aircraft price that the aircraft can be sold for, and that this price is paid over several years. For simplicity's sake, there is one calculation for revenue for all aircraft; different airlines are not treated differently. This revenue calculation is modified from ALCCA's revenue calculation, which assumes a 3% down payment on order, 20% payment a year before delivery, and 77% on delivery (Garcia et al. 2001). The modification was made to increase simplicity and avoid a dramatic increase in revenue at the end of the examined 20 year time period. The aircraft is assumed to be ordered five years before delivery. When the aircraft is ordered, the airline pays 10% of the price. For the next two years, they pay 5% of the price per year, then the year before the aircraft is delivered the airline pays 10% of the price and the final 70% of the aircraft price is due on delivery. This cashflow is created for each year for each option, from year one through year twenty, or from 1985 through 2004.

Now surrogate models need to be generated for each piece of the cashflow as well as all of the performance and other monetary metrics of interest for each aircraft. Initially, all surrogate models were 2nd order linear regression models for each metric. The equations used to create a 2nd order linear regression model are described in Appendix A. After the surrogate models had been created, it was discovered that some of the metrics, particularly the ones necessary to build a cashflow, were not modeled well by RSEs. At this time, all metrics that weren't well modeled by RSEs were then modeled by neural nets, in the process described in Appendix A.

The types of surrogate models were used to create the final models of each metric of interest are listed in Table XII. The metrics modeled by 2nd order RSEs were modeled either with straight 2nd order RSEs or were modeled after a logarithmic transformation. The neural network models used a traditional neural network with the last 20% of the cases used for validation. Surrogate model fits are summarizing in Table XII. The performance metrics were modeled with 2nd order RSEs, as is the RDT&E cost, while the annual delivery schedule and the sustaining costs were modeled using neural networks.

Table XII: Regression Summary

	Response	Surrogate Model Type	Model Fit Error				Model Representation Error			
			Mean	Standard Deviation	Minimum	Maximum	Mean	Standard Deviation	Minimum	Maximum
Derivative Aircraft	TOGW (lb)	RSE	1.12E-06	0.000767	-0.0036	0.003	-4.23E-05	0.001038	-0.0038	0.0033
	TOFL (ft)	RSE	1.11E-06	0.001992	-0.008	0.0076	-0.000234	0.00254	-0.008	0.0084
	LTO NOx (lb)	RSE	1.07E-06	0.029135	-0.1099	0.081	-0.005572	0.033415	-0.1099	0.081
	TOC Max Range ($/ASM)	RSE	3.74E-05	0.29533	-1.4158	1.1429	-0.020966	0.37969	-1.4158	1.1429
	First Unit Cost ($)	RSE	3.95E-05	0.083126	-0.3894	0.3682	0.009737	0.10497	-0.3894	0.4615
	RDT&E Year 1 ($)	RSE	-1.46E-05	0.29518	-1.1575	1.1801	0.07375	0.39288	-1.1575	1.7573
	Sustaining Cost Year 20 ($)	NN	4.35E-03	0.93206	-2.7503	5.8578	0.46559	2.3135	-4.0824	11.6225
	Annual Delivery Year 20	NN	0.016749	1.8353	-7.4888	8.4118	-0.010907	3.7955	-18.6168	16.0252
New Twin-Engine	TOGW (lb)	RSE	1.12E-06	0.000765	-0.0025	0.0022	-3.97E-05	0.000858	-0.0025	0.0025
	TOFL (ft)	RSE	1.12E-06	0.002447	-0.0053	0.0089	0.000374	0.002975	-0.0061	0.0101
	LTO NOx (lb)	RSE	1.12E-06	0.027364	-0.0521	0.064	0.000695	0.028761	-0.0756	0.0665
	TOC Max Range ($/ASM)	RSE	1.82E-05	0.29447	-1.4044	1.1798	-0.020949	0.37885	-1.4044	1.2034
	First Unit Cost ($)	RSE	4.86E-05	0.093203	-0.4042	0.3932	0.010301	0.11749	-0.4042	0.4603
	RDT&E Year 1 ($)	RSE	2.56E-05	0.29634	-1.1433	1.2092	0.074319	0.39438	-1.1433	1.7515
	Sustaining Cost Year 20 ($)	NN	4.37E-03	0.93407	-2.7534	5.8612	0.46637	2.3159	-4.0889	11.6381
	Annual Delivery Year 20	NN	0.016749	1.8353	-7.4888	8.4118	-0.010907	3.7955	-16.1745	16.0252
New Four-Engine	TOGW (lb)	RSE	1.12E-06	0.001169	-0.0038	0.0041	5.85E-05	0.00137	-0.0046	0.0041
	TOFL (ft)	RSE	1.12E-06	0.002833	-0.0064	0.0093	8.70E-05	0.003042	-0.0083	0.0102
	LTO NOx (lb)	RSE	1.11E-06	0.016362	-0.0539	0.0599	0.002729	0.021927	-0.066	0.0701
	TOC Max Range ($/ASM)	RSE	4.73E-05	0.31513	-1.4771	1.1754	-0.024836	0.40503	-1.4771	1.2568
	First Unit Cost ($M)	RSE	4.88E-05	0.09324	-0.4596	0.4041	0.010507	0.1169	-0.4596	0.498
	RDT&E Year 1 ($M)	RSE	-2.57E+00	0.29455	-1.1456	1.202	0.074027	0.39294	-1.1456	1.7424
	Sustaining Cost Year 20 ($M)	NN	4.32E-03	0.92769	-2.8273	5.7974	0.46491	2.3154	-4.0308	9.5845
	Annual Delivery Year 20	NN	0.016749	1.8423	-7.325	8.4188	-0.010921	3.5622	15.5747	-16.1752

In general, the surrogate model fits had small errors for both model fit error and model representation error. The sustaining cost and annual delivery rate had the worst surrogate model fits; these were the only responses with maximum model representation errors greater than 10%. The performance metrics had excellent model fits with error standard deviations significantly less than one and maximum errors less than 0.2%. The TOC at maximum range, first unit cost, and RDT&E costs model fits were also very good with model representation error standard deviations of less than 0.5 and maximum model representation errors less than 2%.

6.2.2 Step 6: Uncertainty Quantification

The uncertainty quantification step in this process involves creating a baseline aircraft that meets all assumptions and then mapping between the different assumptions with their uncertainties, and the variables that are used to model the metrics of interest and the cashflow.

The creation of a set of baseline aircraft is not difficult. It involves determining the settings of each variable such that the initial assumptions are met, i.e., what is supposed to happen. The baseline variable settings are listed in Table XIII. The tail composite composition is the fraction of the tail that is made out of composite materials, while the aluminum k-factor is the weight of the aluminum scale-factor, with one being the traditional FLOPS baseline. Some of the variables are the same for all aircraft, including the RDT&E time, inflation, labor and materials costs, production rates, airline fuel costs and interest rates, and technology factors. These variables are the same since all aircraft are being designed in the same timeframe by the same company. The variables that are different are the production number and the acquisition price of the aircraft; both of these variables are dependent on the market. Market-dependent variables will change with the different aircraft sizes and the different types of aircraft. For acquisition price for a two-aircraft combination, it is assumed that there will be 50% twin-engines and 50% four-engine aircraft produced. For production number, it is assumed that a new aircraft will have more orders than a derivative aircraft.

Table XIII: Baseline Variable Settings

	Derivative	New Twin	New Quad	New Twin & Quad	New Quad & Deriviative
Years_RDTE	7	7	7	7	7
Production_Number	650	900	800	1000	800
Inflation	0.035	0.035	0.035	0.035	0.035
AL_Cost	1	1	1	1	1
ENG_Labor	70	70	70	70	70
Man_Labor	30	30	30	30	30
Year_1_Prod	0.5	0.5	0.5	0.5	0.5
Year_2_Prod	1.5	1.5	1.5	1.5	1.5
Year_4_Prod	6	6	6	6	6
Year_5_Prod	6	6	6	6	6
Year_9_Prod	6	6	6	6	6
AL k-factor	0.95	0.95	0.95	0.95	0.95
Fuel_Cost	0.45	0.45	0.45	0.45	0.45
Airline_Int_Rt	7	7	7	7	7
Tail Composite Composition	0.9	0.9	0.9	0.9	0.9
Avionics Wt	1	1	1	1	1
Acq ($ million)	65	70	80	75	75

Mapping the assumption's uncertainties to the variables is done by hand, one uncertainty at a time. This mapping procedure is done using a scale of -3 to 3, with a -3 corresponding to a large decrease in that variable value, -2 corresponding to a medium decrease, -1 corresponding to a small decrease, 1 corresponding to a small increase, 2 corresponding to a medium increase, and 3 corresponding to a large increase.

It is a time-consuming process; the results of the mapping are illustrated in Table XIV through Table XVIII. The mapping procedure involves looking at each assumption's risk and determining the effects on each variable if that risk were to become true. For example, the first risk under the first assumption in the employment category questions whether there will be enough design engineers. If there are not enough design engineers, the variables will be affected as follows: the RDT&E time will moderately increase since there aren't enough engineers to complete the process in the assumed timeframe. The production number will moderately decrease since the design won't be as good as it could have been and will be late getting to production. The engineering labor cost will greatly increase as the economics of scarcity take over. The early years (years one and two) production rate will slightly decrease as the delays and changes decrease the number of orders. The weight of aluminum and the avionics systems will increase over the assumed weight since new technologies won't be developed or utilized without a knowledge base. The percentage of the tail that is made up of composites will decrease for the same reason.

This process is then completed for each assumption over all five categories. While it is sometimes necessary to also complete a different one for each potential solution family, in this case that was judged to be unnecessary, since each concept alternative was an evolutionary alternative and all alternatives were relatively similar. This is not the case for all potential solution families. Once this risk modeling procedure has been completed, the next step is to complete the risk assessment, which uses the risk model created here.

Table XIV: Employment Risk Mapping

Assumption	Risk	Years_RDTE	Prod_#	Inflation	AL_Cost	ENG_Labor	Man_Labor	Int_rate	Year_1_F	Year_2_F	Year_4_F	Year_5_F	Year_9_F	AL_k-fac	Fuel_Cost	Tail_Comp	Avionics_Wt	Price
Will have, or be able to hire, enough workers to meet demand	Not having enough qualified design engineers	2	-2			3			-1	-1				3		-2	2	
	Not having enough manufacturers--early		-2				3		-2	-1				1			1	
	Not having enough manufacturers--late		-1				3						-2				1	
Accurately anticipate workers costs	Higher turnover rate	1	-1			1	1		-1	-1			-1	1		-1	1	
	Can't afford to keep workers on during cyclic work cycle					1	1											
	Workers labor costs increase					2	2											
	Union boycotts (early in manufacturing cycle)		-1		1		2		-2	-2	-1			1			1	
No language barriers	Workers difficulty communicating between countries	1							-1	-1						-1		
Pay workers competing wages in different countries	Inability to pay workers competing wages in different countries				1	1	1	1										
	Loss of workforce to American companies	1		-1		2	1							2		-1		
	Worker benefits' cost increases					2	2											
No cultural problems between workers	Difficulties working between European countries	2							-1	-1								
	Difficulties working with immigrant labor						2		-1	-1								
	Inability to import unskilled labor						-3		-1	-1	1	1	1					
	Difficulty with communications with outsourced labor	1																
Minimal business losses	Loss due to working with outsourced labor markets			1			2											
Training costs are low compared to productivity	Increased time/cost to effectively training workers in new technology	1				1	1		-1	-1								
	Increased time/cost to effectively skill unskilled workers						1		-2									
Mobile workforce	Inability to move worker locations as necessary				-1		-1		-1									
Stable workforce	Work interruptions due to extenuating circumstances	2	-1						-1	-1			-1					

Table XV: Cultural/Social Risk Mapping

Assumption	Risk	Years_RDTE	Prod_#	Inflation	AL_Cost	ENG_Labor	Man_Labor	Int_rate	Year_1_F	Year_2_F	Year_4_F	Year_5_F	Year_9_F	AL_k-fac	Fuel_Cost	Tail_Comp	Avionics_Wt	Price
Can sell twin for overseas use	Customers uncomfortable on overseas flights on twin		-1						-1	-1								
More travel & wealth within China	Leveling off of Chinese population		-1				1						-1					
China opening to west	Tension between China and Britain/US over Hong Kong		-1												1			
Little travel to SE Asia	Political opening of SE Asia		2		2	-2	-1				1	1	1		1			
There is no change in cultural preferences for American/ European a/c	Asian preference for American aircraft		-2															-2
	Japanese preference for American aircraft		-1															-1
	Middle Eastern preference for American aircraft		-1															-1
	General preference for status quo		1	-1														
America allows government aid for development	American companies boycott European airframers		-2		1				-1	-1								-1
	American consumers boycott European airframers		-1						-1	-1								
No regional/global epidemics	Epidemic decreases flying public		-2								-3	-2						
	Epidemic cuts off S.Asia		-1								-1	-1						
	Epidemic cuts off Africa		-0.5								-1	-1						
Social stability	Civil unrest in China		-0.5															
	Fear of flying due to terrorist incidents		-1								-3	-2						
	Civil unrest in Eastern Europe			1											1			

Table XVI: Economic Risk Mapping

Assumption	Risk	Years_RDTE	Prod_#	Inflation	AL_Cost	ENG_Labor	Man_Labor	Int_rate	Year_1_F	Year_2_F	Year_4_F	Year_5_F	Year_9_F	AL_k-fac	Fuel_Cost	Tail_Comp	Avionics_Wt	Price
Good global economic conditions	Aircraft financing interest rate rises		-0.5					2										
	European recession	1	-1	-1		-2	-1		-1	-1								-1
	Asian recession		-1						-1	-1								-1
	American recession		-1	-1					-1	-1								-1
Stable fuel costs	Cost of fuel increase		-0.5												2			
New security prevents terrorist attacks	Increase in security costs due to terrorist attacks								-1	-1			-1					
4% growth in travel	Business travel decreases		-1															
	Leisure travel decrease		-2															
Steady unemployment	Unemployment increases		-1															
American economy stay strong	Economic growth slows in US			2														
	Lower-than-expected growth projections (for reasons not listed above)		-1										-2					
European tax structure and subsidies remains same	Decrease in British tax revenues (for reasons not listed above)	-1																
	Decrease in French tax revenues (for reasons not listed above)	-1																
	Increase in British tax payouts	1																
	Increase in French tax payouts	1																
	Need outside financing for some development	2																
Derivatives are also viable	Derivatives compete with initial for sales		-1										-1					

Table XVII: Government/Political Risk Mapping

Assumption	Risk	Years_RDTE	Prod_#	Inflation	AL_Cost	ENG_Labor	Man_Labor	Int_rate	Year_1_F	Year_2_F	Year_4_F	Year_5_F	Year_9_F	AL_k-fac	Fuel_Cost	Tail_Comp	Avionics_Wt	Price
Future emissions and noise regulations are as predicted	Differences in American/European noise regulations	2																
	Differences in American/European emissions regulations	1												-1		1	-1	
Middle East stays politically stable	War in the Middle East		-2	-1					-1	-1					3			
	Governmental instability in Middle East														3			
SE Asia is politically stable	Governmental instability in SE Asia		-1															
Continued warming of relations between eastern and western Europe	Cooling of relations between East and West		-1															
	Eastern Europe closes its borders		-1															
US/China relations get better	Tensions in emerging relations between US and China		-1	-1	1													
Britain/India relations stay good	Cooling of India/Britain relations						2											
Nuclear powers keep treaties	Nuclear war/proliferation threat		-0.5															
South American political problems stop	Governmental instability in Latin America		-0.5		1										1			
US Government has no political concerns with European a/c	US will allow American companies to subcontract on this a/c	-1	1						1	1				-1		1	-2	
	US doesn't leave Airbus alone over government subsidizing of aircraft	1						1										-1
	US will easily allow American airlines to buy European aircraft		1															
	Boeing will allow American companies to work sub-contract on this aircraft	-1							1	1						1	-1	
Can develop a/c w/o borrowing excessive money	Cannot get all wanted French funding for a/c							-1						1		-1	1	
	Cannot get all wanted British funding for this a/c							-1						1		-1	1	
	Cannot get enough French funding for this a/c	-1												3		-3	3	-3
	Cannot get enough British funding for this a/c	-1												3		-3	3	-3
Can get everything certified on schedule	Time/cost to get 2 similar a/c certified at same time	1							-1	-1								-1
	Time/cost get ETOPS certification before put in service (twin only)	1							1	1								
Will be able to make a/c	Cannot build new factory in Toulouse	1							-1	-1								

Table XVIII: Technological Risk Mapping

Assumption	Risk	Years_RDTE	Prod_#	Inflation	AL_Cost	ENG_Labor	Man_Labor	Int_rate	Year_1_F	Year_2_F	Year_4_F	Year_5_F	Year_9_F	AL_k-fac	Fuel_Cost	Tail_Comp	Avionics_Wt	Price
Can create larger, composite tail piece	Increasing time/cost to create larger, composite tail piece	1				1	1									-2		
Will be able to use more Composites	Unable to use more composites for non-structural parts	1				1	1								1	-1		
Can easily integrate a/c parts	Inability to integrate a/c parts from multiple manufacturers	1															3	
Can use A300 cross-section	Inability to use existing aircraft cross-section	3					2											
Can meet 6000 nmi range	Cannot meet 6000 nmi range wanted	1	-2															
New lightweight AL can be used	Cannot use lightweight aluminum alloys	1			3	2	1							3	1	1		
Can create carbon-fiber tail	Cannot use carbon-fiber for tail														1	-3		
	Cannot add passengers in lower berth--cargo displacement	1	-1															
Easy-load cargo pellets	Cannot design configuration to easily load cargo pallets	1	-1															
Competitor's a/c has no significant advantage	Competitor aircraft more fuel efficient than anticipated		-2										-2		1			-1
	Competitor aircraft/engine less costly		-1															-1
Can create best aircraft in industry	Time/cost to create most fuel-efficient a/c in industry	3	2												-1			
	Time/cost to create lowest per-seat-mile cost in industry	3	1															
	Cannot use winglet drag reduction technology														-1			
One a/c platform for twin and quad	Cannot create one a/c body to support both twin and quad	-2																
Can use common cockpit with A320 and all updates	Cannot create electronic fly-by-wire system	1	-1														2	
	Inability to use more digital display in cockpit	1	-1															
	Inability to create a common-cockpit with A320 for larger aircraft	1	-2															
No industry-altering technology	Competitor's industry-altering technology		-3												3			-2
Derivatives can be created	Cannot create derivatives using same technology	-1											-1					

6.2.3 Step 7: Risk Assessment

Now that the assumptions and their uncertainties have been modeled, it is time to determine the severity of not meeting these assumptions: determine the risk of each uncertainty. This process is completed in several steps, the first of which is to collate the scenarios and determine the variable distributions for each variable over all the scenarios in order to complete a Monte Carlo analysis.

This is done by taking each variable, and then determining a variable distribution over each scenario. For example, the best-case scenario may have an RDT&E time distribution of: a triangular distribution, minimum of six years, maximum of seven years, with a peak at 6.5 years. The worse-case scenario may be: triangular distribution, minimum of 7.5 years, maximum of nine years, peak at 8.5 years. The scenario distributions are then multiplied by the likelihood of occurrence of each scenario and added together, as depicted in Figure 46.

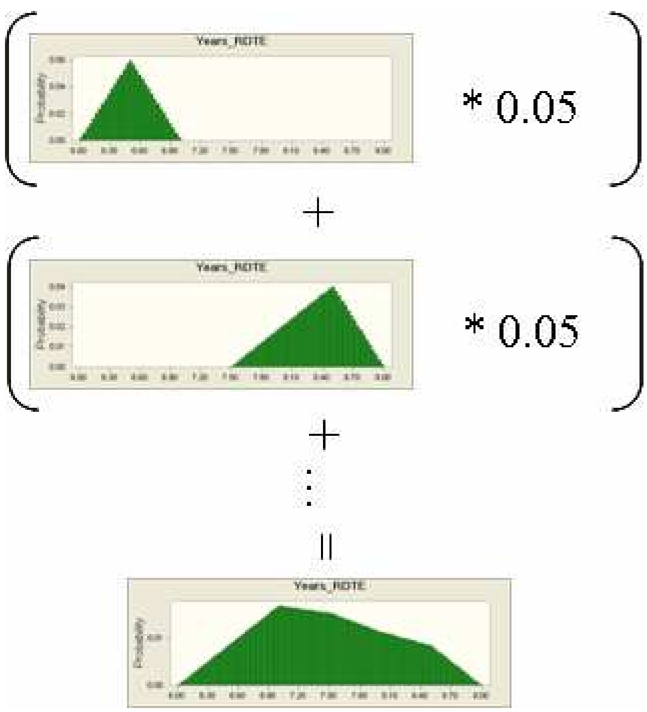

Figure 46: Building Distributions Using Scenarios

This analysis is completed for all variables.

The distributions for variables that are the same for all potential solutions are illustrated in Figure 47. These distributions were created using Crystal Ball, an add-in for MS Excel®.

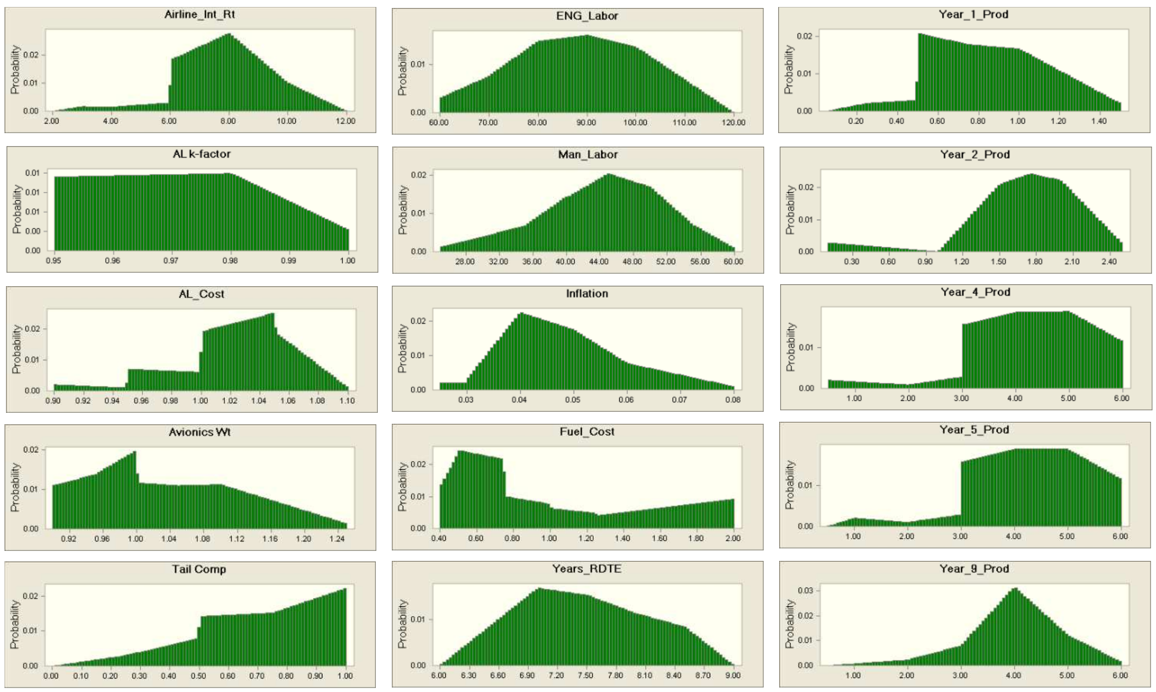

Figure 47: Variable Distributions

The distributions look different than traditional Monte Carlo analysis distributions because they were created using probabilistic scenarios instead of a traditional probabilistic analysis. The use of scenarios adds some traceability to this analysis and provides uncertainty bounds: now instead of challenging an entire distribution, a devil's advocate can challenge the distribution over a particular scenario. The distributions over each scenario are narrower than the entire distribution, and the distribution over all scenarios is potentially narrower than a traditional probabilistic analysis distribution would be, and certainly shaped differently. For example, for all five years of production rate used as variables, it is much more likely that nothing will go wrong and the production rate will be higher than it is that the production rate will be low. This is reflected in the distributions of all five variables; however, it would be difficult to capture in a traditional probabilistic analysis due to the limitations on choosing distributions.

Other variables change with the potential solution being examined. In this case, two variables change with the solution being examined, the airline's acquisition price and the manufacturer's production number. These variables' distributions are illustrated in Figure 48. The most likely acquisition price increases as one moves toward a larger aircraft or one with more engines. It should also be noted that the most likely production number increases as one moves away from derivatives and toward new aircraft. It also increases again with the number of aircraft being created.

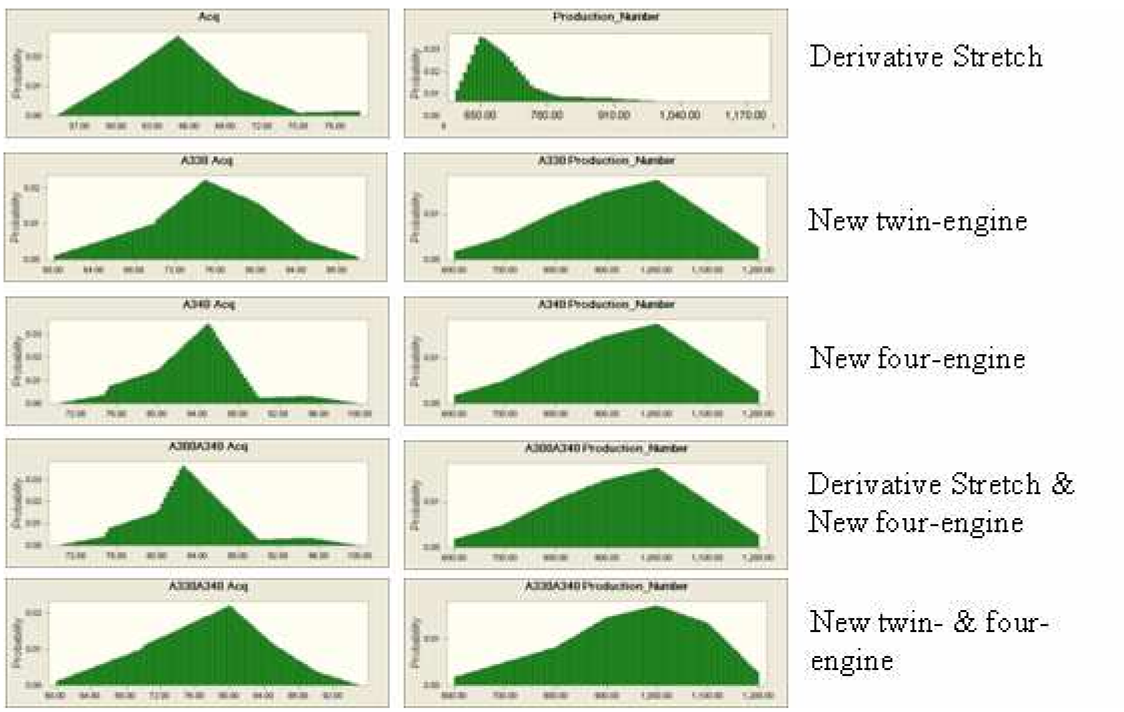

Figure 48: Variable Distributions over Different Potential Solutions

While many of these distributions appear to be triangular, more or less, in nature, it would still be very difficult to capture them without a scenario-based analysis. For these distributions, one is more likely to be nearer to the most likely variable setting than in a traditional triangular distribution. So a triangular distribution would underestimate the probability of being near the more likely variable settings and overestimate the probability of being very close to the edge of the variable range. Such a change will likely also cause changes in the solutions, which may change the final decision of which solution to explore more thoroughly.

Now that the variables are modeled over each scenario, a Monte Carlo analysis is run over all scenarios using the constructed distributions. This Monte Carlo analysis will help determine the severity of the consequences of not meeting the assumptions. This Monte Carlo analysis produces results for all the metrics of interest: performance, cashflow, and airline. The results of the Monte Carlo are saved for future use, except in the case of the cashflow analysis, where the 1% and 99% cashflow solutions and the baseline cashflow are plotted for each potential solution, for comparison purposes. Any performance metrics that have constraint values, like TOFL, are also noted, and the TOFL is flagged if the metric value violates the constraint.

Now that the Monte Carlo is completed and the results plotted on the cashflow diagrams, it is time to determine the probabilities and consequences associated with the uncertainties for each assumption.

Determining consequences can be time-consuming. First, the variable values from the risk mapping matrix corresponding to -3, -2, -1, 1, 2, and 3 need to be determined so that the consequences can be assessed accurately. For the variables whose ranges and distributions do not change with potential solutions, the risk setup matrix is given below in Table XIX. Some of the variables have linear changes with increasing or decreasing consequences, some do not. Whether the scale is linear or not depends on the baseline value, the variable range, and whether or not the variable has a linear or non-linear effect on any of the metrics of interest.

Table XIX: Risk Setup Matrix

	Baseline				Risk Setup Matrix		
	0	-3	-2	-1	1	2	3
Years_RDTE	7	6	6.25	6.5	7.5	8	9
Inflation	0.035	0.025	0.03	0.032	0.04	0.06	0.08
AL_Cost	1	0.9	0.95	0.98	1.02	1.05	1.1
ENG_Labor	70	60	65	68	80	100	120
Man_Labor	30	25	27	29	35	45	60
Year_1_Prod	0.5	0.05	0.2	0.4	0.7	1	1.5
Year_2_Prod	1.5	0.1	0.5	1	1.8	2.1	2.5
Year_4_Prod	6	0.5	3	5	6	6	6
Year_5_Prod	6	0.5	3	5	6	6	6
Year_9_Prod	6	0.5	3	5	6	6	6
AL k-factor	0.95	0.95	0.95	0.95	0.96	0.98	1
Fuel_Cost	0.45	0.4	0.42	0.44	0.6	1	2
Airline_Int_Rt	7	2	4	6	8	10	12
Tail Comp	0.9	0	0.5	0.75	0.92	0.95	1
Avionics Wt	1	0.9	0.95	0.98	1.05	1.15	1.25

Another risk setup matrix is also determined for the variables of production number and acquisition price, which change with the potential solution. The risk matrix for these variables is illustrated below in Table XX. It contains production numbers and acquisition prices for all five potential solutions. Notice that for production number, not all of the variable range is used for each solution. This effect could have been achieved by creating five different variables, one for each solution. However, it was less time-consuming for both human and computer to have only a single variable over a wide range, rather than five variables over narrower ranges.

Table XX: Risk Setup Matrix for Production Number and Acq$

	Baseline				Risk Setup Matrix			
	0	-3	-2	-1	1	2	3	
Production_Number	650	600	615	625	700	750	850	A300 Stretch
Acq	65	50	55	60	70	75	80	
Production_Number	900	600	700	800	1000	1100	1200	New Twin
Acq	70	55	60	65	75	80	85	
Production_Number	800	600	700	750	900	1000	1100	New Quad
Acq	75	60	65	70	80	85	90	
Production_Number	800	600	700	750	1000	1100	1200	A300 Stretch
Acq	75	65	68	72	78	82	85	& New Quad
Production_Number	1000	700	800	900	1100	1150	1200	New Twin &
Acq	75	60	65	70	80	85	90	Quad

Now consequences are calculated for each uncertainty for each potential solution. This is done by taking the risk matrix, and, for each risk, using the corresponding risk setup matrix to change the variable values and then looking at the performance, airline, and cashflow results. To determine the severity of the consequences, guidelines can be used, but ultimately, the choice is left up to a human decision maker. Some of the guidelines that were used include the total amount of profit relative to the baseline profit, when was the breakeven point (or whether there was a breakeven point), and whether any constraints were violated or a metric was getting close to a constraint. The consequences are the same no matter what the scenario is, so this only needs to be completed once for each potential solution. For uncertainties whose consequences met all performance constraints, some rules of thumb were employed to determine the severity of the consequences, including the amount of degradation in performance and the increase or decrease in cost. A scale of 1 to 5 was employed with one being minimal consequences and five being catastrophic consequences. In general, if the breakeven point was within one year of the baseline and the final profit was within one billion dollars, the consequence was a one. If the aircraft had not reached breakeven point by 2004, the consequence was a four, and it appeared that the aircraft would never breakeven, the consequence was a five. For performance constraints, violating the TOFL constraint was an automatic five for consequences, since technical feasibility must be reached before economic viability is considered.

Probabilities are determined for each risk for each scenario per potential solution. This is a time-consuming process to carry out by hand, but probably cannot be automated as it is necessary to have the human judge whether there is a low, medium, or high probability of occurrence for a particular situation. As there are five scenarios, and the scenarios have different probabilities of occurrence, a weighted average of the scenario's probabilities for each uncertainty is calculated. The probabilities are also on a 1 to 5 scale, with one meaning extremely unlikely and 5 meaning likely. Given a scenario, each risk has a probability of occurring in that scenario. Another scenario may produce a higher or lower probability of occurrence for a particular risk. The cumulative probability of occurrence is calculated with scenarios one and two at a 5% weighting each and scenarios three through five at a 30% weighting each.

The probabilities and consequences associated with each risk are listed in Table XVI through Table XXV. These probabilities and consequences calculated for each uncertainty lead to risk, since risk implies both probability and consequences.

Table XXI: Employment Probabilities and Consequences

Assumption	Risk	Cumulative	Scenarios					Consequence				
		Probability	1	2	3	4	5	Twin	Quad	Derivative	Twin/Quad	Derivative/Quad
Will have, or be able to hire, enough workers to meet demand	Not having enough qualified design engineers	1.3	4	4	1	1	1	3	3	3	3	3
	Not having enough manufacturers--early	1.75	4	1	3	1	1	4	5	4	4	5
	Not having enough manufacturers--late	2.25	2	1	4	2	1	3	4	3	2	4
Accurately anticipate workers costs	Higher turnover rate	2.05	4	1	3	1	2	1	1	1	1	1
	Can't afford to keep workers on during cyclic work cycle	1.15	1	4	1	1	1	0.5	1	0.5	0.5	1
	Workers labor costs increase	3.2	3	1	5	2	3	1	2	2	1	2
	Union boycotts (early in manufacturing cycle)	1.7	2	2	1	1	3	3	5	4	3	5
No language barriers	Workers difficulty communicating between countries	2	1	3	2	3	1	0	0	1	1	1
Pay workers competing wages in different countries	Inability to pay workers competing wages in different countries	1.1	1	3	1	1	1	1	3	2	2	3
	Loss of workforce to American companies	2.35	4	1	3	1	3	1	1	2	2	2
	Worker benefits' cost increases	2.25	1	2	4	2	1	1	2	2	2	2
No cultural problems between workers	Difficulties working between European countries	1.95	2	1	1	3	2	1	1	1	1	1
	Difficulties working with immigrant labor	2.25	2	1	1	3	3	0.5	1	2	1	2
	Inability to import unskilled labor	1.9	1	1	3	2	1	0	0	0	1	0
	Difficulty with communications with outsourced labor	1.65	2	1	2	2	1	0.5	0	1	0	1
Minimal business losses	Loss due to working with outsourced labor markets	2.75	5	2	5	1	2	0	2	2	1	2
Training costs are low compared to productivity	Increased time/cost to effectively training workers in new technology	1.65	2	1	1	1	3	1	1	1	1	1
	Increased time/cost to effectively skill unskilled workers	1.95	2	1	1	3	2	0.5	1	0.5	0.5	1
Mobile workforce	Inability to move worker locations as necessary	2	3	1	3	2	1	1	0	0	1	1
Stable workforce	Work interruptions due to extenuating circumstances	2.65	1	4	4	3	1	2	1	2	2	2

Table XXII: Cultural/Social Probabilities and Consequences

Assumption	Risk	Cumulative	Scenarios					Consequence				
		Probability	1	2	3	4	5	Twin	Quad	Derivative	Twin/Quad	Derivative/Quad
Can sell twin for overseas use	Customers uncomfortable on overseas flights on twin	1.6	1	1	1	2	2	1	1	0.5	0.5	1
More travel & wealth within China	Leveling off of Chinese population	1.7	1	3	2	1	2	1	0.5	0.5	1	0.5
China opening to west	Tension between China and Britain/US over Hong Kong	2.3	3	1	2	1	4	1	1	0	1	1
Little travel to SE Asia	Political opening of SE Asia	1.7	3	1	1	2	2	2	2	3	2	3
There is no change in cultural preferences for American/ European a/c	Asian preference for American aircraft	1.9	1	1	1	3	2	4	4	3	3	4
	Japanese preference for American aircraft	1.8	3	3	1	2	2	2	2	1	1	2
	Middle Eastern preference for American aircraft	1	1	1	1	1	1	2	2	1	1	2
	General preference for status quo	2	1	3	3	2	1	0	-1	-1	-1	0.1
America allows government aid for development	American companies boycott European airframers	1.4	1	3	1	2	1	4	4	3	4	4
	American consumers boycott European airframers	1.65	1	2	1	3	1	2	1	1	1	1
No regional/global epidemics	Epidemic decreases flying public	2.3	2	2	4	2	1	2	3	2	2	3
	Epidemic cuts off S.Asia	1.35	1	2	2	1	1	2	2	2	2	2
	Epidemic cuts off Africa	2.55	1	2	5	2	1	1	2	2	1	2
Social stability	Civil unrest in China	2.1	4	2	1	2	3	1	0.5	0.5	1	0.5
	Fear of flying due to terrorist incidents	2.55	1	2	2	4	2	2	2	2	2	2
	Civil unrest in Eastern Europe	4.35	5	4	4	4	5	1	0	0	0	0

Table XXIII: Economic Probabilities and Consequences

Assumption	Risk	Cumulative	Scenarios					Consequence				
		Probability	1	2	3	4	5	Twin	Quad	Derivative	Twin/Quad	Derivative/Quad
Good global economic conditions	Aircraft financing interest rate rises	1.7	3	1	1	3	1	1	0.5	1	1	1
	European recession	2.1	1	5	2	3	1	2	1	2	2	2
	Asian recession	1.75	1	4	3	1	1	2	1	2	2	2
	American recession	1.8	1	5	2	1	2	2	1	2	2	2
Stable fuel costs	Cost of fuel increase	2.4	3	3	1	5	1	1	0	0.5	0.5	1
New security prevents terrorist attacks	Increase in security costs due to terrorist attacks	3.15	1	2	3	4	3	0	0	0	0	0
4% growth in travel	Business travel decreases	3	2	4	3	2	4	1	0.5	0.5	1	0.5
	Leisure travel decrease	2.1	1	5	2	3	1	2	1	0.5	1	1
Steady unemployment	Unemployment increases	2.7	1	5	4	2	2	1	0.5	0.5	1	0.5
American economy stay strong	Economic growth slows in US	2.7	1	5	4	3	1	0.5	0	0	0	0
	Lower-than-expected growth projections (for reasons not listed above)	2.4	1	5	3	2	2	1	0	0	0	0
European tax structure and subsidies remains same	Decrease in British tax revenues (for reasons not listed above)	2.1	1	5	2	3	1	0.5	0.5	2	0.5	2
	Decrease in French tax revenues (for reasons not listed above)	2.1	1	5	2	3	1	0.5	0.5	2	0.5	2
	Increase in British tax payouts	2.7	1	5	4	3	1	0	0	1	2	1
	Increase in French tax payouts	2.7	1	5	4	3	1	0	0	1	2	1
	Need outside financing for some development	1.45	1	4	1	1	2	1	1	1	2	1
Derivatives are also viable	Derivatives compete with initial for sales	1.85	5	2	2	2	1	1	0.5	0	0.5	0.5

Table XXIV: Government/Political Probabilities and Consequences

Assumption	Risk	Cumulative Probability	Scenarios 1	2	3	4	5	Consequence Twin	Quad	Derivative	Twin/Quad	Derivative/Quad
Future emissions and noise regulations are as predicted	Differences in American/European noise regulations	1	1	1	1	1	1	1	1	1	1	1
	Differences in American/European emissions regulations	1.35	2	1	1	2	1	0.5	0	1	1	1
Middle East stays politically stable	War in the Middle East	2.25	1	2	1	5	1	2	0.5	2	2	2
	Governmental instability in Middle East	2.9	1	3	2	5	2	0.5	0	1	1	1
SE Asia is politically stable	Governmental instability in SE Asia	2.3	2	2	4	1	2	1	1	0.5	1	1
Continued warming of relations between eastern and western Europe	Cooling of relations between East and West	2.25	2	1	3	3	1	1	1	0.5	1	1
	Eastern Europe closes its borders	1.95	1	2	3	2	1	1	1	0.5	1	1
US/China relations get better	Tensions in emerging relations between US and China	1.95	2	1	3	1	2	2	3	2	2	3
Britain/India relations stay good	Cooling of India/Britain relations	1.65	2	1	3	1	1	0.5	2	2	1	2
Nuclear powers keep treaties	Nuclear war/proliferation threat	1.9	1	1	1	3	2	1	0.5	0	0.5	0.5
South American political problems stop	Governmental instability in Latin America	2.25	2	1	4	1	2	2	2	2	2	2
US Government has no political concerns with European a/c	US will allow American companies to subcontract on this a/c	1.75	2	3	2	1	2	-2	-1	0	1	0
	US doesn't leave Airbus alone over government subsidizing of aircraft	1	1	1	1	1	1	1	2	2	2	2
	US will easily allow American airlines to buy European aircraft	1.7	1	3	1	2	2	-0.5	-1	-0.5	-1	0
	Boeing will allow American companies to work sub-contract on this aircraft	1.4	2	2	1	1	2	0.5	-1	2	0.5	2
Can develop a/c w/o borrowing excessive money	Cannot get all wanted French funding for a/c	2.35	1	4	3	2	2	0.5	0.5	0	0.5	0.5
	Cannot get all wanted British funding for this a/c	2.65	1	4	3	3	2	0.5	0.5	0	0.5	0.5
	Cannot get enough French funding for this a/c	1.8	1	5	2	2	1	4	5	4	5	5
	Cannot get enough British funding for this a/c	2.1	1	5	2	3	1	4	5	4	5	5
Can get everything certified on schedule	Time/cost to get 2 similar a/c certified at same time	0									2	2
	Time/cost get ETOPS certification before put in service (twin only)	2	1	3	1	4	1	1	0	2	2	2
Will be able to make a/c	Cannot build new factory in Toulouse	1.95	2	1	2	1	3	2	0	1	1	1

Table XXV: Technological Probabilities and Consequences

Assumption	Risk	Cumulative Probability	Scenarios 1	2	3	4	5	Consequence Twin	Quad	Derivative	Twin/Quad	Derivative/Quad
Can create larger, composite tail piece	Increasing time/cost to create larger, composite tail piece	1.9	1	1	2	3	1	1	1	2	1	2
Will be able to use more Composites	Unable to use more composites for non-structural parts	2.65	2	3	3	4	1	1	1	2	1	2
Can easily integrate a/c parts	Inability to integrate a/c parts from multiple manufacturers	2.3	3	1	3	1	3	0.5	0	1	0.5	1
Can use A300 cross-section	Inability to use existing aircraft cross-section	2.05	2	3	2	2	2	4	2	2	2	2
Can meet 6000 nmi range	Cannot meet 6000 nmi range wanted	2.05	2	3	2	2	2	1	1	2	1	2
New lightweight AL can be used	Cannot use lightweight aluminum alloys	2.6	1	3	3	4	1	5	5	5	5	5
Can create carbon-fiber tail	Cannot use carbon-fiber for tail	2	1	3	2	3	1	1	0.5	0.5	2	0.5
	Cannot add passengers in lower berth--cargo displacement	1.3	1	1	1	2	1	0.5	0.5	1	0.5	1
Easy-load cargo pellets	Cannot design configuration to easily load cargo pallets	1.05	1	2	1	1	1	0.5	0.5	1	0.5	1
Competitor's a/c has no significant advantage	Competitor aircraft more fuel efficient than anticipated	2	3	1	1	3	2	3	3	3	3	3
	Competitor aircraft/engine less costly	3.15	2	1	1	4	5	2	3	2	2	3
Can create best aircraft in industry	Time/cost to create most fuel-efficient a/c in industry	2.3	3	1	1	3	3	0.5	1	1	1	1
	Time/cost to create lowest per-seat-mile cost in industry	2.3	3	1	1	3	3	1	2	2	2	2
	Cannot use winglet drag reduction technology	1	1	1	1	1	1	0	0	0	0	0
One a/c platform for twin and quad	Cannot create one a/c body to support both twin and quad	1.4	1	3	1	2	1				2	
Can use common cockpit with A320 and all updates	Cannot create electronic fly-by-wire system	1.05	1	2	1	1	1	1	0.5	1	2	1
	Inability to use more digital display in cockpit	2.05	2	3	2	2	2	1	0.5	1	2	1
	Inability to create a common-cockpit with A320 for larger aircraft	2	2	2	2	2	2	2	1	2	2	2
No industry-altering technology	Competitor's industry-altering technology	1.65	2	1	1	1	3	5	4	3	3	4
Derivatives can be created	Cannot create derivatives using same technology	1	1	1	1	1	1	1	1		1	1

These probabilities and consequences are used to calculate the actual risk associated with each uncertainty. Some of the risks are larger than others. The larger risks may be able to be mitigated, as will be shown in the next step. The final risk calculation is illustrated in the following five figures. The calculation is carried out using Equation 6, from above:

$$R(x) = p_x * 2^{C_x} \tag{6}$$

These risk calculations show which uncertainties have the largest risk associated with them, and, consequently, what risks are the best candidates for mitigation. While not all risks can be mitigated by better engineering design, it will be easy to see the monetary consequences of those that can be mitigated.

Table XXVI: Employment Risk Analysis

Assumption	Risk	Risk: Twin	Quad	Derivative	Twin/Quad	A300/Quad
Will have, or be able to hire, enough workers to meet demand	Not having enough qualified design engineers	10.40	10.40	10.40	10.40	10.40
	Not having enough manufacturers--early	28.00	56.00	28.00	28.00	56.00
	Not having enough manufacturers--late	18.00	36.00	18.00	9.00	36.00
Accurately anticipate workers costs	Higher turnover rate	4.10	4.10	4.10	4.10	4.10
	Can't afford to keep workers on during cyclic work cycle	1.63	2.30	1.63	1.63	2.30
	Workers labor costs increase	6.40	12.80	12.80	6.40	12.80
	Union boycotts (early in manufacturing cycle)	13.60	54.40	27.20	13.60	54.40
No language barriers	Workers difficulty communicating between countries	2.00	2.00	4.00	4.00	4.00
Pay workers competing wages in different countries	Inability to pay workers competing wages in different countries	2.20	8.80	4.40	4.40	8.80
	Loss of workforce to American companies	4.70	4.70	9.40	9.40	9.40
	Worker benefits' cost increases	4.50	9.00	9.00	9.00	9.00
No cultural problems between workers	Difficulties working between European countries	3.90	3.90	3.90	3.90	3.90
	Difficulties working with immigrant labor	3.18	4.50	9.00	4.50	9.00
	Inability to import unskilled labor	1.90	1.90	1.90	3.80	1.90
	Difficulty with communications with outsourced labor	2.33	1.65	3.30	1.65	3.30
Minimal business losses	Loss due to working with outsourced labor markets	2.75	11.00	11.00	5.50	11.00
Training costs are low compared to productivity	Increased time/cost to effectively training workers in new technology	3.30	3.30	3.30	3.30	3.30
	Increased time/cost to effectively skill unskilled workers	2.76	3.90	2.76	2.76	3.90
Mobile workforce	Inability to move worker locations as necessary	4.00	2.00	2.00	4.00	4.00
Stable workforce	Work interruptions due to extenuating circumstances	10.60	5.30	10.60	10.60	10.60

Table XXVII: Cultural/Social Risk Analysis

Assumption	Risk	Risk: Twin	Quad	Derivative	Twin/Quad	A300/Quad
Can sell twin for overseas use	Customers uncomfortable on overseas flights on twin	3.20	3.20	2.26	2.26	3.20
More travel & wealth within China	Leveling off of Chinese population	3.40	2.40	2.40	3.40	2.40
China opening to west	Tension between China and Britain/US over Hong Kong	4.60	4.60	2.30	4.60	4.60
Little travel to SE Asia	Political opening of SE Asia	6.80	6.80	13.60	6.80	13.60
There is no change in cultural preferences for American/ European a/c	Asian preference for American aircraft	30.40	30.40	15.20	15.20	30.40
	Japanese preference for American aircraft	7.20	7.20	3.60	3.60	7.20
	Middle Eastern preference for American aircraft	4.00	4.00	2.00	2.00	4.00
	General preference for status quo	2.00	1.00	1.00	1.00	2.14
America allows government aid for development	American companies boycott European airframers	22.40	22.40	11.20	22.40	22.40
	American consumers boycott European airframers	6.60	3.30	3.30	3.30	3.30
No regional/global epidemics	Epidemic decreases flying public	9.20	18.40	9.20	9.20	18.40
	Epidemic cuts off S.Asia	5.40	5.40	5.40	5.40	5.40
	Epidemic cuts off Africa	5.10	10.20	10.20	5.10	10.20
Social stability	Civil unrest in China	4.20	2.97	2.97	4.20	2.97
	Fear of flying due to terrorist incidents	10.20	10.20	10.20	10.20	10.20
	Civil unrest in Eastern Europe	8.70	4.35	4.35	4.35	4.35

Table XXVIII: Economic Risk Analysis

Assumption	Risk	Risk: Twin	Quad	Derivative	Twin/Quad	A300/Quad
Good global economic conditions	Aircraft financing interest rate rises	3.40	2.40	3.40	3.40	3.40
	European recession	8.40	4.20	8.40	8.40	8.40
	Asian recession	7.00	3.50	7.00	7.00	7.00
	American recession	7.20	3.60	7.20	7.20	7.20
Stable fuel costs	Cost of fuel increase	4.80	2.40	3.39	3.39	4.80
New security prevents terrorist attacks	Increase in security costs due to terrorist attacks	3.15	3.15	3.15	3.15	3.15
4% growth in travel	Business travel decreases	6.00	4.24	4.24	6.00	4.24
	Leisure travel decrease	8.40	4.20	2.97	4.20	4.20
Steady unemployment	Unemployment increases	5.40	3.82	3.82	5.40	3.82
American economy stay strong	Economic growth slows in US	3.82	2.70	2.70	2.70	2.70
	Lower-than-expected growth projections (for reasons not listed above)	4.80	2.40	2.40	2.40	2.40
European tax structure and subsidies remains same	Decrease in British tax revenues (for reasons not listed above)	2.97	2.97	8.40	2.97	8.40
	Decrease in French tax revenues (for reasons not listed above)	2.97	2.97	8.40	2.97	8.40
	Increase in British tax payouts	2.70	2.70	5.40	10.80	5.40
	Increase in French tax payouts	2.70	2.70	5.40	10.80	5.40
	Need outside financing for some development	2.90	2.90	2.90	5.80	2.90
Derivatives are also viable	Derivatives compete with initial for sales	3.70	2.62	1.85	2.62	2.62

Table XXIX: Government/Political Risk Analysis

Assumption	Risk	Risk				
		Twin	Quad	Derivative	Twin/Quad	A300/Quad
Future emissions and noise regulations are as predicted	Differences in American/European noise regulations	2.00	2.00	2.00	2.00	2.00
	Differences in American/European emissions regulations	1.91	1.35	2.70	2.70	2.70
Middle East stays politically stable	War in the Middle East	9.00	3.18	9.00	9.00	9.00
	Governmental instability in Middle East	4.10	2.90	5.80	5.80	5.80
SE Asia is politically stable	Governmental instability in SE Asia	4.60	4.60	3.25	4.60	4.60
Continued warming of relations between eastern and western Europe	Cooling of relations between East and West	4.50	4.50	3.18	4.50	4.50
	Eastern Europe closes its borders	3.90	3.90	2.76	3.90	3.90
US/China relations get better	Tensions in emerging relations between US and China	7.80	15.60	7.80	7.80	15.60
Britain/India relations stay good	Cooling of India/Britain relations	2.33	6.60	6.60	3.30	6.60
Nuclear powers keep treaties	Nuclear war/proliferation threat	3.80	2.69	1.90	2.69	2.69
South American political problems stop	Governmental instability in Latin America	9.00	9.00	9.00	9.00	9.00
US Government has no political concerns with European a/c	US will allow American companies to subcontract on this a/c	0.44	0.88	1.75	3.50	1.75
	US doesn't leave Airbus alone over government subsidizing of aircraft	2.00	4.00	4.00	4.00	4.00
	US will easily allow American airlines to buy European aircraft	1.20	0.85	1.20	0.85	1.70
	Boeing will allow American companies to work sub-contract on this aircraft	1.98	0.70	5.60	1.98	5.60
Can develop a/c w/o borrowing excessive money	Cannot get all wanted French funding for a/c	3.32	3.32	2.35	3.32	3.32
	Cannot get all wanted British funding for this a/c	3.75	3.75	2.65	3.75	3.75
	Cannot get enough French funding for this a/c	28.80	57.60	28.80	57.60	57.60
	Cannot get enough British funding for this a/c	33.60	67.20	33.60	67.20	67.20
Can get everything certified on schedule	Time/cost to get 2 similar a/c certified at same time	0.00	0.00	0.00	0.00	0.00
	Time/cost get ETOPS certification before put in service (twin only)	4.00	2.00	8.00	8.00	8.00
Will be able to make a/c	Cannot build new factory in Toulouse	7.80	1.95	3.90	3.90	3.90

Table XXX: Technological Risk Analysis

Assumption	Risk	Risk				
		Twin	Quad	Derivative	Twin/Quad	A300/Quad
Can create larger, composite tail piece	Increasing time/cost to create larger, composite tail piece	3.80	3.80	7.60	3.80	7.60
Will be able to use more Composites	Unable to use more composites for non-structural parts	5.30	5.30	10.60	5.30	10.60
Can easily integrate a/c parts	Inability to integrate a/c parts from multiple manufacturers	3.25	2.30	4.60	3.25	4.60
Can use A300 cross-section	Inability to use existing aircraft cross-section	32.80	8.20	8.20	8.20	8.20
Can meet 6000 nmi range	Cannot meet 6000 nmi range wanted	4.10	4.10	8.20	4.10	8.20
New lightweight AL can be used	Cannot use lightweight aluminum alloys	83.20	83.20	83.20	83.20	83.20
Can create carbon-fiber tail	Cannot use carbon-fiber for tail	4.00	2.83	2.83	8.00	2.83
	Cannot add passengers in lower berth--cargo displacement	1.84	1.84	2.60	1.84	2.60
Easy-load cargo pellets	Cannot design configuration to easily load cargo pallets	1.48	1.48	2.10	1.48	2.10
Competitor's a/c has no significant advantage	Competitor aircraft more fuel efficient than anticipated	16.00	16.00	16.00	16.00	16.00
	Competitor aircraft/engine less costly	12.60	25.20	12.60	12.60	25.20
Can create best aircraft in industry	Time/cost to create most fuel-efficient a/c in industry	3.25	4.60	4.60	4.60	4.60
	Time/cost to create lowest per-seat-mile cost in industry	4.60	9.20	9.20	9.20	9.20
	Cannot use winglet drag reduction technology	1.00	1.00	1.00	1.00	1.00
One a/c platform for twin and quad	Cannot create one a/c body to support both twin and quad	1.40	1.40	1.40	5.60	1.40
Can use common cockpit with A320 and all updates	Cannot create electronic fly-by-wire system	2.10	1.48	2.10	4.20	2.10
	Inability to use more digital display in cockpit	4.10	2.90	4.10	8.20	4.10
	Inability to create a common-cockpit with A320 for larger aircraft	8.00	4.00	8.00	8.00	8.00
No industry-altering technology	Competitor's industry-altering technology	52.80	26.40	13.20	13.20	26.40
Derivatives can be created	Cannot create derivatives using same technology	2.00	2.00	1.00	2.00	2.00

Now that the risk has been calculated for each assumption over the five categories, it can be compared between potential solutions. A risk comparison between potential solutions is illustrated in Figure 49. The y-axis contains a measure of risk. In the comparison, the derivative stretch aircraft version has the lowest overall risk. This is expected, since the stretch aircraft would be a derivative, while the other aircraft would be new. The derivative aircraft also has the lowest governmental risk, since it is likely to be easier to acquire safety and other certifications. Of the three new aircraft, the new four-engine aircraft has the largest absolute technology risk. As there are no other newer four-engine aircraft in this class, it makes sense that the technology risk would be greater for an aircraft that is first in its class to be developed than for an aircraft making inroads into an existing class of aircraft. The same reasoning applies to the economic risk: the economic risk is higher for the twin-engine aircraft because it has to compete in a market where there are other aircraft, while the four-engine aircraft is not competing in such a market. The aircraft combination option with the most risk is the derivative stretch aircraft and the new four-engine aircraft. The increased risk may be due to the long time before breakeven point for the baseline aircraft and the high potential for a non-viable aircraft combination.

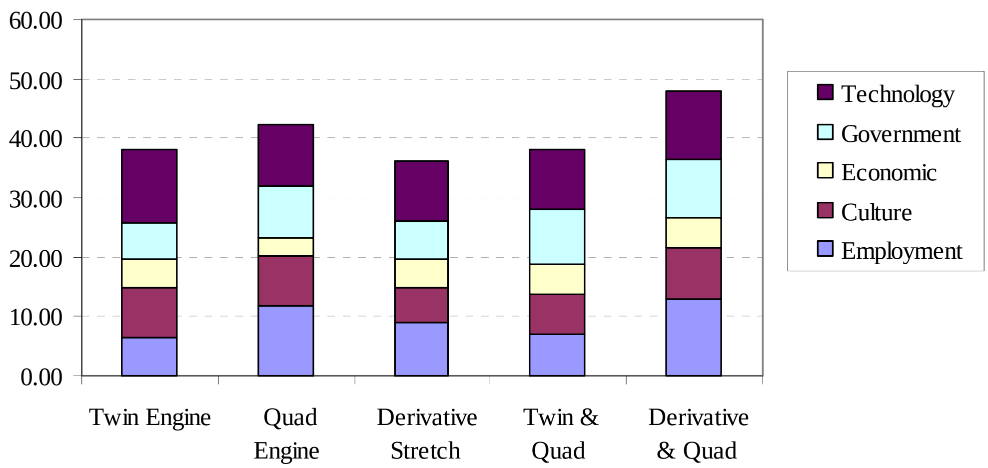

Figure 49: Total Risk Comparison Between Potential Solutions

Risk can be compared not only between different potential solutions, but also between scenarios for a particular solution. In Figure 50, there is a comparison of risk between the five scenarios for a twin-engine aircraft and four-engine aircraft. For both solutions options, scenario two has the largest risk. This is unsurprising, since that scenario is designed to be the worst-case scenario. Interestingly, the governmental risk for that scenario is significantly larger for the four-engine aircraft option than for the twin aircraft only. The larger sunk cost and additional reliance on government funding should account for this discrepancy. In both cases, scenario five is the lowest risk scenario, since it involves so much new technology development. As scenario one was designed to be the lowest risk scenario, this is an unexpected finding, but again is probably due to the technology boom that aids the aerospace industry. It should also be noted that scenarios one and five have the smallest economic risk. This is also expected since for a best-case or very technology dependent economy an aircraft manufacturer should do well. On a final note, the employment risk is largest for scenario one, the best-case scenario, since employees will be difficult to hire and will demand more money when economic conditions are generally good.

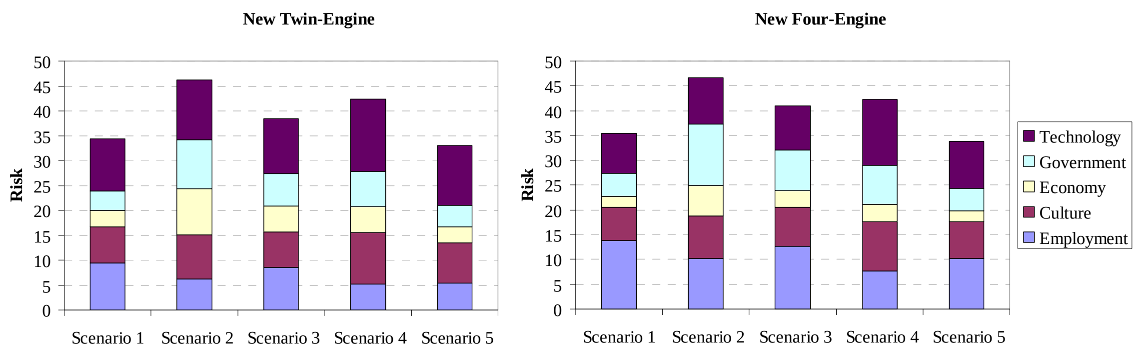

Figure 50: Comparison of Risk Across Scenarios

These risk analyses take into account the risk associated with the five different categories. It is easy to compare the risk between the different solutions; however, it can be difficult to compare only the risk and determine the best solution for a given situation. Other factors, including manufacturer and airline economic and performance factors, must also be compared and compared with the program's risk. This comparison is completed using a TOPSIS model in the decision support phase of this process and will be explained in Section 6.3.

Now that all the uncertainties have been analyzed and their risk calculated, a risk mitigation procedure can be put in place. The risk analysis process carried out here allows the decision maker to see what risks are large and what ones are small. The large risks need to be mitigated, if possible, or tracked to determine whether they are getting larger or smaller with time. While this procedure is designed to be completed early in the concept design phase, other risk analysis processes are designed to be completed later in design. Some of these procedures can be used to track risk and determine whether it is increasing or decreasing with time, and, if it is increasing, what mitigation processes can be put into place to decrease the risk at a later date.

6.2.4 Step 8: Risk Mitigation

Now that the risk analysis process is completed and the user knows which uncertainties pose the largest risk, it is time to see about mitigating some of the risk. Risk mitigation is traditionally a process in which a specific type of risk is analyzed and then a person (or group) determines what steps are necessary to take to decrease that risk. In this case, that process is slightly different. The risk mitigation model here only helps the user determine the effects of mitigating risk, not the process one should go through to complete a risk mitigation procedure.

In order to complete this risk mitigation, the first thing to be done is to determine which risks can be mitigated and which cannot. It is important to determine what risks can be mitigated by engineering design, because if risks cannot be mitigated they need to be carefully tracked. For those risks that can be mitigated, it is important to know the cost in both dollars and performance to mitigate risk. Determining which risks can be mitigated is relatively straightforward. Anything that the design engineers, manufacturers, or the company in general can change is a risk that can be mitigated. For example, employment risk is on the left side of Figure 51. There are many risks that the aircraft manufacturer can mitigate. The manufacturer has the ability to hire more workers now to decrease the risk of not having enough workers later, and can also offset the increased cost of hiring workers when they become more expensive. The manufacturer can also set up a corporate culture where cooperation between countries and cultures is the norm, which will decrease the potential for problems with immigrant labor or potential communication problems between workers of different cultures or nationalities. Some risks cannot be mitigated. Work force interruptions due to extenuating circumstances, such as terrorist events, or high workforce turnover rates due to cultural shifts, not low pay, cannot be changed by management. Figure 51 through Figure 53 show which risks can be mitigated with a check box. Those that cannot be mitigated are still to be tracked.

☐	Not having enough qualified design engineers
☐	Not having enough manufacturers--early
☐	Not having enough manufacturers--late
	Workforce stability (turnover rate)
	Can't afford to keep workers on during cyclic work cycle
☐	Workers costs increase
	Union boycotts (early in manufacturing cycle)
☐	Workers' difficulty communicating between countries
☐	Inability to pay workers competing wages in different countries
	Loss of workforce to American companies
☐	Worker benefits' cost increases
☐	Difficulties working between European countries
☐	Difficulties working with immigrant labor
	Inability to import unskilled labor
☐	Communications with outsourced labor
	Loss due to corruption/graft/money laundering in outsourced labor markets
☐	Time/cost to effectively training workers in new technology
☐	Time/cost to effectively skill unskilled workers
☐	Ability to move worker locations as necessary
	Work interruptions due to extenuating circumstances (war, terrorist attack, epidem

☐	Increasing time/cost to create larger, composite tail piece
	unable to use more composites for non-structural parts
☐	inability to integrate a/c parts from multiple manufacturers
☐	Inability to use A300 cross-section (widebody only)
☐	Cannot meet 6000 nmi range wanted
☐	Cannot use lightweight aluminum alloys
☐	Cannot use carbon-fiber composite tail
	Cannot add passengers in lower berth--cargo displacement (widebody only)
☐	cannot design configuration to easily load cargo pallets
	Competitor aircraft more fuel efficient than anticipated
	Competitor aircraft/engine less costly
☐	Time/cost to create most fuel-efficient a/c in industry
☐	Time/cost to create lowest per-seat-mile cost in industry
	Utilization of winglet drag reduction technology
	can create one a/c body to support both twin and quad (widebody only)
☐	cannot create electronic fly-by-wire system
☐	Inability to use more digital display in cockpit
☐	Inability to create a common-cockpit with A320 for larger aircraft
	competitor's industry-altering technology
	cannot create derivatives using same technology

Figure 51: Employment (left) and Technology (right) Risks That Can be Mitigated

☐	Aircraft financing interest rate rises
☐	European recession
	Asian recession
	American recession
	Cost of fuel increase
	Increase in airline payouts and security costs due to terrorist attacks
	Business travel decreases
	Leisure travel decrease
	Unemployment increases
	Economic growth slows in US
	lower-than-expected growth projections (for reasons not listed above)
	decrease in British tax revenues (for reasons not listed above)
	decrease in French tax revenues (for reasons not listed above)
	increase in British tax payouts
	increase in French tax payouts
☐	need to finance some development
☐	Derivatives compete with initial for sales

	Increase in telecommunications causes decrease in travel
	Customers uncomfortable on overseas flights on twin
	Leveling off of Chinese population
	Tension between China and Britain/US over Hong Kong
	Opening of SE Asia
	Asian preference for American aircraft
	Japanese preference for American aircraft
	Middle Eastern preference for American aircraft
	General preference for status quo
☐	American companies boycott European airframers
☐	American consumers boycott European airframers
	Epidemic decreases flying public
	Epidemic cuts off S Asia
	Epidemic cuts off Africa
	Civil unrest in China
	Fear of flying due to terrorist incidents
	Civil unrest in Eastern Europe

Figure 52: Economic (left) and Cultural (right) Risks That Can be Mitigated

☐	Differences in American/European noise regulations
☐	Differences in American/European emissions regulations
	War in the Middle East
	Governmental instability in Middle East
	Governmental instability in SE Asia
	Cooling of relations between East and West
	Eastern Europe closes its borders
	Tensions in emerging relations between US and China
	Cooling of India/Britain relations
	Nuclear war/proliferation threat
	Governmental instability in Latin America
☐	US will not allow American companies to subcontract on this a/c
☐	US doesn't leave Airbus alone over government subsidizing of aircraft
☐	US will easily allow American airlines to buy European aircraft
	Boeing will allow American companies to work sub-contract on this aircraft
☐	Cannot get all wanted French funding for a/c
☐	Cannot get all wanted British funding for this a/c
☐	Cannot get enough French funding for this a/c
☐	Cannot get enough British funding for this a/c
	Time/cost to get 2 similar a/c certified at same time (widebody only)
☐	Time/cost get ETOPS certification before put in service (twin only)
☐	cannot build new factory in Toulouse

Figure 53: Governmental Risks That Can be Mitigated

The mitigation procedure itself is carried out as detailed in Chapter 5. The first mitigation step completed was the technological mitigation step. It involved defining technology positions. The assumed new technology impact was labeled point zero. Fallback point one was between the new and existing technology, fallback point two was also between new and existing technology and fallback point three was defined as existing technology. The three technology variables that cover the technology space examined here are the tail composition, the scale factor on the weight of aluminum, and the scale factor on the avionics weight. Point zero has a tail composition of 0.9, an aluminum weight scale factor of 0.95, and an avionics weight scale factor of 1. Point one, the first fallback position, has a tail composition of 0.75, an aluminum weight scale factor of 0.96, and an avionics weight scale factor of 1.05. The second fallback position has a tail composition of 0.5, an aluminum weight scale factor of 0.98, and an avionics weight scale factor of 1.15. The third and final fallback position has a tail composition of 0.0 (as in, all aluminum), an aluminum weight scale factor of 1.00, and an avionics weight scale factor of 1.25. Moving to a fallback position for the technology factors allows the decision maker to see the impact on performance and economic metrics of interest if the technology does not do what it is intended to do.

Seeing the economic impact of mitigating risk is a more complicated process, but is completed as outlined in Chapter 5. The five aircraft options are examined to determine whether changes in variables lead to linear (or almost linear) changes in metric value. It was found that most metrics are either generally linearly increasing or decreasing with changes in variables or the variable has little effect on the metric. It is also noted that changes in variables tend to affect a set of metrics similarly; for example, increasing the manufacturing labor rate increases the sustaining costs for all years at approximately the same rate. In these cases, one risk mitigation matrix can be completed for each aircraft or aircraft pair using only a limited number of metrics: first unit cost, RDT&E cost, and sustaining cost. Relative changes in the cost of these metrics are put into a set of mapping tables for each aircraft. Part of one of these tables is below in Table XXXI. As can be seen in the Figure, not every variable has an impact on every metric that makes up the cashflow.

Table XXXI: Mitigation Impact Matrix

Assumption	Uncertainty							
		Years_RDTE		Prod_#	AL_Cost		ENG_Labor	
		RDT&E	Sust	Sust	Sust	FUC	RDT&E	Sust
Will have, or be able to hire, enough workers to meet demand	Not having enough qualified design engineers	0.000	-0.077	-0.154	0.000	0.000	0.307	0.054
	Not having enough manufacturers--early	0.000	0.000	-0.154	0.000	0.000	0.000	0.000
	Not having enough manufacturers--late	0.000	0.000	-0.084	0.000	0.000	0.000	0.000
Accurately anticipate workers costs	Workforce stability (turnover rate)	0.000	-0.037	-0.084	0.000	0.000	0.061	0.014
	Can't afford to keep workers on during cyclic work cycle	0.000	0.000	0.000	0.000	0.000	0.061	0.014
	Workers costs increase	0.000	0.000	0.000	0.000	0.000	0.183	0.048
	Union boycotts (early in manufacturing cycle)	0.000	0.000	-0.084	0.059	0.119	0.000	0.000
No language barriers	Workers difficulty communicating between countries	0.000	-0.037	0.000	0.000	0.000	0.000	0.000
Pay workers competing wages in different countries	Inability to pay workers competing wages in different countries	0.000	0.000	0.000	0.059	0.119	0.061	0.014
	Loss of workforce to American companies	0.000	-0.037	0.000	0.000	0.000	0.183	0.048
	Worker benefits' cost increases	0.000	0.000	0.000	0.000	0.000	0.183	0.048
No cultural problems between workers	Difficulties working between European countries	0.000	-0.077	0.000	0.000	0.000	0.000	0.000
	Difficulties working with immigrant labor	0.000	0.000	0.000	0.000	0.000	0.000	0.000
	Inability to import unskilled labor	0.000	0.000	0.000	0.000	0.000	0.000	0.000
	Communications with outsourced labor	0.000	-0.037	0.000	0.000	0.000	0.000	0.000
Minimal bribe losses	Loss due to corrpuption/graft/money laundering in outsourced labor markets	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Training costs are low compared to productivity	Time/cost to effectively training workers in new technology	0.000	-0.037	0.000	0.000	0.000	0.061	0.014
	Time/cost to effectively skill unskilled workers	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Mobile workforce	Ability to move worker locations as necessary	0.000	0.000	0.000	-0.053	-0.106	0.000	0.000
Stable workforce	Work interruptions due to extenuating circumstances (war, terrorist attack, epidemic	0.000	-0.077	-0.084	0.000	0.000	0.000	0.000

This process is set up to show the effects of mitigating risk by planning up front to spend the money that would be spent if that risk came to pass. For example, if one of the risks is not having enough design engineers, then the cost of fully mitigating that risk would be the cost of hiring those engineers. When one of the risks is checked for mitigation, the matrix is used to detail how much of an increase (or decrease) in cost it would be for that risk to be mitigated. For example, if the one of the risks chosen for mitigation has an impact on the first unit cost of 0.1, or 10%, the first unit cost would increase 10% over the current value if the risk was fully mitigated. Risks can be mitigated partially or fully, to whatever extent the decision maker is willing to pay for the decrease in risk.

Now that a risk mitigation module has been put in place with the risk analysis module, it is time to figure out how to use this data and information in such a fashion that it is useful for decision support. If the data cannot be visualized and trade studies cannot be completed with it, the process is not useful in engineering conceptual design.

6.3 Decision Support

Unlike the two previous focus areas, which were very defined, the decision support focus area is more nebulous. The goal of decision support is to create an environment or interface that allows for tradeoffs and game-playing with different choices for problem solutions, scenarios, and risk mitigation practices. The ability to see the effects of changing technology, increasing fuel costs, or decreasing production numbers, as well as risk mitigation tactics, is very important to making good decisions. In order to do all of these things, and to see the effects of all those changes on various metrics of interest, an MS Excel® interface was created. This interface has many parts, but all work together to allow for trade studies and game-playing types of analyses.

The first part of the interface to see and interact with is the risk mitigation check boxes. The interface contains the list of assumptions and the risks associated with not meeting those assumptions. The risks that have the potential to be mitigated, that is, those that can be mitigated through either engineering design or other engineering or management decisions have check-boxes next to them. To see the economic and performance effects of mitigating these risks, the boxes need to be checked. Checking the risk mitigation boxes only allows the user to choose which risks he wants to examine the effects of mitigating; it does not show the effect of mitigating the risk by itself. A sample of the risk mitigation check boxes is illustrated in Figure 54. This Figure shows two snapshots of part of the risk mitigation interface. In the top snapshot, no risks are selected for mitigation, while in the bottom snapshot two risks are selected for potential mitigation. Now that these risks are selected, it is possible to see the effects of mitigating them for any of the potential solutions.

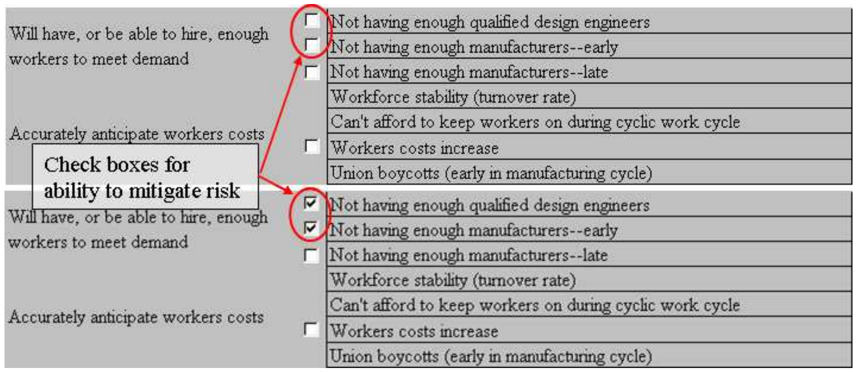

Figure 54: Check Boxes for Risk Mitigation

Now that the risk mitigation check boxes have been explained, once the mitigation boxes have been checked, those risks can be reduced. Each uncertainty has a baseline risk that was calculated in the risk analysis step of this process. Those baseline risk values are displayed, along with a slide bar allowing for decreases in risk to be input by the user. Figure 55 illustrates the baseline risk associated with each uncertainty, as well as the ability to change and decrease that risk for some uncertainties. Decreasing the risk has the potential to change the performance and economic characteristics of the problem. While the problem framed with all initial assumptions may point to a particular potential solution, the problem as it was originally posed may have too much risk for the decision makers to be comfortable choosing a design solution. By decreasing the risk, the best solution to the problem may change. It is also easy to see on the graphic in Figure 55 which uncertainties have high risk associated with them that cannot be mitigated. These risks must be tracked throughout the design process.

Mitigating the risks as demonstrated above will change the performance and economic metric values, but so will changing some of the aircraft variables. Games can be played and trade studies can be completed with some of these variables, too. This part of the interface also contains the technology position, from point zero to point three. This part of the interface gives the user the ability to see the effects of changes in production number, aircraft sale price, and fuel cost on performance and economic metrics. Since these are market variables and not directly under the control of the manufacturer, it is important to see their effects even outside of the normal risk mitigation process. Once again, these variables are on slide bars to facilitate trade studies or deterministic scenario game-playing.

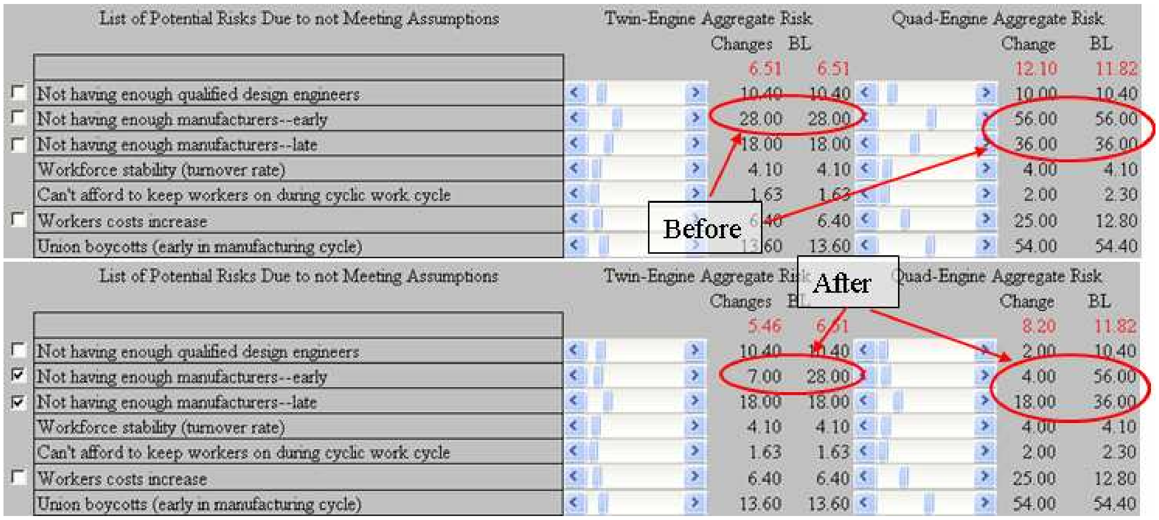

Figure 55: Scrollbars for Game-Playing and Trade Studies

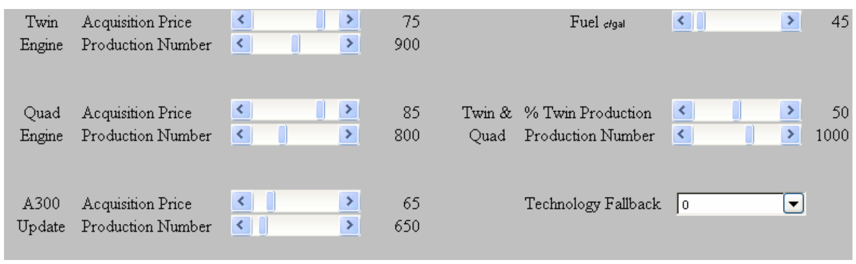

Figure 56: Variable Scrollbars for Game-Playing and Trade Studies

Having the ability to change all of these variables, risk levels, etc creates a very powerful interface for the user. He can see the effects of many different types of game-playing: he can complete trade studies where he determines the largest benefit/cost ratio for risk reduction, or he can see what happens if the aircraft price decreases due to a future not envisioned by either the scenarios or the design engineers in their assumption gathering procedure.

Being able to see the effects of these changes is very important. Performance metrics must be available for comparison between the initial baseline aircraft and any changes due to technology point changes or potential risk mitigation strategies. In Figure

57, the TOFL and fuelburn/ASM for the design range are illustrated. On the left is the baseline aircraft at technology point zero, while on the right is technology point three.

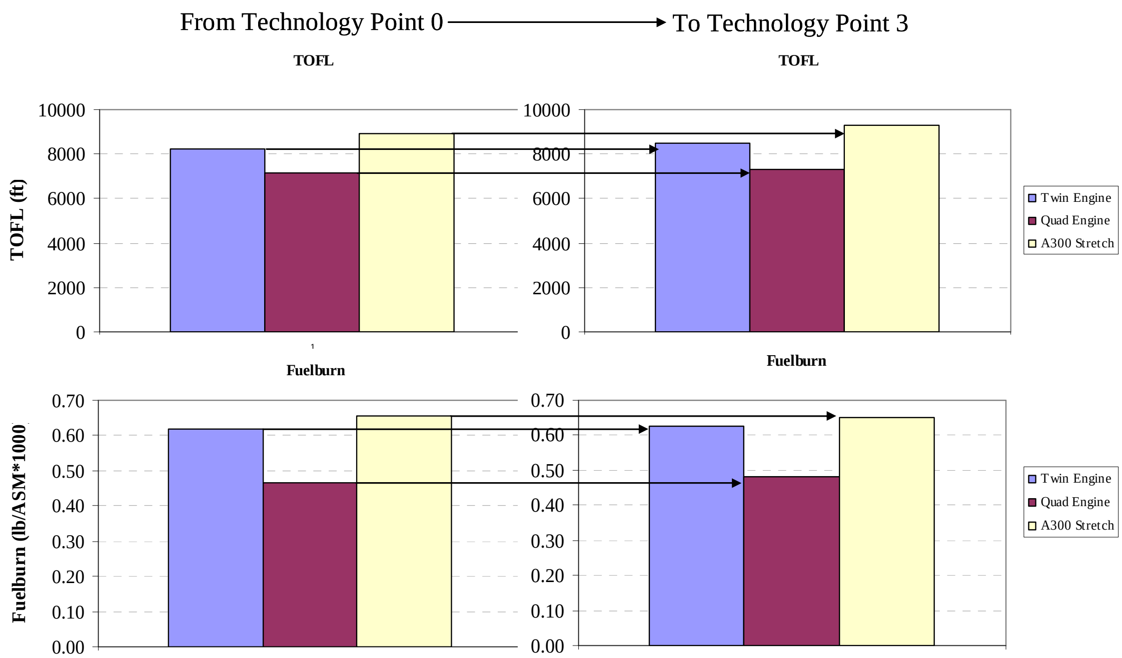

Figure 57: Changes in Performance Metrics from Effects of Changing Technology Points

As expected, as one goes from technology point zero, or all new technology, to technology point three, existing technology, there is an increase TOFL and fuelburn/ASM. Since the purpose of the new technologies was to decrease aircraft weight and, by extension, decrease fuelburn, this is the expected result. Other performance metrics, including TOGW and landing field lengths, are also available for comparison. Any metric of choice can be added to the interface as necessary.

Along with having performance metrics for each aircraft, an airframer's cashflow is displayed for each potential solution concept. One such cashflow, the one for both the new twin-engine and the new four-engine aircraft, is illustrated in Figure 58. This cashflow contains the baseline solution as well as the 1% and 99% solutions gathered from the scenario-based Monte Carlo analysis and a new cashflow based on any changes from the baseline. The 1% and 99% solutions are there for comparison purposes, so the user knows that if he is close to or over those lines that a particular outcome is unlikely.

The changes from the baseline are important, since that curve illustrates the cost of mitigating a risk (or set of risks) or not meeting a market assumption. The cashflow is a powerful tool since, if an aircraft meets all of its performance requirements, decisions will be primarily based on the potential of earning money for the manufacturer. Therefore, it is an important piece of information to have available.

Cashflow--New Twin and Quad

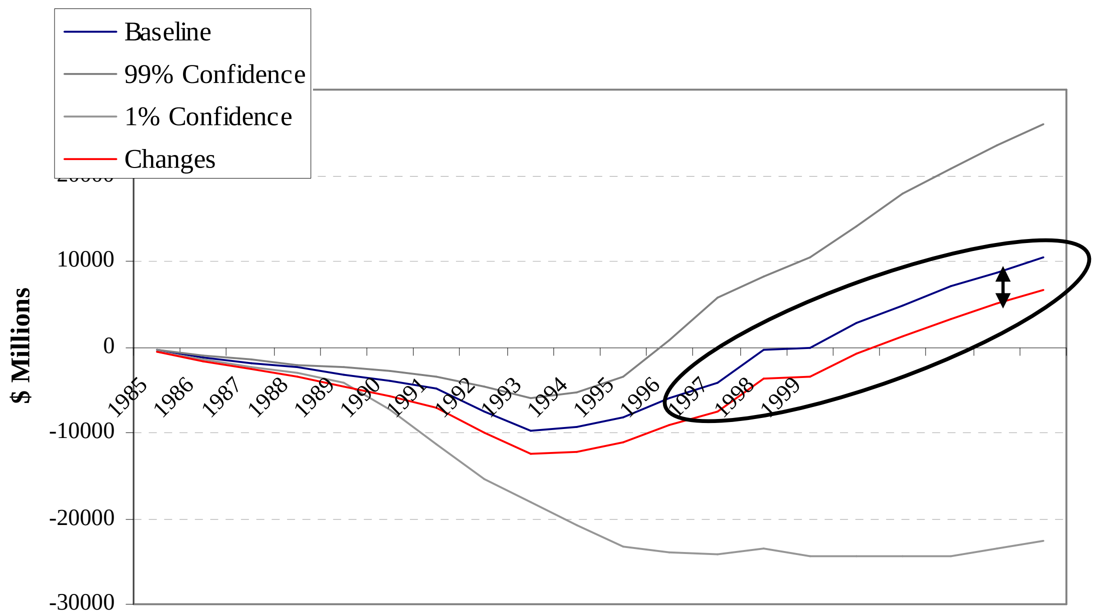

Figure 58: Changes in Cashflow from Effects of Changing Variables and Mitigating Risk

Along with the aircraft manufacturer's cashflow as an economic metric of interest is the airline's economic metrics of interest as measured, in this case, by the total operating cost per aircraft seat-mile. This measure is more standard across airlines and scenarios than the measure of revenue-passenger mile, which, like aircraft sale price or fuel cost, is very market dependent. The TOC for a notional airline at four different ranges is illustrated below in Figure 59. The Figure shows that, as anticipated, increasing fuel prices increases airline operating costs. It also shows that the operating costs increase as the range decreases, also expected.

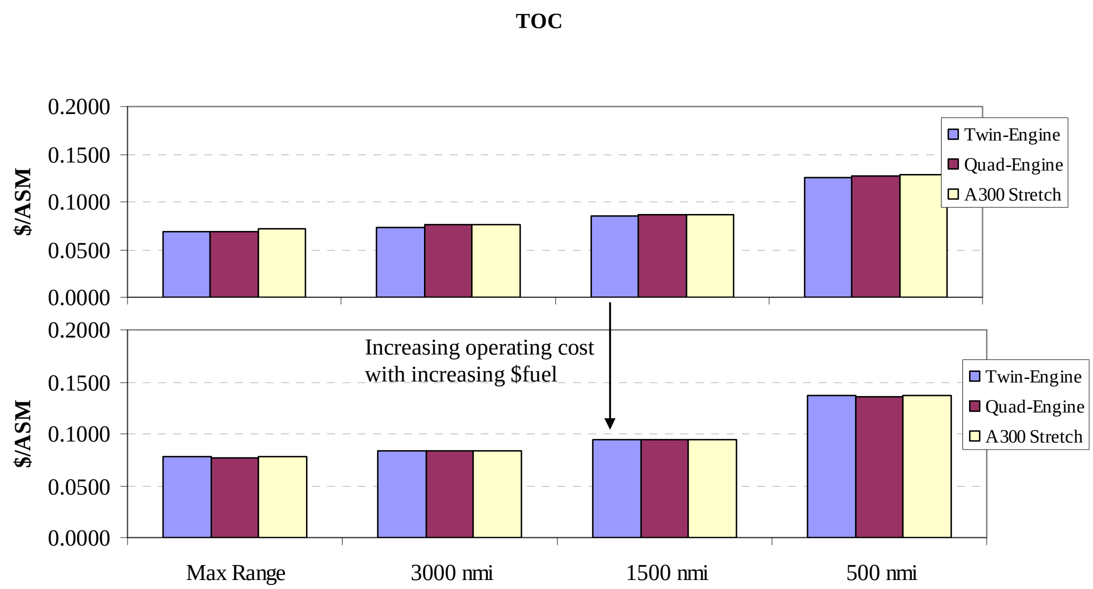

Figure 59: Increasing Operating Cost with Variable Changes and Risk Mitigation

Interestingly, the cheapest aircraft to operate changes as the cost of fuel increases: with low fuel costs, the twin-engine aircraft was more cost effective to operate, while with higher fuel costs the four-engine aircraft was cheaper to operate. This was an unexpected finding, and may be due to the nature of the engine models used to generate the aircraft's fuel flow. The engine models for the twin-engine aircraft were scaled from a slightly smaller aircraft, so the scaled fuel flow may be slightly larger than the actual fuel flow that would be used, and could, therefore, make fuel a larger part of the airline's operating costs. Airline's economic considerations are important to the manufacturer, since a new aircraft will need lower operating costs than existing aircraft in order to break into the aircraft market.

The final piece of the decision support interface is a TOPSIS analysis that takes into account all the pieces of the interface and determines the best solution family for a given problem with a given set of conditions. The TOPSIS, illustrated in Figure 60, takes into account risk, performance metrics, and airline and airframer economic metrics. Weighting values can be assigned to each of the metrics, and changed as necessary. As risk mitigation takes place and the production, aircraft price, and fuel cost is changed, the TOPSIS is updated automatically.

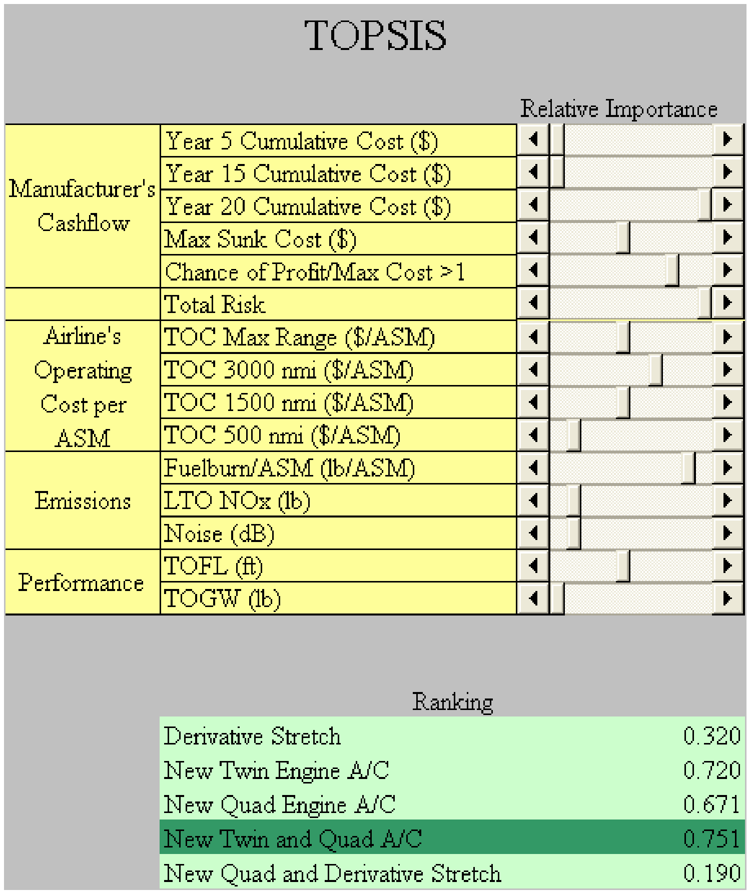

Figure 60: TOPSIS Using Decision Support Data

The TOPSIS can contain any metrics that are desired, and can be coded to the desired precision. While its use in determining whether any particular solution family is the best in all circumstances is limited, it is useful in determining which solution families are more likely to be better in most circumstances. In the Figure, solutions containing a derivative stretch version fare much worse than solutions featuring all new aircraft. In this case, it may be better to concentrate available time and effort into learning more about the new aircraft, and to make the decision later as to which aircraft family to continue designing. However, since this is only one set of metric weightings, it would be beneficial to illustrate the effects of changing the importance weightings on some of the metrics.

Changing the weightings of the metrics in the cashflow can change the best outcome; however, the best outcome is always one of the middle three choices: new twin-engine, new four-engine or both. In Figure 60, there is heavy weighting on the total risk and the final profit for the manufacturer and less weighting on the airline's operating costs and performance parameters. This weighting yields the result that a new two aircraft family is best. If more emphasis is put on the airframer's economic metrics, increasing the weightings of the manufacturer's cashflow and decreasing the weighting of risk and airline economic metrics, the best result changes. The new best aircraft, according to the TOPSIS results, is a new twin-engine aircraft. The twin-engine aircraft has a lower development cost than the two aircraft option, and almost as much potential for profitability. The TOPSIS weightings for this condition are illustrated in Figure 61. As in the previous example, the new aircraft options are significantly better than the design options using a derivative aircraft.

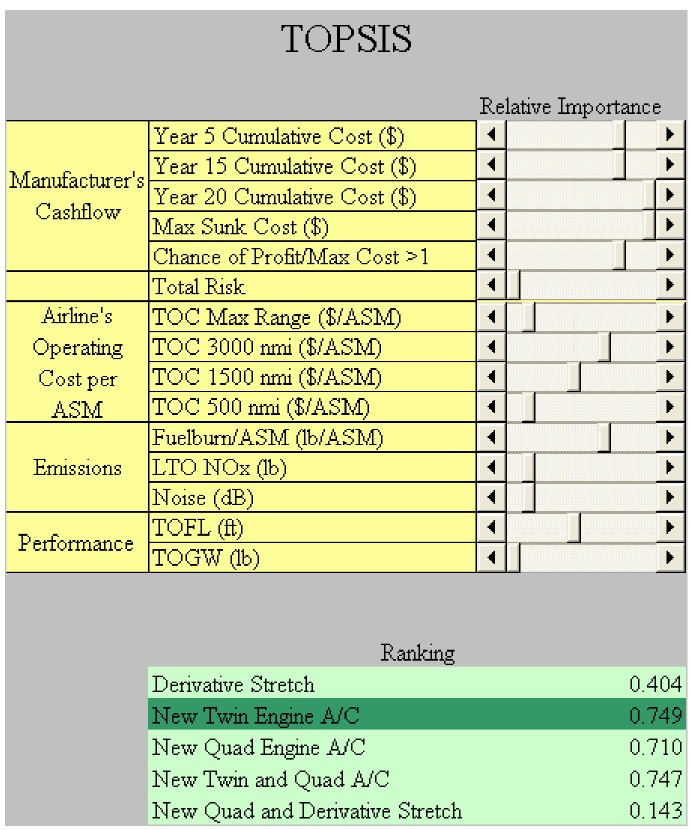

Figure 61: TOPSIS with Airframer Economic Emphasis

Other changes can also be made to affect the TOPSIS outcome. Figure 62 shows the TOPSIS outcome if there is an emphasis on airline economics and short range flights. In this case, the new twin-engine aircraft is again the best option; it is followed closely by the dual aircraft combination. Some airlines may be interested in using these aircraft for shorter-range missions, such as those within a country. Due to the presence of these airlines, the manufacturer may be interested in exploring the potential to market either the initially developed aircraft or a derivative aircraft in the same family for short-range missions. All the current aircraft design options are sized and designed for longer-range missions; however, there is no guarantee that some purchased aircraft wouldn't be used primarily on a 500-1500 nmi range set of missions.

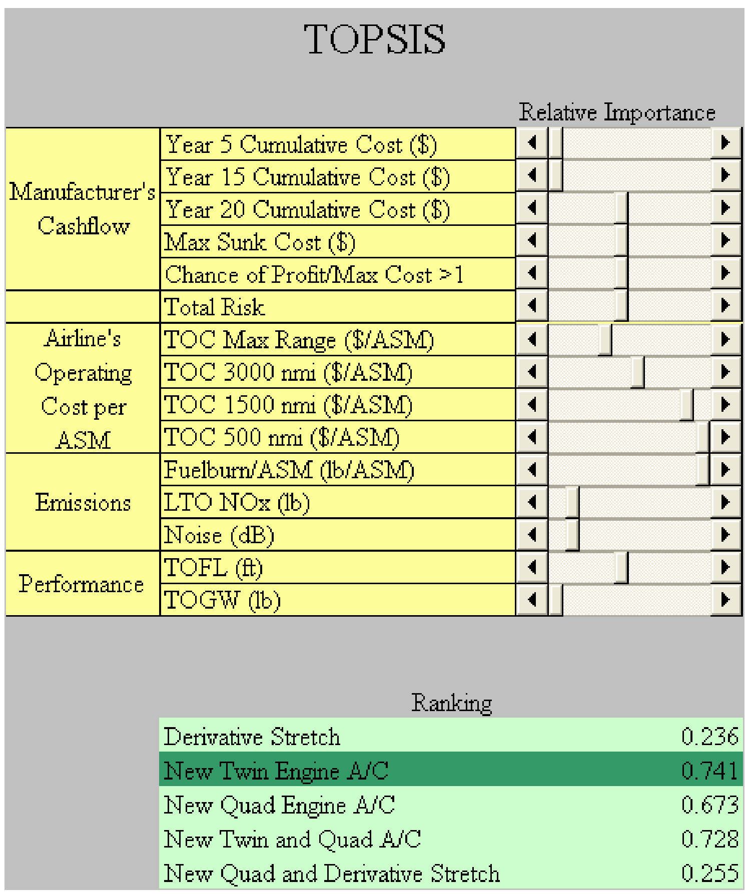

Figure 62: TOPSIS with Short Range Airline Economic Emphasis

Another game that can be played includes changing the characteristics of the aircraft market. In the event of an increase in fuel price to an average of $0.80 and a 10% decrease in market size for a twin-engine aircraft, the new four-engine aircraft becomes the best choice. Increasing the cost of fuel should drive the solution toward the four-engine aircraft, and decreasing the market for that aircraft should drive the solution to the twin-engine aircraft, potentially making a compromise solution the best. However, in this case, the preferred solution was a four-engine aircraft, as illustrated in Figure 63. As in the previous cases, the three new aircraft options were rated significantly higher than those with a derivative aircraft.

The decision support interface and all of its components bring together a large amount of information. The interface allows for more comparison of alternatives than is usually available at this stage of design. It is important to have information available and be able to examine different design alternatives over a wide set of futures, which this interface allows.

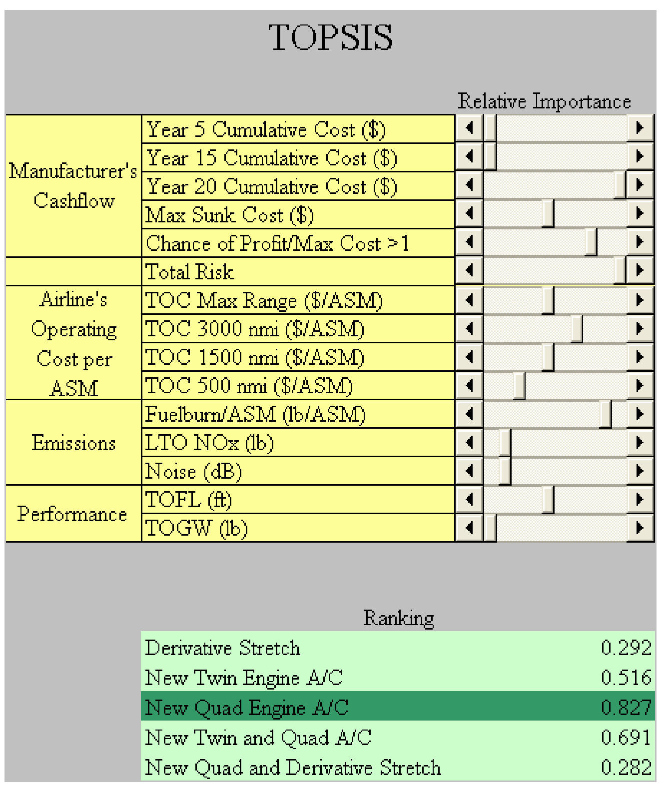

Figure 63: Increased Fuel Price and Twin-engine Aircraft Market 10% Smaller than Predicted

6.4 Hypotheses Test

This section goes through the hypothesis test outlined in Section 5.4. Testing hypotheses is a necessary step in the demonstration of the scientific method. If the hypotheses are invalid, they can be changed and retested, or declared to be incorrect. Testing the hypotheses allows for the use of the scientific method in the creating of a design process. As design processes used to be created ad-hoc, this step toward testability is a recent improvement.

6.4.1 Hypothesis One Test

> A risk analysis along with the outcome analysis will allow consequences and uncertainty to permeate the business case and increase information available for decision making without overwhelming the decision maker.

This hypothesis is tested by the skipping of steps six through eight in the proposed process and determining whether there is still enough information to support decision making. Now that the decision support interface is limited to only a manufacturer's cashflow, performance metrics, airline economic metrics, and the ability to change variables, the outcome can change. For comparison purposes, a TOPSIS that leaves out all the risk analysis data was created. This TOPSIS can be compared with the TOPSIS that contains the risk analysis data to determine whether additional information can change the outcome of the decision while not providing the decision maker with an overwhelming amount of data. A comparison of the two TOPSIS cases is shown below in Figure 64.

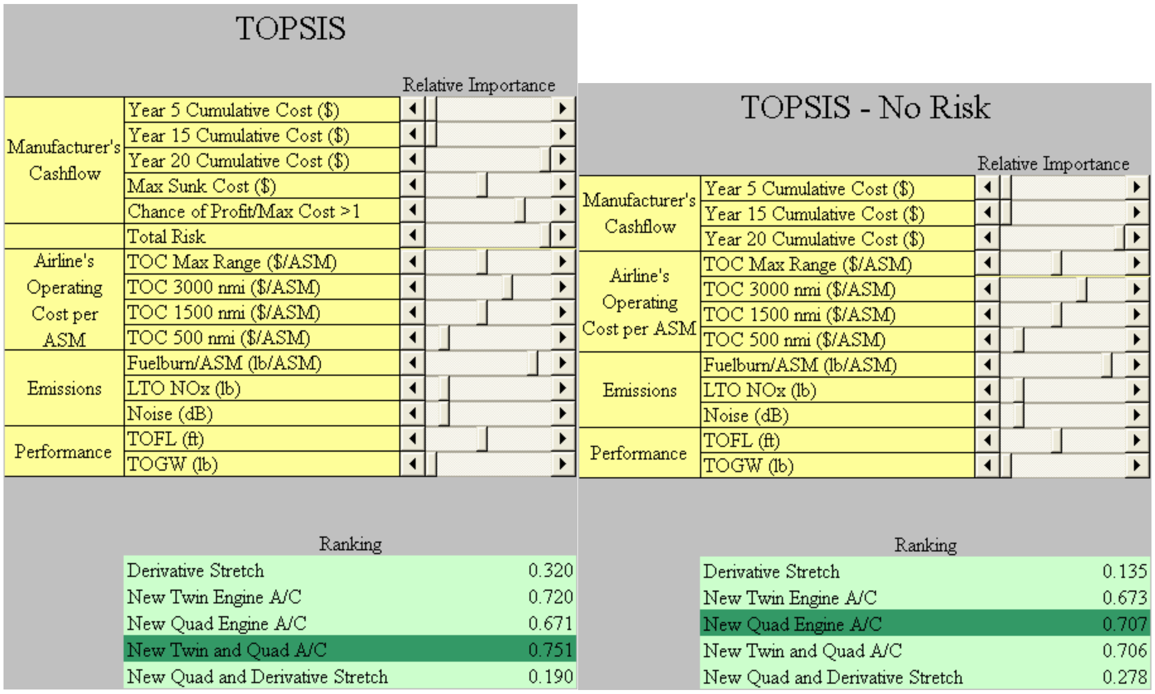

Figure 64: TOPSIS Comparison Baseline Case

The no risk case shows that the new four-engine aircraft is the best option to design. For the TOPSIS with risk, the two-aircraft option with twin-engine and four-engine aircraft is the best option to design. The TOPSIS with risk adds more information that drives the solution toward the two-aircraft outcome. This implies that the two-aircraft outcome has a lower overall risk than the single-aircraft outcome, which makes sense: two aircraft, while slightly more costly to produce, can cover more of the solution space than a single aircraft. However, both TOPSIS have three aircraft whose rankings are very close, so changes in a few of the weightings could flip the rankings, and, since the calculated values between the new twin-engine, four-engine and the two aircraft option are so similar, all three of those aircraft should be carried along for later design decisions.

The relative importances of each metric can be changed. The addition of the risk analysis adds three more metrics for importance weightings. These metrics are weighted highly, since there would be no reason to complete a risk analysis if the outcome was of little importance. The other very important metrics are the profit (20 Year Cumulative

Cost) and the fuelburn metrics. Fuelburn is important since fuel is a commodity whose price is not very stable.

Since the importance weightings can be changed, it is important to understand how these weightings affect the aircraft's rankings. The sensitivities of the aircraft's rankings to each weighting change between the no risk option and the option that includes risk. Table XXXII lists the sensitivities of each aircraft's TOPSIS result with the TOPSIS weights for the case that includes risk, while Table XXXIII does the same without risk. This partial derivative was taken with all other weightings held constant at five, or halfway between the minimum and maximum. The equation used to calculate the sensitivities is illustrated below in Equation 9.

$$AircraftSensitivity = \frac{\Delta ChangeInAircraftTOPSIS}{\Delta TOPSISWeighting} \tag{9}$$

The two tables below show the aircraft's TOPSIS sensitivity results to changing the metric weighting scheme. When risk is present, the derivative is most sensitive to changes in changes in the weightings of Max Sunk Cost, TOGW, and Year 5 Cumulative Cost. Without risk, that aircraft is most sensitive to changes in the weightings of TOGW and Year 5 Cumulative cost. Since the maximum sunk cost doesn't exist without the risk calculation, it cannot be a factor there. The Twin-engine aircraft is most sensitive to changes in the noise weighting in both conditions, while the four-engine aircraft is most sensitive to changes in the weighting for TOGW and NO_x under both conditions. For the aircraft, increasing some metric weightings increases the aircraft's ranking, while others will decrease it. This is expected, since the aircraft are compared relative to each other, not on an absolute scale. There are some changes in the aircraft's sensitivities to the different weightings depending on whether risk is present or not, but those changes are generally small. This means that, while the risk analysis adds information, the trends between the two TOPSIS results will be similar, but not identical.

Table XXXII: Weighting Sensitivities with Risk

		Sensitivity to Changes in Weightings				
		Derivative	Twin	Quad	Twin & Quad	Derivative & Quad
Manufacturer's Cashflow	Year 5 Cumulative Cost ($)	7.81E-03	-9.73E-04	1.70E-04	-1.51E-03	-3.23E-03
	Year 15 Cumulative Cost ($)	6.43E-03	2.84E-03	3.90E-03	2.89E-03	-3.23E-03
	Year 20 Cumulative Cost ($)	2.83E-03	2.14E-04	3.09E-03	3.18E-03	-3.23E-03
	Max Sunk Cost ($)	7.81E-03	1.45E-03	9.08E-04	-8.26E-04	-3.23E-03
	Chance of Profit/Max Cost >1	-2.72E-03	3.70E-04	-1.53E-04	3.18E-03	-3.23E-03
	Total Risk	7.81E-03	-6.48E-05	-3.47E-03	1.90E-03	-3.23E-03
Airline's Operating Cost per ASM	TOC Max Range ($/ASM)	-5.40E-03	9.64E-04	3.90E-03	2.03E-03	4.69E-03
	TOC 3000 nmi ($/ASM)	-5.40E-03	2.88E-03	-3.37E-03	2.74E-04	3.34E-04
	TOC 1500 nmi ($/ASM)	-5.40E-03	2.88E-03	-1.94E-03	8.46E-04	1.19E-03
	TOC 500 nmi ($/ASM)	-5.40E-03	1.91E-03	3.90E-03	2.60E-03	4.69E-03
Emissions	Fuelburn/ASM (lb/ASM)	7.44E-04	2.68E-03	-8.71E-03	-2.21E-03	-1.09E-03
	LTO Nox (lb)	-5.40E-03	6.94E-04	3.89E-03	1.85E-03	4.70E-03
	Noise (dB)	-5.40E-03	-6.26E-03	3.90E-03	-2.30E-03	4.69E-03
Performance	TOFL (ft)	-5.40E-03	-5.14E-03	3.90E-03	-4.84E-03	-3.23E-03
	TOGW (lb)	7.81E-03	-4.65E-03	-9.31E-03	-7.19E-03	3.37E-03

Table XXXIII: Weighting Sensitivities without Risk

		Sensitivity to Changes in Weightings				
		Derivative	Twin	Quad	Twin & Quad	Derivative & Quad
Manufacturer's Cashflow	Year 5 Cumulative Cost ($)	1.11E-02	-1.03E-03	-7.12E-05	-1.44E-03	-5.04E-03
	Year 15 Cumulative Cost ($)	9.37E-03	3.73E-03	4.58E-03	4.05E-03	-5.04E-03
	Year 20 Cumulative Cost ($)	4.87E-03	4.49E-04	3.58E-03	4.41E-03	-5.04E-03
Airline's Operating Cost per ASM	TOC Max Range ($/ASM)	-5.40E-03	1.39E-03	4.58E-03	2.98E-03	4.85E-03
	TOC 3000 nmi ($/ASM)	-5.40E-03	3.78E-03	-4.49E-03	7.85E-04	-5.91E-04
	TOC 1500 nmi ($/ASM)	-5.40E-03	3.78E-03	-2.71E-03	1.50E-03	4.79E-04
	TOC 500 nmi ($/ASM)	-5.40E-03	2.57E-03	4.58E-03	3.69E-03	4.85E-03
Emissions	Fuelburn/ASM (lb/ASM)	1.47E-03	3.68E-03	-1.20E-02	-2.14E-03	-3.24E-03
	LTO Nox (lb)	-5.40E-03	1.05E-03	4.58E-03	2.77E-03	4.85E-03
	Noise (dB)	-5.40E-03	-7.63E-03	4.58E-03	-2.43E-03	4.85E-03
Performance	TOFL (ft)	-5.40E-03	-6.23E-03	4.58E-03	-5.60E-03	-5.04E-03
	TOGW (lb)	1.11E-02	-5.63E-03	-1.19E-02	-8.53E-03	3.20E-03

If the situation changes, the results change. For example, if the price of fuel increased from an average of $0.45/gal to $0.80/gal, the results will change for both of the TOPSIS modules, as illustrated in Figure 65. In both TOPSIS models, the increasing fuel cost drove the solution toward a four-engine aircraft, which has a lower long-range operating cost per seat mile. For the no risk TOPSIS, the fuel cost is a driver on four of the eleven metrics examined, while for the TOPSIS with risk it is a driver for the same four of fourteen metrics. In both cases, the same three design options are still better than the other two, although in the TOPSIS without risk that delineation is more difficult to make, so it appears that changing the metric rankings or variable inputs doesn’t affect the solution enough to make a derivative aircraft a good design option.

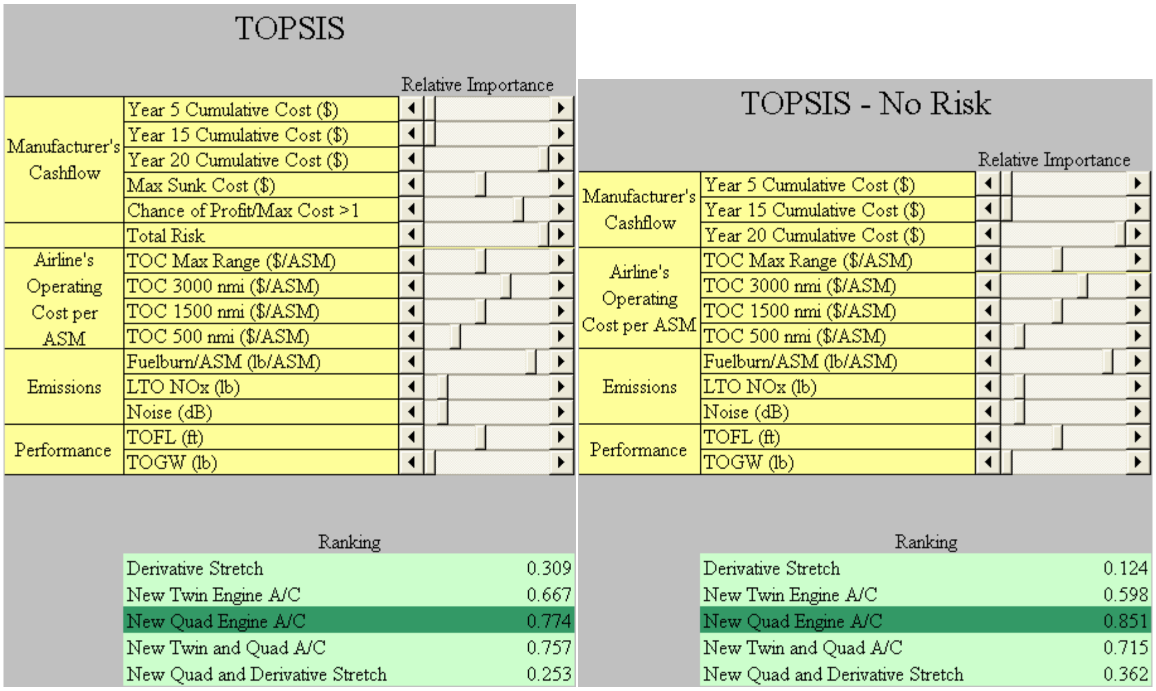

Figure 65: TOPSIS Comparison Increasing Fuel Cost

If one adds some risk mitigation to the TOPSIS process, the results change even further. In the event of mitigating the risks checked in Figure 55 and moving to technology point two, the TOPSIS with risk still declares the best decision is a two-aircraft family with a new twin-engine and a new four-engine aircraft; however, the difference between the best decision and the 2nd best decision is larger. The best decision is now more than 10% better than the next one, which indicates that mitigating risk has a profound effect on the aircraft development choice. In this case, a decision maker may determine that the two-aircraft family is overwhelmingly the best decision; therefore, it is unnecessary to continue to carry the other two aircraft families further into the design process. Without the addition of risk and risk mitigation, a decision maker is more likely to determine that three aircraft family designs should be carried forward in the design process. Carrying all three designs means increasing cost and time to analyze more potential aircraft families. These TOPSIS models are illustrated in Figure 66. In this Figure, the TOPSIS with risk declares that a two-aircraft family will be the best use of design time and money, while the no risk TOPSIS is still declaring that developing only a four-engine aircraft is the best option.

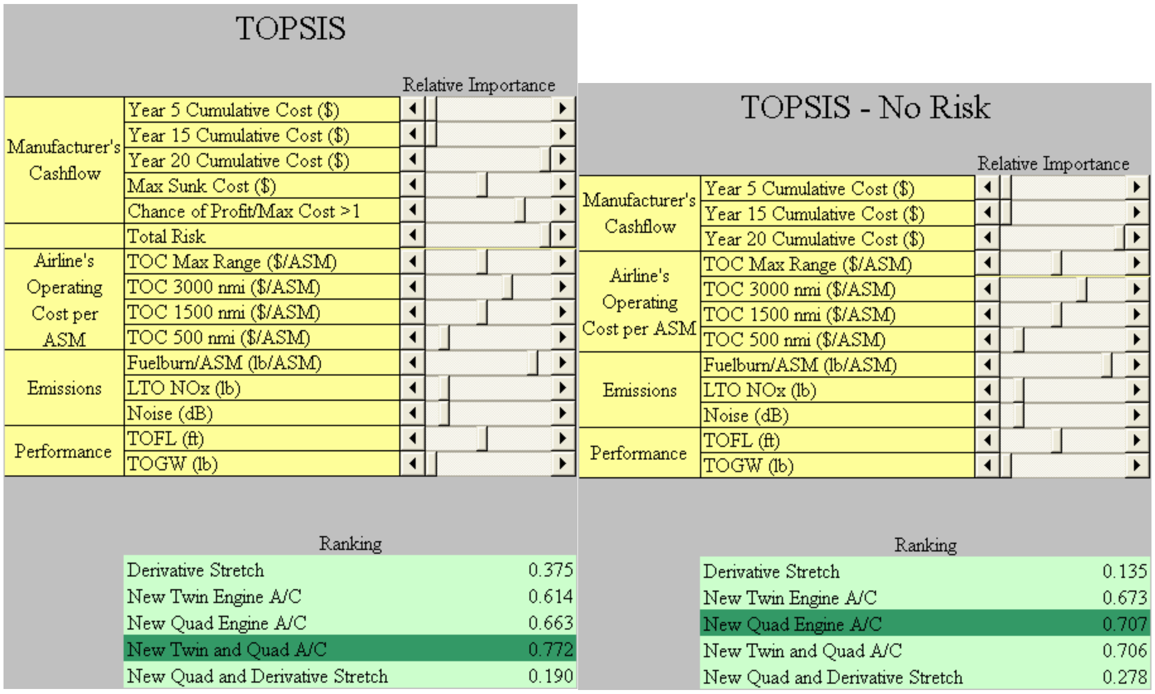

Figure 66: TOPSIS Comparison with Risk Mitigation

The changes in the TOPSIS ranking and values illustrate that the addition of a risk analysis and mitigation process has the potential to change the outcome of the problem. During the early stages of conceptual design, performance and economic metrics are tracked; however, there is often little examination of the assumed future. The addition of a risk analysis of the sort used here allows a decision maker to examine his assumptions about the future and provides insight into the consequences if the future is different than assumed. The initial hypothesis may have been too strong a statement to be proven given the amount of information available. A revised hypothesis that can be demonstrated with the available information can be:

> The addition of an operating environment risk analysis to the performance and economic analysis completed during conceptual design will allow for the examination of assumptions and the consequences of not meeting

> those assumptions. This new information can be used for decision making without overwhelming the decision maker.

This statement has been demonstrated using the tests described above. New information has been provided to a decision maker, who is able to examine assumptions about the future operating environment of the system, as well as the consequences of not meeting those assumptions. Also, the addition of three new metrics for a decision making model is unlikely to overwhelm a decision maker.

6.4.2 Hypothesis Two Test

> Both qualitative and quantitative information are available and can be used in decision making; the ability to use both types of information increases the number of applications for a risk-benefit analysis without overwhelming a human decision maker.

This hypothesis is tested by limiting the amount of information available to the decision maker. Several questions were asked of this hypothesis in Section 5.4, and they will be answered here. In this case, it would not be necessary to limit the number of potential solutions if one were limited to quantitative information only, since all solutions are similar to existing aircraft and require only evolutionary technology changes. In this case, limiting the information available to only quantitative information would eliminate the risk analysis portion of this process, since the probabilities were determined qualitatively. Eliminating the risk analysis changes the solution to the problem, as evidenced earlier in this section. By extension, the addition of a risk analysis, which is the addition of qualitative information, increases the amount of information available for decision making.

For the second point in this hypothesis, that allowing both quantitative and qualitative information to be used increases the number of applications for a risk analysis, this is also true. In this case, if qualitative information was not available for decision making purposes, then there would be no risk analysis. In other cases, it may be possible to conduct a risk analysis utilizing actual quantitative probabilities; however, these scenarios were not set up for that purpose. If numerical probabilities could have been assigned to each uncertainty and a measure of consequences could also have been assigned to each uncertainty (decrease in profit? breakeven time?) then a quantitative risk analysis could have been completed for this problem. Allowing for the use of qualitative information allowed the risk analysis process here to be used for this example problem, while if the process were only limited to quantitative information it would not have been usable for this problem.

6.4.3 Hypothesis Three Test

> Too much uncertainty, handled improperly, can render a risk analysis meaningless; the use of future scenarios can assist in bounding uncertainty and allowing decision makers to better manage it.

Testing hypothesis three involves comparing the scenario-based analysis to a traditional probabilistic analysis in a Monte Carlo analysis. The first comparison takes place in Figure 68, and is comparing metric values for both of these conditions. In this Figure, the traditional probabilistic analysis is represented by the red points for a new twin-engine aircraft, the pink points for a new four-engine aircraft, the light green points for the derivative aircraft, the black points for the derivative and new four-engine aircraft, and the dark blue points for the new twin-engine and new four-engine aircraft. The scenario-based probabilistic analysis is represented by the light red points for a new twin-engine aircraft, light purple points for a new four-engine aircraft, light green points for the derivative aircraft, gray points for the derivative and new four-engine aircraft, and light blue points for the new twin-engine and new four-engine aircraft. Outputs for the design of two aircraft are only seen in the 1989, 1999, and 2004 cumulative cashflow. Each of the points on this Figure represents a single design point with a single set of variable settings. The variable settings of two design points, one from the scenario-based analysis and one from the traditional probabilistic analysis, are illustrated in Figure 67. These points have different settings and are located in slightly different points in the design space; however, they were both evaluated using the same set of surrogate models.

Acq	80.91	83.92
Airline Int Rt	9.49	5.16
Al k-Factor	0.9528	0.9751
Al Cost	0.9712	0.9493
Avionics Wt	0.9414	1.224
Eng Labor	70.75	75.77
Fuel Cost	0.7126	1.244
Inflation	0.0405	0.446
Man Labor	46.26	36.62
Prod Number	1087	1150
Tail Comp	0.92	0.53
Year 1 Prod	1.05	1.00
Year 2 Prod	1.75	0.47
Year 4 Prod	4.07	5.64
Year 5 Prod	5.32	4.43
Year 9 Prod	3.13	5.57
Years RDT&E	7.39	6.25
Nox	801.4	805.4
TOC 500 nmi	0.1273	0.1392
TOC 5600	0.0708	0.0799
TOFL	8225	8366
1989	-3076.73	-3473.79
1999	6709.53	19002.61
2004	21200.44	35811.87

Figure 67: Variable Settings for Two Points

Some of the differences between a traditional probabilistic analysis and a scenario-based analysis are illustrated in Figure 68. If the fuelburn/ASM metric is examined, it can be seen that there are only small differences between the scenario-based analysis and the traditional probabilistic analysis, even though the input variable distributions and bounds were different between the two analyses. The fuelburn range across the traditional probabilistic analysis is slightly greater for all three aircraft than that range for the scenario-based analysis. Since the scenario-based analysis is designed to bound (Schwartz 1991) and decrease uncertainty, this finding is unsurprising. TOFL, the other performance metric illustrated, shows a similar trend: three distinct aircraft bands with a slightly greater band width for the traditional probabilistic analysis.

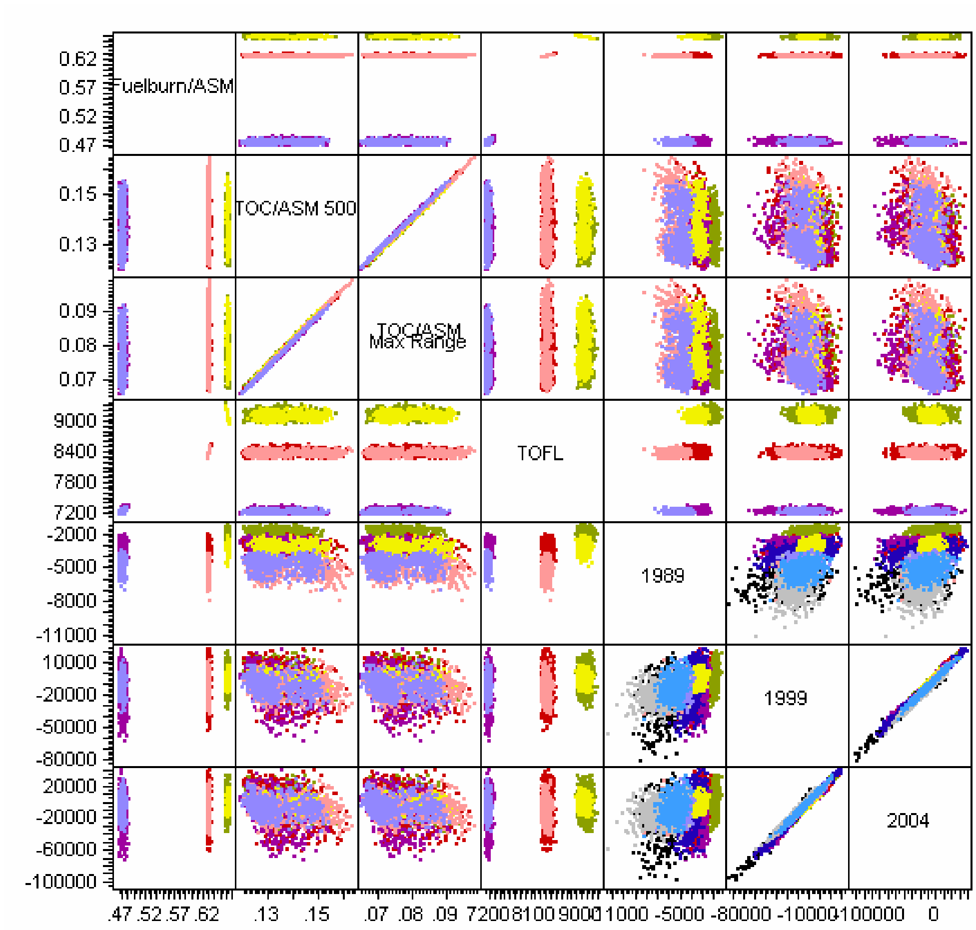

Figure 68: Comparison Between Traditional Probabilistic and Scenario-based Analysis

The shrinking of variability is more clearly illustrated in the airframer's cashflow metrics. For all five aircraft design options, there is a smaller degree of variability of the cumulative cashflow for the scenario-based analysis than for the traditional probabilistic analysis. This decrease in variability can make decision making easier, since distinguishing characteristics of design options become more evident (Black 2001). In the traditional probabilistic analysis, it is difficult to determine which aircraft or combination will have the largest chance of being profitable with the smallest chance for loss. However, for the scenario-based analysis, it can be noted that the derivative and new four-engine aircraft has a smaller chance of producing a profitable aircraft than the other options. Both the probabilistic analysis and the scenario-based analysis predict the smallest degree of variability in economic metrics for the derivative aircraft; the small variability was expected as some costs are likely to be more certain for a derivative than for a new aircraft.

Examining the aircraft modeling inputs to determine whether there are differences between the scenario-based and traditional probabilistic analyses should be done. For the new twin-engine aircraft option, a comparison of some of the variable inputs between a new traditional probabilistic analysis and a scenario-based analysis are illustrated in Figure 69. In this Figure, the traditional probabilistic analysis points are in red, the best-case scenario is green, the worst-case scenario is in black, scenario three, the AIDS epidemic scenario is in gray, scenario four, the Middle Eastern conflict scenario, is in orange, and scenario five, the technology explosion scenario, is in blue. It is even clearer in this Figure than in the previous one that scenarios can be used to help bound uncertainty. Each scenario has a significantly smaller variability than the traditional probabilistic analysis. In general, the variability of the best and worst scenarios is smaller than that for the middle, more likely, scenarios. This is because the best and worst scenarios are “wild card” scenarios whose probabilities are extremely unlikely. These scenarios, instead of having wide distributions, are closer to deterministic in nature than the more likely scenarios (Chandler and Cockle 1982).

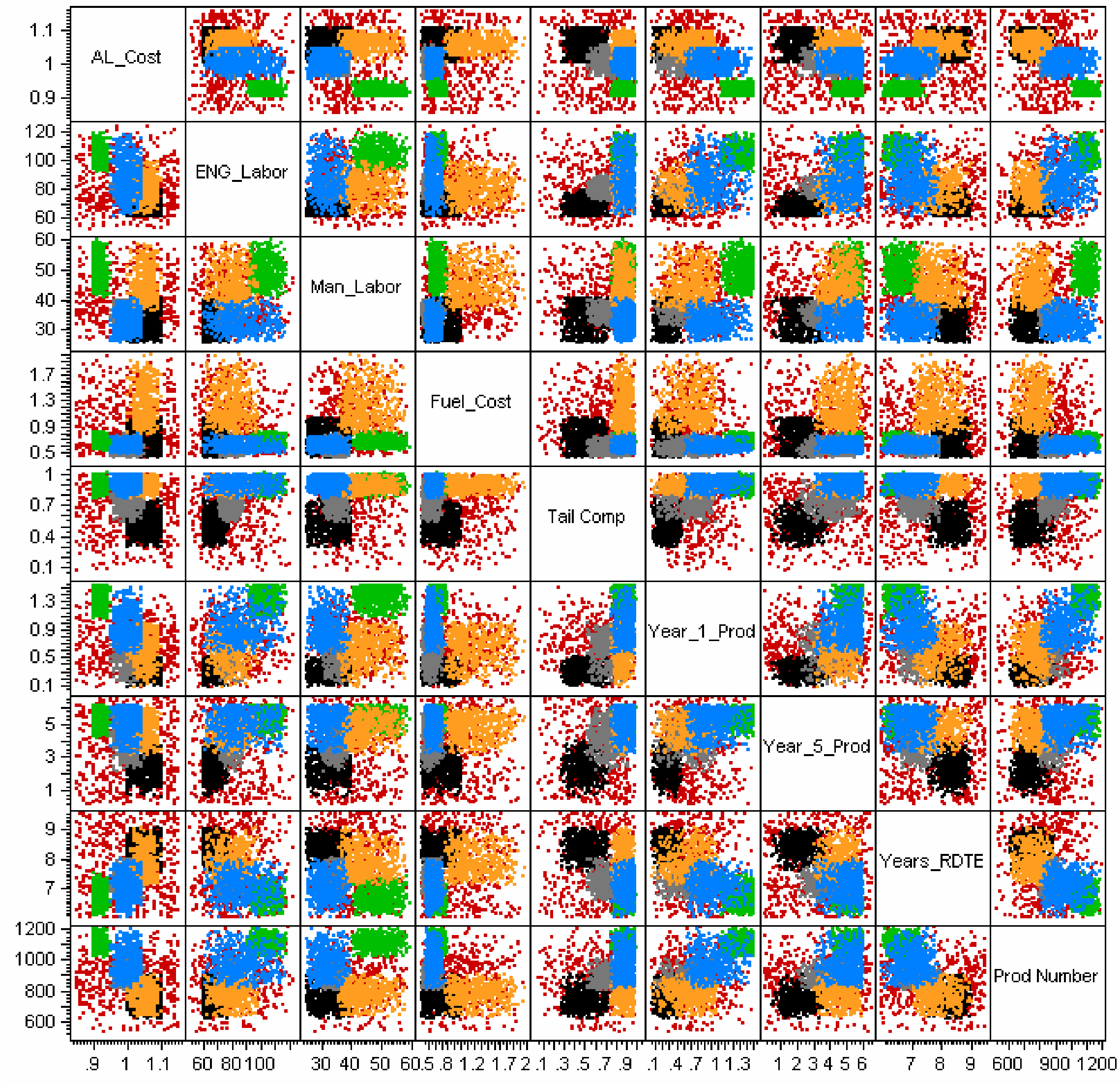

Figure 69: Comparison of Inputs Between Traditional Probabilistic and Scenario-based Analyses

For the results, a similar trend to the inputs is seen in Figure 70. There is significantly more variability in the responses of the traditional probabilistic analysis than for any of the scenario analyses.

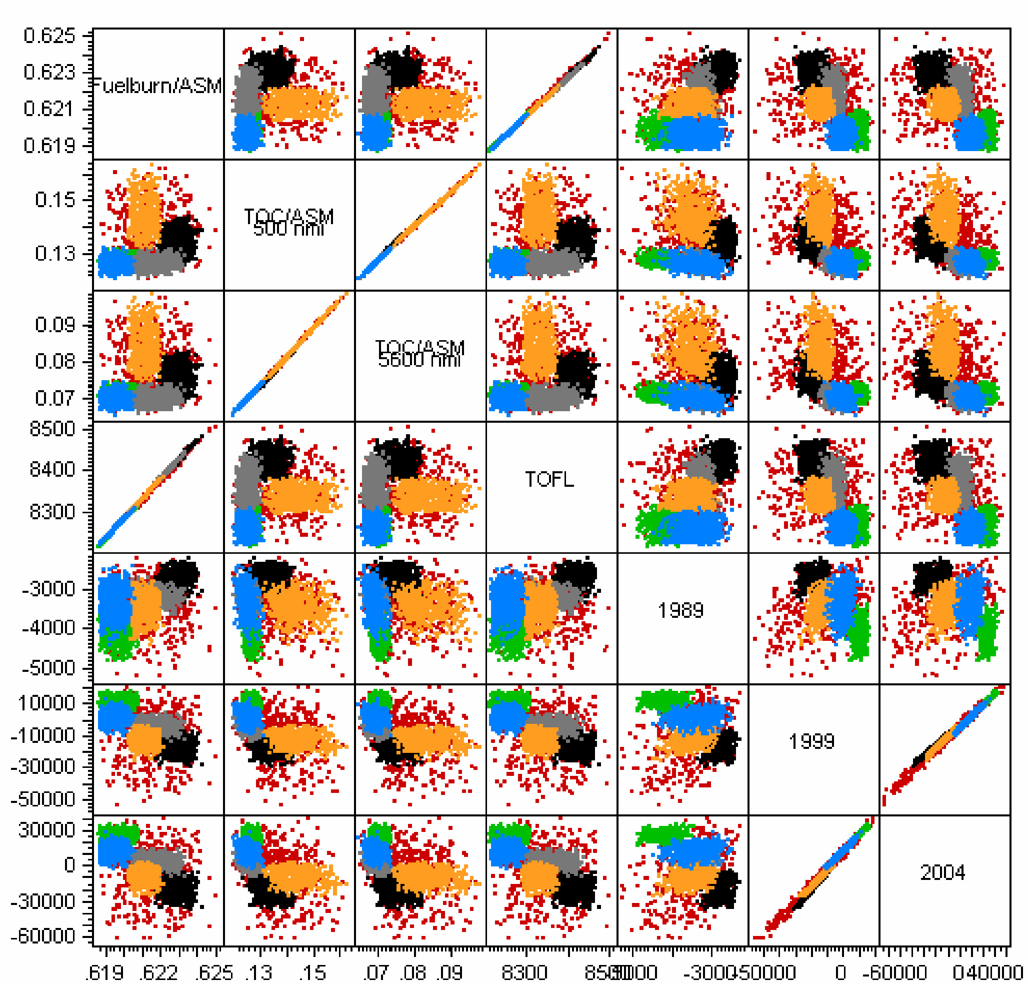

Figure 70: Metric Comparison Between Traditional Probabilistic and Scenario-based Analyses

Like the inputs, the best scenario and worst scenarios have slightly smaller variability than the middle three scenarios. The scenario with the most variability, particularly with the airline economic metrics, is the Middle East conflict scenario. Since fuel cost is significant driver for the airline's operating cost, it was expected that the operating costs would be high for that scenario. Overall, the scenarios show decreased variability for the manufacturer's economic metrics as compared to the traditional probabilistic analysis. While there is more change in the maximum loss between the scenarios and the traditional analysis, the variability shrinks on both the profit and loss ends.

The use of scenarios gives different results than the use of a traditional probabilistic analysis. Since both the scenario-based and traditional probabilistic analysis are being used to predict the future, it is impossible to say which one is absolutely correct. One advantage the scenario-based analysis has over the traditional probabilistic analysis is in the ability for each scenario to shrink the variability in the responses of interest, thereby potentially enabling a better comparison between alternatives (Black 2001). The use of scenarios also forces the creator to examine his assumptions about the future (Schwartz 1991), while a traditional probabilistic analysis only requires that one set variable bounds.

There are situations where, even when uncertainty is handled properly, a decision maker will still be unable to distinguish between options. In these cases, a decision cannot be made based on the metrics present for the decision maker's use. Scenarios can aid in handling uncertainty properly by helping to correctly bound it. Correctly bounding and distributing uncertainty can help enable a decision maker to make a decision when possible and know when he cannot make a decision based on the information provided.

6.5 Comparison to Actual Events

One of the purposes of using a historical example was to be able to compare the example to what actually took place in the last 20 years. The purpose of this comparison is to see how well the scenarios line up against what actually happened and to see how the initial assumptions resemble the actual series of events.

The first comparison is which aircraft was designed. In the analysis, choosing to develop two aircraft instead of only a single aircraft showed the highest development cost and also the largest overall profit. In actuality, two aircraft were developed, the A330 and the A340. These aircraft have proven to be viable, as predicted. Since it is impossible to determine whether or not a single aircraft configuration would have been equally viable, that cannot be compared. It can be speculated that a single aircraft configuration would also have proven to be viable, particularly a twin-engine aircraft since there have been so many A330 orders.

The initial assumption for the number of aircraft ordered was 1000 aircraft between the two configurations including derivatives. The actual number of aircraft ordered was 1173 through December 2004 (“Historical Orders and Deliveries” 2006) between the two configurations including all derivatives: A330-200, A330-300, A340-200, A340-300, A340-500, and A340-600. The prediction was also that the A330 would have 60% of the orders; in actuality there were 604 A330s and 469 A340s ordered, so that assumption was also very accurate (“Historical Orders and Deliveries” 2006). The prediction was that there would be 880 deliveries by 2004; in actuality there would by 329 deliveries of each aircraft for a total of 658 deliveries (“Historical Orders and Deliveries” 2006). The delivery schedule initially assumed was too aggressive for Airbus to actually complete.

For many of the other variables, the initial assumptions were also very accurate. The RDT&E time was assumed to be seven years; this was a relatively accurate assumption. The A330/A340 was announced in February 1986; the first delivery was in late 1993 (“Airbus A330” 2002), giving an RDT&E time of a little more than seven years. Inflation was assumed to be 3.5%; it was actually 2.77% (“The Inflation Calculator” 2005). The new avionics system, composite tail, and lighter weight aluminum alloys were able to be used as anticipated. There wasn’t a labor shortage for either engineering or manufacturing labor, and there were no production interruptions. While French government aid was given in the form of low-interest loans instead of pledges, the money is being paid back. Fuel prices have been higher than predicted: prediction was an average of $0.45, while the actual price was $0.63 (“Daily Spot Prices…” 2006).

As for the scenarios, none of the scenarios came true, but there were some aspects of each that were accurate. For much of the early 1990s and late 2001 to 2003, the worst-case scenario looked promising: there was a recession and terrorist attacks to contend with that decreased airline profits and travel. The late 1990s were good years for the American economy and travel increased as incomes increased. Oil prices were low, and airlines were profitable. In the early 1990s, the USSR collapsed into 15 different countries, with Russia as the largest. While not all countries became western-style democracies, all hold some free elections. The economies of India and China have taken off, and there is significant outsourcing from the United States to those countries. AIDS has not become the epidemic that was feared, except in sub-Saharan Africa. There has been some instability in the Middle East, most notably in 1990-1991 and later in 2002-2004. The actual future was different from all scenarios but incorporated pieces of all the different scenarios.

CHAPTER 7

CONSLUSIONS

7.1 Project Goal

Times have changed since the dawn of commercial jet aviation. Today, large aerospace engineering projects have longer design cycles than in years past. With these longer design cycles comes increased RDT&E costs and, thus, more borrowed money. As engineers receive design requirements and continue to design aircraft, they have been unable to analyze programmatic life cycle risk. This analysis was previously carried out by marketing and finance teams before the design requirements were set. The initial product design and launch decisions were made based on potential technical merit, potential project cost, and potential project risk, but engineers were only analyzing technical merit and cost, with just a cursory examination of risk.

Since decisions are made based on cost and risk, as well as technical merit, all three of these objectives should be examined. Processes already exist to examine technical merit and cost, as well as some aspects of risk. Other aspects of risk, including risk associated with government and culture, are poorly served by existing engineering processes. The goal was to create a process that allows for the examination, for the purpose of decision making, of technical and economic objectives, as well as programmatic risk and risk control and mitigation strategies.

The initial decision makers, often not engineers, formulate a number of assumptions about the future before they make design decisions. These assumptions have some risk of not being met. Understanding these assumptions and their associated risks is essential to understanding how decision makers make concept-level decisions and how these decisions can be made in a better fashion. A diagram of the process designed to bring these assumptions and decision making processes down into engineering design is illustrated in Figure 71. The process allows the engineer to see the information that is available to the management decision making team and to gain insight into how design decisions are made on the basis of risk and reward.

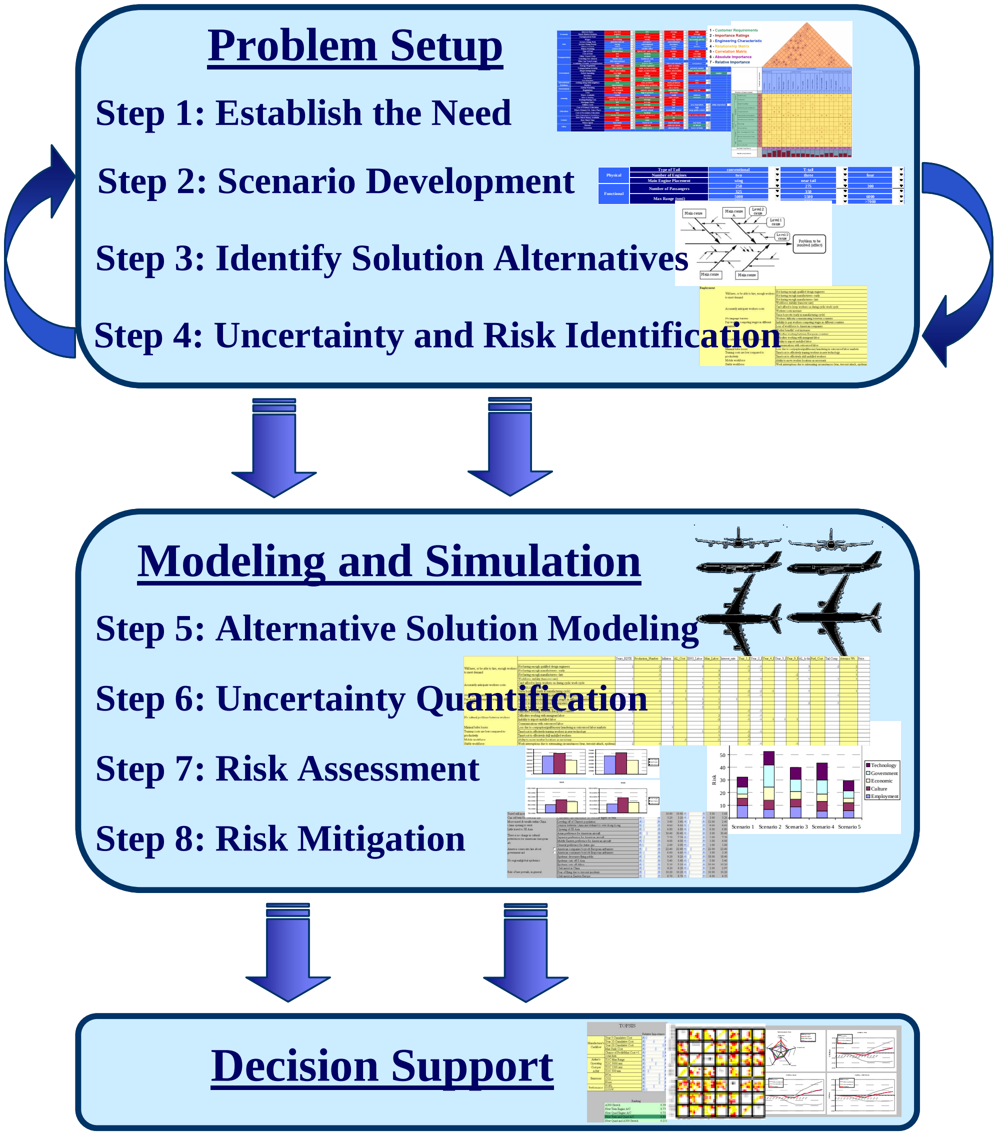

Figure 71: Risk Analysis and Decision Support Process

This process has several important features that differ from existing risk analysis processes. These features address the gaps discussed in Section 5.1 and will be highlighted again in Section 6.2 below. The first important feature of this process is that it emphasizes traceability. This process allows for the examination of a set of assumptions about the design problem and the future. The risks associated with these assumptions are examined; it is easy to demonstrate where the risk originated and how the probabilities and consequences were determined.

The other important feature of this process is the problem insight. Traditional risk analysis processes are designed to provide traceability and problem insight; however, these processes are not set up to work early in conceptual design with limited information. The new process is designed to work in early conceptual design and with little, uncertain information. The results provide traceable information about a set of assumptions and risks that was previously unavailable. This allows for the potential to eliminate feasible and viable, but too risky, design options early in the design process before spending a significant amount of money to examine them. Along with the ability for engineers to eliminate risky design options is the ability to demonstrate why these options were eliminated. Since design options that are too risky can be eliminated, potential product designs can be chosen with the express purpose of being robust to changes in the assumed future. Being able to choose designs that are robust over a variety of potential future scenarios can increase the probability of the company making a profit. As profit is the primary driver for most companies, this is a powerful tool. Finally, this process allows the engineer to have a better understanding of how management decision makers view the design problem: not in terms of performance metrics, but also in terms of life cycle cost and risk.

7.2 Follow-on Work

There are many pieces of follow-on work, a few of which will be highlighted here. One potential piece of future work is to create an algorithm or process to determine which risks should be mitigated. Since the real-world contains budgetary constraints as well as performance constraints, mitigating risk while keeping within these constraints is an important piece of follow-on work to be completed. Knowing which risks to mitigate and the budget necessary to mitigate those risks will add more information that is useful for a team of decision makers. Knowing which risks can and should be mitigated within a set budgetary constraint will further enable the decision makers to make design and configuration decisions that best fit their company's long-term goals.

Another piece of follow-on work that also concerns the mitigation process is to compile a more rigorous risk mitigation analysis, using the same modeling and simulation environment used for the solution modeling process. The current risk mitigation process assumes that risk mitigation is continuous, i.e. that risk can be partially mitigated. While this is true of many types of risk, it may not be true of all types. It also assumes that mitigating one risk has no effect on other risks or on the design variables. Again, this assumption is not true in all cases. A risk mitigation procedure that addresses these concerns would also be useful in determining which risks to mitigate and some of the 2^{nd}-order effects of mitigating those risks.

A third piece of follow-on work is to determine a process for updating and tracking changes in risk through time. If possible, it would be advantageous to know whether certain risks are increasing or decreasing with time, and it would also be good to be able to update the risk process quickly as new information became available. As new information became available, more modeling and simulation would need to take place and the new information would need to be transmitted to the risk analysis process and collated into a useful form. However, if risk is tracked over time, it may be possible to reallocate mitigation funds where they are most needed at a particular time, instead of just waiting to see what will happen in the future. Also, if risk is tracked with time, hazardous events may be easier to predict as the risk of a particular outcome increases.

These three potential pieces of additional work are not the only options for potential future work. They are, however, some of the options that this author feels would be the most useful for the overall process and the project goals. This author thinks that an algorithm for choosing which risks to mitigate is the most important piece of future work, since it would better enable the engineers to take this product up to the decision makers and understand the design decisions.

APPENDIX A

SURROGATE MODELING TECHNIQUES

Many engineering designs are created with the help of computer modeling codes. In the aerospace industry, designs for large systems are extremely complicated—too complicated for a human to do by hand. So these computer codes model the new design or system and help the human understand the behavior of the system. For well defined systems, this approach works very well and the human decision maker has all the data necessary to make design decisions and test theories. However, during conceptual design, design problems can be poorly defined and the design solutions themselves are also poorly defined. Therefore, instead of running a computer code one time to see how a systems behaves under one set of conditions, computer codes will be run multiple times to see how different systems behave under a variety of conditions. The amount of computer time necessary to run computer codes at all possible designs and conditions is staggering for even small designs and modern computers. For this reason, surrogate modeling techniques are used. Surrogate modeling techniques, also called metamodeling techniques, involve the creating of "models of models." The computer codes are models of the real system, and the metamodels are models of the computer codes. There are many surrogate modeling techniques available, a sampling of which will be highlighted below.

A.1 Response Surface Methodology

Response surface technqies have been used by many people in differnet scienctific industries for many years. Response surfaces involve creating empirical models to approximate system behavior (Breyfogle 1999). Since the models are empirical, they have no meaning by themseleves and can only explain a limited amount of system behavior. Response surface models can be created in any mathematical fashion that their creator chooses, but as a practical matter they are often linear, second order polynomial equations based on a Taylor series approximation with a least squares fit (Box and Draper 1987), such as the one illustrated below in Equation 10.

$$R = b_o + \sum_{i=1}^{n} b_i x_i + \sum_{i=1}^{n} b_{ii} x_i^2 + \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} b_{ij} x_i x_j + \varepsilon \tag{10}$$

In the above equation, R is the response, b_0 is the response intercept, b_i are the coefficient for the first order terms, b_{ii} are the coefficient for the second order terms, b_{ij} are the coefficient for the cross terms, and x_i and x_j are the independent variables and ε is the error term. The coefficients b_i, b_j, and b_{ij} are generally calcualted using a least squares fit. The response, R, can now be estimated for any combination of variables x_i that are in the model. These second order response models are often created using three level DoEs, but they can be created using four or more level DoEs (Breyfogle 1999). These DoEs can be created in a variety of ways and have a variety of designs including central composite design, D-optimal design and others. These DoE have variable ranges within which the response surface equation is valid and outside which it is not.

Response surface equations (RSEs) have positive and negative attributes. They are easy to understand and use—anyone who has taken algebra knows what a quadratic equation is—and can be easily generated. However, they cannot predict the response bahavior outside of the variables ranges used to create the response surface. Response surface equations also cannot model non-linear system behavior, which is common in aerospace systems. Using Equation 10, these models also can only model systems with continuous variables while many engineering systems have non-continuous variables.

A.2 Neural Networks

Neural Networks are a surrogate modeling technique inspired by biological brain function. A neural network, like a brain, takes in input, translates that input into a form it understands, and then gives an output (Fraser 1998). These processes take place in what are called layers. The first layer is the input layer and it contains the model inputs, the last layer is the output layer and it contains the response models and the layers in between are called the hidden layers. These layers have the function of developing the model, and there can be several of them. This process is illustrated in Figure 72, for one hidden layer, which is the simplest and most common form of neural nets. The mathematics of neural networks can become very complicated in the hidden nodes. Almost any functional form can be used in the hidden nodes to map the analysis inputs to the regression outputs, but most neural nets use a logistic function (Johnson and Schutte 2006). One common type of single hidden layer neural network uses the logistic sigmoid function given in Equation 11.

$$R_k = e_k + \sum_{j=1}^{N_H} \left(f_{jk} \left(\frac{1}{1 + e^{-\left(a_j + \sum_{i=1}^{N} \left(b_{ij} X_i \right) \right)}} \right) \right) \tag{11}$$

In Equation 11, a_j is the intercept term for the j^{th} hidden node, b_{ij} is the coefficient for the i^{th} design variable, X_i is the value of the i^{th} design variable, N is the number of input variables, e_k is the intercept term for the k^{th} response, f_{jk} is the coefficient for the j^{th} hidden node and k^{th} response, and N_H is the number of hidden nodes (Johnson and Schutte 2006). Often, a least squares error type of regression is used to fit the data; however, other types of regressions can be used. Neural Networks need two sets of data, a training set and a validation set. The training set of data is used to generate Equation 11 (i.e. it is used to “train” the network), while the validation set of data is used to check the response equations for accuracy.

Neural Networks have some advantages and disadvantages over response surfaces. Neural Networks are non-linear and so can accurately handle non-linear responses; however, they do require continuous and differentiable hidden node equations. They accurately model non-linear, multimodal spaces, which makes them well-suited for problems that response surfaces have trouble modeling. The equations for neural nets are complicated, and it is not usually clear which variables are driving the response. However, a person with knowledge of calculus can understand the mathematics behind neural networks even though the process is very opaque. Neural networks are more complicated than response surfaces and can take time to generate responses and train the networks. Neural networks can be used in situations where response surfaces are not giving the desired results.

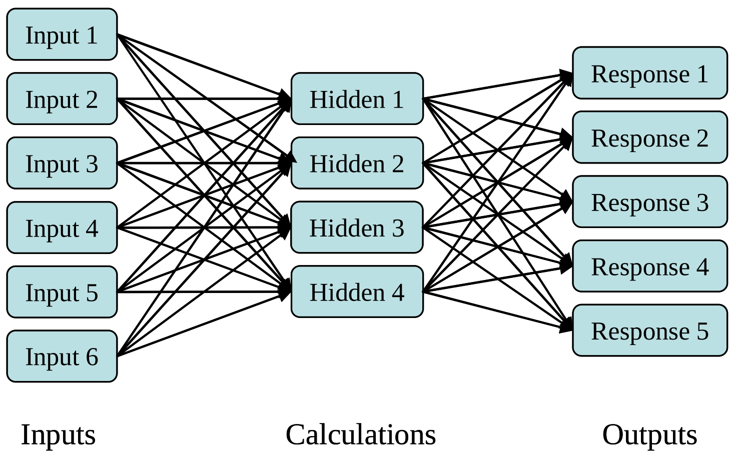

Figure 72: One Hidden Layer Neural Network

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VITA

VICTORIA KATHERINE THOMAS

Victoria Katherine Thomas was born in Philadelphia, PA in 1981. She grew up in Cherry Hill, NJ with her parents, sister, and brother. She attended public schools from kindergarten through 12th grade. She entered Syracuse University in Syracuse, NY in 1999, where she chose to major in aerospace engineering. While at Syracuse University she participated in AIAA's Design/Build/Fly competition. She received a Bachelor's of Science in Aerospace Engineering from Syracuse University in 2002. Victoria entered the Aerospace Systems Design Laboratory (ASDL) at Georgia Institute of Technology in August 2002. While at ASDL she worked with a variety of aircraft engine manufacturers and government agencies. Victoria received a Master's of Science in Aerospace Engineering from Georgia Tech in May 2002 and a Doctor of Philosophy in Aerospace Engineering from Georgia Tech in May 2007. She currently resides in New Hampshire with her husband.