A DECISION SUPPORT FRAMEWORK FOR AIRCRAFT CONCEPTUAL DESIGN IN THE PRESENCE OF COMPETITION

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Michael Z. Miller

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A DECISION SUPPORT FRAMEWORK FOR AIRCRAFT CONCEPTUAL DESIGN IN THE PRESENCE OF COMPETITION

Approved by:

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

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

Dr. Simón I. Briceño
School of Aerospace Engineering
Georgia Institute of Technology

Professor Brian J. German
School of Aerospace Engineering
Georgia Institute of Technology

Professor Willie J. Belton
School of Economics
Georgia Institute of Technology

Date Approved: 12 May 2016

To Mom, Dad, Jeffrey

& Sarah

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Nomenclature

β	Linear Coefficients of Equations in RSM
$\beta(2,5)$	Beta Distribution with shape parameters set to (2,5)
$\beta(3,3)$	Beta Distribution with shape parameters set to (3,3)
$\beta(5,2)$	Beta Distribution with shape parameters set to (5,2)
ϵ	Residual Term from Surrogate Model
λ	Comparison Relationship Between DMU Evaluated and Other DMUs
λ-factors	Correction Factors Used To Model Effects of Enterprises
μ	output "weights"
ν	input "weights"
Π	Profit
θ	DMU's Efficiency Score
k-factor	Correction Factor Used To Model Effects of Technologies
\$/RPM	Average Required Yield Per Revenue Passenger Mile
AC	Average Cost
ALCCA	Aircraft Life Cycle Cost Analysis
ANN	Artificial Neural Nets
AR	Average Revenue
BL	Baseline
BRAINN	Basic Regression Analysis for Integrated Neural Networks
C_t	Costs in year t
$C_{M,Tot}$	Manufacturing Costs
$C_{R,Tot}$	RDT&E Costs
$C_{S,Tot}$	Sustainment Costs
CCF	Cumulative Cash Flow
CCR	Charnes, Cooper, and Rhodes

CDF	Cumulative Distribution Function
CoDeS	Competition-influenced Decision Support
D	Drag
D^M	Market Demand
D_{Prof}	Profile Drag
DEA	Data Envelopment Analysis
DMU	Decision Making Unit
DOC	Direct Operating Costs
DoE	Design of Experiments
DoI	Direction of Improvement
Ent-IES	Enterprise Identification Evaluation and Selection
Ent-IF	Enterprise Impact Forecasting
f	Inflation Rate
FLOPS	FLight OPtimization System
GE	General Electric
I_t	Incomes in year t
IOC	Indirect Operating Costs
L	Lift
$L_{Tot,LC}$	Length of Trips Flown Throughout Aircraft Life Cycle
lb_f	Pounds of Force
lb_m	Pound Mass
LF	Load Factor
M&S	Modeling and Simulation
MC	Marginal Cost
MCDM	Multi-Criteria Decision Making
MCS	Monte Carlo Simulation
MFE	Model Fit Error

MLC	Manufacturer's Learning Curve
MR	Marginal Revenue
MRE	Model Representation Error
MRSN	Multi-Response Signal to Noise
N_S	Number of Seats on an Aircraft
NE	Nash Equilibrium
NEO	New Engine Option
NEO+	Technology Package of NEO and Winglets
nmi	Nautical Miles
NPV	Net Present Value
NSGA-II	Non-dominated Sorting Genetic Algorithm II
O	Objectives
OEC	Overall Evaluation Criterion
OEM	Original Equipment Manufacturer
P_D	Price Charged in a Duopoly
P_i	Amount of Cash in Year i
P_M	Price Charged by Monopoly
$P_{1,B}$	Price Firm 1 Charges in Bertrand Duopoly
$P_{2,B}$	Price Firm 2 Charges in Bertrand Duopoly
$P_{M,R}$	Reservation Price
PDF	Probability Density Function
PEST	Political, Economic, Social, and Technological
PPI	Producer Price Index
Q_D	Quantity Produced in a Duopoly
Q_M	Quantity produced in a monopoly
$Q_{1,C}$	Quantity Firm 1 Produces in Cournot Duopoly
$Q_{2,C}$	Quantity Firm 2 Produces in Cournot Duopoly

q_∞	Dynamic Pressure
QL	Normalized Quality Loss
R	Response in RSM
R^2	Coefficient of Determination
R_1	Firm 2's Reaction to Firm 1
R_2	Firm 1's Reaction to Firm 2
RDT&E	Research, Development, Testing, and Evaluation
ROI	Return on Investment
RSM	Response Surface Methodology
S^M	Market Supply Line
s^+	Slack – output shortfalls
s^-	Slack – input excesses
S/N	Signal to Noise Ratio
S&S	Sizing and Synthesis
SME	Subject-Matter Expert
SQP	Sequential Quadratic Programming
SWOT	Strengths, Weaknesses, Opportunities, and Threats
T/W	Thrust-to-Weight Ratio
TIES	Technology Identification, Evaluation, and Selection
TIF	Technology Impact Forecasting
TNQL	Total Normalized Quality Loss
TOC	Total Operating Costs
TOPSIS	Technique for Ordered Preferences by Similarity to Ideal Solution
TSFC	Thrust-Specific Fuel Consumption
TSFC	Thrust-Specific Fuel Consumption
U	Utility value
US	United States

Util	Utilization
w_i	Weighting for ith Objective
W/S_{wing}	Wing Loading

SUMMARY

Most conceptual design techniques for aircraft implicitly assume that the aircraft manufacturer operates in a monopoly. This is because these techniques do not directly account for the possible actions of a competitor. By examining several motivating examples from the aviation industry, it was determined that in the presence of a competitor the design of an aircraft can be impacted. Therefore, current design approaches were deemed lacking because they do not account for the fact that aircraft markets are best characterized as a duopoly where two manufacturers are competing for market share. It was also determined that most forms of competition can be categorized as technology infusions or enterprise-based solutions. There was a need identified to determine how to select an appropriate strategy in the presence of competition. This problem is further complicated by the inherent uncertainty that exists in designing an aircraft compounded with the lack of perfect knowledge of a competitor.

The main objective of this dissertation was to construct a framework for facilitating the direct comparison between an aircraft design and a competitor's design during the early phases of conceptual design. This framework should parametrically account for design considerations and possible competitive strategies in an integrated environment to not only analyze the physical performance of an aircraft, but also the economic viability for a given market. This lead to the development of the Competition-influenced Decision Support (CoDeS) Framework, which allows for the interactive exploration of competitive strategies using exploratory or normative forecasting. These strategies were assessed using a validated modeling and simulation environment by implementing the established technique of k-factors to represent

technology strategies and the developed technique of λ-factors to represent enterprise strategies.

In order to gain a clear understanding about the interdependencies that exist between an aircraft design, a competitor's design, and competitive strategies (technology and enterprise), the effects of uncertainty were mitigated using a two-step approach. First, the large variability from the effects of uncertainty where mitigated by using scenario-based analysis. Secondly, a hybrid formulation using a modified Taguchi's signal-to-noise ratio approach combined with a multi-criteria decision making technique. Two techniques were considered: an overall evaluation criterion and the technique for ordered preferences by similarity to ideal solution to compare strategies between two aircraft competing for market share.

Finally, the CoDeS Framework was implemented for three use cases in order to demonstrate its capabilities. The first use case examined an exploratory forecasting approach for analyzing a proposed enterprise strategy. The second use case examined normative forecasting of enterprise strategies in order to determine a minimum threshold for a competitive strategy. Finally, the third use case examined a hypothetical scenario of two aircraft manufacturers trying to enter the Asian market – in this scenario, one manufacturer competes using technologies and the other competes using a maintenance-based enterprise strategy. The completion of this research yielded a parametric, integrated framework that can be used interactively in order to assess the effects of competition during the conceptual design of an aircraft.

CHAPTER I

MOTIVATION

"Since the origin of the species, men have been making decisions, and other men have been telling them how they either make or should make decisions."
Peter C. Fishburn [62]

The conceptual design of an aircraft is a difficult process. This difficulty arises for multiple reasons, including but not limited to: multiple stakeholders, high interdependencies between design variables, non-obvious system-level impacts from changes in design variables, large amounts of uncertainty, and significant consequences for a failed design. For these reasons, aircraft design should be thought of as something that requires the rigors of a scientific process. Hazelrigg summarizes this notion by stating:

> [the] process of creating something physical requires allocation of nature's resources; therefore engineering design is, essentially, the effective allocation of resources. The allocation of resources is, by definition, decision making. [73]

While experience and intuition may allow for better decisions [66], it may be more useful to consider these to be two of the many possible tools available to a decision-maker. Since the 1940s, there has been a significant push to improve decision making from a variety of disciplines, including: mathematics, economics, social sciences, behavioral sciences, philosophy, and engineering. [66] By cross-fertilizing techniques from these disciplines, a decision-maker has more *tools* available to support their decisions. For instance, a mental model may allow for a decision-maker to better understand the interdependencies that exist in a system; however, by including an engineering model, which is based on the underlying physics and mathematics of the system, one may be able more accurately quantify sensitivities of the system.

As the system being designed becomes more complicated or when there is high risk (i.e., consequences), there is a need for more and/or better tools to conduct analysis. Both of these characteristics are present when designing aircraft, which means that decision-makers desire tools that can allow them to gain more insight. This dissertation sought to explore the impacts of competition during the conceptual design of an aircraft. The remainder of this chapter provides necessary background information and motivating examples in order to understand which aspects of competition are most important to explore during the conceptual design of an aircraft.

1.1 Aircraft Design

When considering the design of an aircraft, multiple parameters may need to be determined in order to meet the system's criterion(a) for success. Ideally, these parameters should be chosen in order to meet or exceed the stakeholders' requirements; the design that most efficiently meets the system's requirements may be considered the best or optimal design. Very early on in the design process, a simplified model of an aircraft may be considered to reduce the number of factors under consideration. But even when considering a simplified system with only a few parameters and one requirement, a decision-maker may have difficulty with, or may be incapable of, identifying the optimal design. [73, 10] As the number of parameters and criteria increases, which occurs further along the design process, decision making can become exponentially difficult. [94] This nonlinear increase in difficulty can occur from a variety of factors, including: inability to deductively reason at various stages [119], non-obvious interactions between parameters and criteria [155], path-dependency of decision making within a group/design team [140, 73], high risk [94, 72] and/or high uncertainty [62], etc. These factors are often indicative of a complex system. While a variety of definitions exist, a complex system can be thought of as one that exhibits one, some, or all of the previously mentioned factors, which are summarized below:

Interdependencies Changes in one subsystem or component can have cascading effects through other subsystems.

Non-Obvious Behavior Changes in one parameter may propagate through the system and result in unintended behavior.

High Risk Failed designs can lead to large consequences.

High Uncertainty There exists some forms of reducible and irreducible uncertainty. It may be impossible to accurately extrapolate to a single point.

An aircraft is an example of a complex system. The concept of a complex system is not introduced as a means for analyzing the design of an aircraft. Rather, it further motivates the need for rigor for any process followed during the design of an aircraft. The complexities that exist require that analysis be traceable, defensible, and repeatable in order for a decision-maker to have confidence in their decisions.

Not only does the aircraft have numerous components and subsystems working together to achieve more than the sum of their individual parts, but these components and subsystems also are highly interdependent. For example, consider the initial sizing of fuel required for an aircraft: to increase the range of a given aircraft, more fuel is required, which means a larger wing is needed to provide more lift for the increased weight, which in turn increases the weight of the wing structure thus requiring more fuel, etc. [8, 137, 105] An aircraft's components and subsystems can also exhibit non-obvious behavior. For example, consider the design of a wing; a small increase in the thickness-to-chord ratio can result in large structural weight savings. The reason for the significant weight saving is due to changes in the moment of inertia of the wing, which increase the stiffness, thus requiring less structural weight to support the loads. [58] However, it should be noted that this increase in thickness-to-chord may also have other effects on other performance metrics, including lift-to-drag ratio, aeroelastic performance, etc. Understanding and accounting for these non-obvious yet modelable effects is critical for analyzing an aircraft's performance. To fully capture these effects, a non-heuristic model should be used to allow for changes in a subsystem/component to propagate through the entire system. A clear understanding of an aircraft's performance is necessary to determine whether a proposed design is capable of meeting stakeholders' needs.

These stakeholders can impose many requirements, either directly or indirectly, which may affect the aircraft throughout the stages in its life cycle. For example, airports are mainly concerned with the operations of an aircraft, but a supplier would be more concerned with the manufacturing of the aircraft. Failure to meet those requirements may result in a failed design, which could prevent certification, decrease number of aircraft purchased, limit operations, etc. The following list is representative of some stakeholders and their concerns in the life-cycle of an aircraft.

Aircraft Manufacturer How do I create and deliver a technically feasible and economically viable aircraft in an appropriate time frame?

Airports Will this aircraft cause a disruption in the current operations of this airport?

Airport Planners What are the necessary procedures associated with the operation of this aircraft

Airline Companies (i.e., Customers) How will this aircraft impact the overall performance of my fleet?

Airline Employees How do we know the aircraft will be safe and reliable?

Component Manufactures What are the tolerances necessary in the manufacturing process for this aircraft?

Consumers (i.e., Travelers) Will this aircraft yield ticket prices that are affordable?

Engine Manufacturer What are the propulsive requirements (e.g., thrust, noise, emissions, fuel burn) for this aircraft?

Investors When will the aircraft provide an acceptable return on investment?

Maintenance Companies/Divisions What are the mean time to failures of the various components?

Neighborhoods Around Airport How will this airplane affect my daily life?

Raw Material Extractors Will extracting the necessary materials for this aircraft require a new facility?

Regulators Will this aircraft pass the certification standards?

Subsystem Manufactures What are the requirements of the various subsystems for this aircraft?

Transporters How will the various subsystems be transported in an efficient and cost-effective manner?

The generalized life cycle of any system can be divided into a series of major categories, which often occur in series to one another. A notional depiction of these categories can be seen in Figure 1 [59, 51]. After analyzing the market and determining the *need* for the system (i.e., aircraft), the next step is the *conceptual design* of the system. *preliminary and detailed design phases* follow the *conceptual design phase.*

At this point, the design is finalized and *manufacturing* begins. After a system is manufactured it is then *deployed*, which begins the *operations and support phases* of a system's life-cycle. While Figure 1 represents one approach to designing a system, multiple authors have demonstrated the need to shift knowledge gained about a design as early as possible through this process.

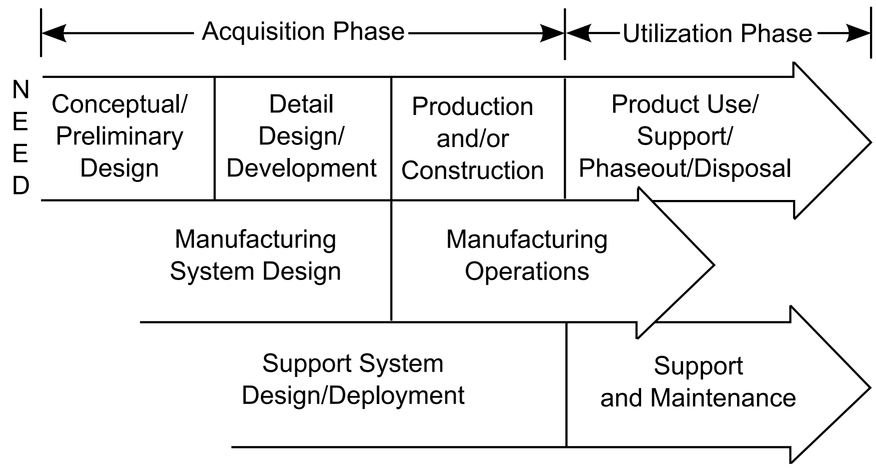

Figure 1: Notional depiction of the serial process of design. [59, 51]

This need can be seen in the current aircraft design practice, which is undergoing a paradigm shift as shown in Figure 2 [59]. This shift can be characterized as trying to bring knowledge earlier in the design process. In Figure 2, Fabrycky illustrates that approximately 66% of the costs are committed to the design of the aircraft by the end of the *conceptual design phase*. [59] Besides Fabrycky, Dieter also shows a similar trend, where approximately 75% of the costs are committed by the end of the *conceptual design phase*, which is shown in Figure 3. [51] While both Figure 2 and 3 are notional trends, they illustrate the generally accepted belief that a large amount of the costs of the design of an aircraft are committed before sufficient knowledge may be gained to make informed decisions. This means that design changes should be made as early as possible in the design phase before a substantial amount of funds are committed. As seen in Figure 2, traditional design practices result in difficulty in making

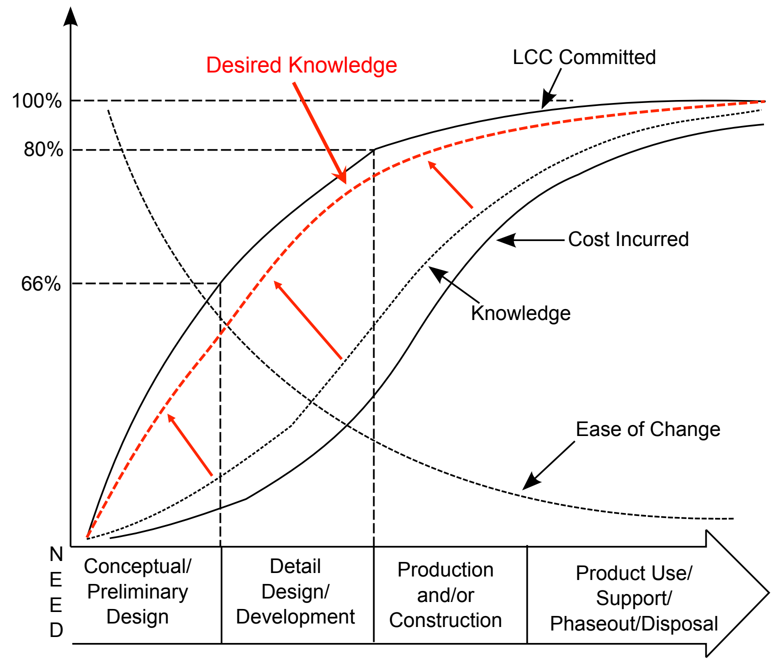

Figure 2: Paradigm shift to bring knowledge earlier in the design of aircraft. Modified from Fabrycky. [59]

decisions early because less is known about the design's performance and subsystems' interdependencies during the *conceptual design phase*. To minimize the number of design changes occurring after the *conceptual design phase*, the decision-maker must increase knowledge of the design's performance in the presence of uncertainty about the future. These uncertainties include, but are not limited to: environmental, economical, and competitive. A decision-maker could gain more knowledge earlier in the *conceptual design phase* by implementing a process that addresses these three sources of uncertainty.

These sources of uncertainty pertaining to design are both aleatory (i.e., irreducible) and epistemic (i.e., reducible). This dissertation does not seek to reduce the epistemic uncertainty in conceptual aircraft design. Instead all uncertainty is

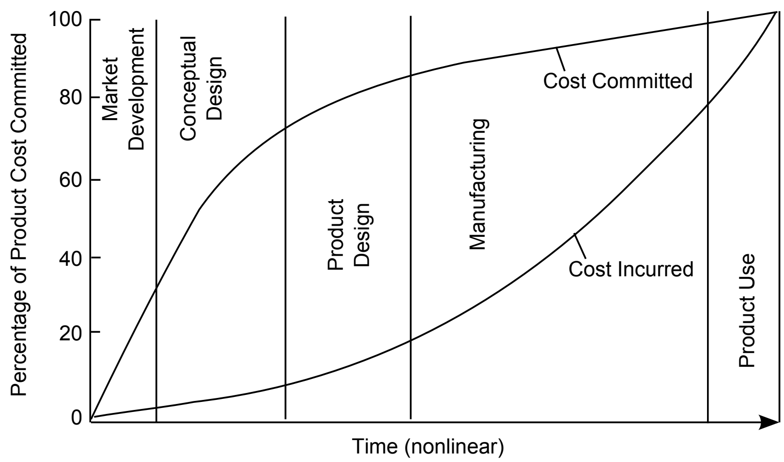

Figure 3: Dieter's approximation of the committed cost to the design of a complex system. [51]

examined as if it were aleatory and only approaches to mitigate its effects were explored. The main concern with uncertainty is that it reduces the ability of a decision-maker to predict the impacts (i.e., consequences) of their decisions, and can cause large amounts of risk for an aircraft manufacturer because of these consequences. [66, 62, 94] An aircraft manufacturer's risks can be better understood by assuming that they are profit-maximizing companies. This means that all decisions made by an aircraft manufacturer are intended to maximize their profit. Therefore, the consequences from uncertainty can be directly related to the amount of profit (or loss) that is expected from any given design.

To further expand on the impacts that uncertainty can have on the design of aircraft, several examples from industry are examined in the following sections. The five examples presented can be divided into two separate categories: 1) cases of negative consequences due to market issues, and 2) cases of aircraft Original Equipment Manufacturers (OEMs) solutions to market/competition issues. By examining these examples from industry, the requirements of a framework to analyze conceptual design of an aircraft in the presence of a competitor were derived. From these requirements,

Table 1: Layout of Motivating Examples in Following Sections

Negative Consequences Due to Market Issues	
§ 1.2.1	Lockheed Martin L-1011
§ 1.2.2	Airbus A380
OEM Strategies to Market/Competitor Issues	
§ 1.3.1	Boeing B787 v. Airbus A350
§ 1.3.2	Boeing 737MAX and Airbus A320NEO
§ 1.3.3	Boeing Enterprise Solutions

the objective of this research was formulated.

1.2 Negative Consequences Due to Market/Competitor Issues

These first two examples examined involve the Lockheed Martin L-1011 and the Airbus A380. These examples provide two main sources of insight. Firstly, they both show the tremendous economic pressure that exists for these aircraft – neither of these aircraft could be described as technical failures.

The L-1011 represented the last commercial transport aircraft built by Lockheed Martin because it was a financial disaster – more information is given on this example in § 1.2.1. One could infer from this behavior that the decision-makers at Lockheed Martin determined the commercial aircraft market to be too risky. Today, Lockheed Martin is one of the most profitable defense contractors in the world.[101]

The A380 could be described as a modern marvel in terms of engineering. Not only can the aircraft carry a very large number of passengers, but the range of the aircraft is almost unprecedented. In early 2016, an A380 flew 8,824 miles, nonstop from Dubai to New Zealand. [138] Even with these strong technical benchmarks, the A380 has struggled financially – more information on this is given in § 1.2.2.

This section will provide further background detail on both of these aircraft and an analysis of the problems that have limited/reduced their success. At the end of each sub-section is a key observation that was used to directly motivate the objective of this research.

1.2.1 Motivating Example: Lockheed Martin L-1011

Lockheed Martin is currently a well-known and well-established "global security and aerospace company ... [that] is principally engaged in the research, design, development, manufacture, integration and sustainment of advanced technology systems." [101] The history of Lockheed Martin can be traced back to 1912. Before the Lockheed Corporation and Martin Marietta merger in 1995, the Lockheed Corporation manufactured commercial aircraft. One of the more notable aircraft was the L-1011 TriStar, which was produced in the 1970s and 1980s and can be seen in Figure 4. According to Lockheed Martin, 250 L-1011 jets were produced. [101]

Figure 4: A prototype L-1011 TriStar during final assembly in 1970. [63]

This aircraft was notable for a variety of reasons. It was the first commercial aircraft to be able to automatically fly from takeoff to landing, which made it one of the most technologically advanced aircraft of its day. [101] The aircraft was also one of the most admired double-aisle aircraft from an aerodynamic perspective. [125] While these all seem like characteristics of a successful aircraft, many would consider the L-1011 to be a failed design because at the end of production, around 1981, the Lockheed Corporation had lost approximately $2.5 billion USD. [125] L-1011 was the last commercial aircraft produced by the Lockheed Corporation. [101]

This example lends itself to multiple observations, which may provide further insight on aircraft design. Even though the L-1011 TriStar was a technologically advanced aircraft that received numerous praises from industry insiders, the aircraft was ultimately not economically viable. Lockheed Martin's website highlights several difficulties that existed in the design process, stating that "[divergent] needs from competing airlines led to design challenges. Financial difficulties ravaged its engines manufacturer. And a recession, fueled by the world's first oil crisis, lessened the demand for commercial airliners." [101] This quote highlights the various uncertainties that existed not only in the customers' requirements, but also the economic environment. These uncertainties can become especially problematic because of the long life cycle associated with many aircraft. The L-1011 was initially conceived in the 1960s, but was manufactured for approximately ten years during the 1970s and 1980s. It is necessary to note that some of these concerns have been addressed in the literature.

Summary of Key Observations:

Uncertainty This example highlights uncertainty associated with requirements and economic climate in which the aircraft is not only designed but also operated.

Economic Viability Besides the performance of an aircraft, the financial aspects need to be considered. The economic constraints on a design must be considered, especially with modern aircraft that have long-range capabilities.

Long Life-cycle Not only do aircraft take numerous years to design and manufacture, but airlines will often operate the aircraft for a long period of time.

1.2.2 Motivating Example: Airbus A380

In terms of wide-body commercial aircraft, The Boeing Company (Boeing) and Airbus are currently the main, if not only, aircraft manufacturers. Currently the B747 is Boeing's largest aircraft and can hold over 400 passengers, depending on the configuration. The B747 was initially deployed in 1969, and has been a successful aircraft for Boeing. [23] Airbus's A380 can hold 500-800 passengers. [2] Figure 5 shows a picture of an A380. The first A380 was delivered in 2007, but it is not completely certain whether the aircraft will be profitable over its life cycle. This has to do with issues concerning the initial deployment of the A380 and the long-term acceptance of very large aircraft.

The A380 began its formal development in the early 1990s. While the double-decker design was not unique, it did provide several challenges for Airbus. One of these challenges can still be readily seen in the United States (US). Due to the immense size of these aircraft, most US airports are not large enough to accommodate them. In fact, "the Atlanta airport had to widen two runways and three taxiways by a total of more than 855,000 square feet." [121] Besides runway length, the jetports would require a new design in order to board passengers in a timely manner. This may be an issue for longterm profitability because the required additional investment required by airports, which limits the market penetration of the A380. As of early 2016, experts believe that the Airbus A380 may reach its breakeven point in the coming years, based on the current number of orders. [173] Even though it has been seven years since the A380's first commercial flight, only eight airports in the US, which is currently the largest market for commercial aircraft, can accommodate the aircraft. Of those eight airports, five only offer one destination for the A380. [5]

Figure 5: Prototype A380 about to land on its maiden flight. [54]

Another large concern with the A380 involved several delays in the initial delivery of the aircraft. One announcement about a delay in delivery caused Airbus's (formally EADS) stock price to drop by 11.7% in a single day. [22] Another announcement about a delay in delivery and reduction in initial delivers caused their stock price to drop by 26.3% in a single day. [37] This high volatility of a company's stock price could have significant consequences for an aircraft manufacturer. While *too big to fail* may be a current colloquialism with financial institutions and US auto makers, there is no reason to believe that a significant drop in stock price could not potentially bankrupt an aircraft manufacturer. These consequences are easily related to the L-1011; there is a need to analyze possible future scenarios that could impact the design of an aircraft. One way to handle this need is to use parametric scenarios where all variables of interest, not just design variables, can easily be adjusted and their effects calculated.

Summary of Key Observations:

Market Penetration Different markets may have unique standards or requirements in order to enter them. This may result in increased cost or a decrease in acceptability. All airlines cannot be assumed to have the same needs or the same preferences when considering new aircraft purchases.

Market Volatility Bad news could cause investors to quickly lose confidence and possibly bankrupt the company. Designing a new aircraft could mean that the aircraft manufacturer is figuratively *betting the farm.* These considerations can be difficult to account for because of investors' susceptibility to human emotion. This highlights the need to examine financial information throughout the life-cycle and not only the estimated profit at the end of the life-cycle.

1.3 OEM Strategies to Market/Competitor Issues

Two of the next three examples pertain to a specific situation involving a direct competition between Boeing and Airbus. The first case examines the infusion of new technologies associated with a new design concept. The second example examines the use of a different type of strategy option that does not necessarily require a new geometry. The final example looks at specific business practices that have been implemented and are not related to any specific geometric design or technology.

Boeing and Airbus are currently the only manufacturers of large commercial aircraft that are in deployment. While their competitive strategies are not identical, they do often directly compete in some key areas. The Boeing 787 and Airbus A350 were designed to capture similar segments of the commercial aviation market. The inclusion of advanced structural technologies by Boeing caused Airbus to make changes to their proposed design.

Due to the large risks and cost associated with designing a geometrically novel aircraft, Boeing and Airbus have looked at other strategy options to make their designs more competitive. One of these options is referred to as a New Engine Option

(NEO). This approach basically replaces an engine from an existing aircraft with a more advanced engine, while requiring minimal geometric changes to occur.

Finally, the last example will examine some of the business practices of OEMs, specifically focusing on Boeing. The strategies presented in this section are especially important because they are not directly related to any specific aircraft design. However, the impacts of these strategies can be very large for bot the OEM and their customers.

This section will further examine these different strategy options in more detail by focusing on background information and consequences of those strategies. By analyzing key observations from these strategies, more detailed requirements for the proposed framework can be determined.

1.3.1 Motivating Example: Boeing B787 and Airbus A350

As previously stated, large aircraft manufacturing can be characterized as a duopoly, which means that there are two main competitors: Airbus and Boeing. However, when considering the manufacturing of smaller aircraft, the market resembles more of an oligopoly, which means there are several competitors (e.g., Airbus, Boeing, Bombardier, Embraer, Comac). This is an important distinction because a company's behavior is expected to be influenced by the type of competitive market in which they are competing. To set the context, an example concerning the design of Boeing's B787 and Airbus' A350 is presented; these aircraft can be seen in Figure 6. These two aircraft are both trying to capture the 200+ passenger aircraft market, which is currently a duopoly. After this example, economic theory related to duopoly competition will be discussed. This theory will then be compared to the example presented in this section to gain more insight into the expected behavior of aircraft manufacturers in a duopoly.

Figure 6: Photographs of prototypes for the Boeing B787 [150] and Airbus A350 [53].

Airbus began designing the A350 in 2004. [120] Around the same time, Boeing announced that its B787 aircraft would be made out of 50% composite materials. [143] Boeing's use of composites in its design could be thought of as a strategy of infusing a new technology into the design of an aircraft. Even though aircraft manufacturers have been utilizing composites in their designs for decades, the B787 would use more composites than any other commercial aircraft. By using a large amount of composites, Boeing, either intentionally or unintentionally, fundamentally changed the market. This caused the airlines to start desiring aircraft that took advantage of the benefits of composites, specifically the fuel savings that come with reducing weight. This idea is further supported by the fact that after being unable to gain an adequate number of orders, Airbus changed the A350 design to include significantly more composites. [120] The new A350 design is slated to be made of approximately 53% composite material. [3] As of February 2014, over 820 orders had been placed for the A350, but no aircraft had been delivered. [3] One may assume that Airbus will lose out on profits by not being the first to enter the composite aircraft market. However, the adoption of the composites, or any technology, may not be that intuitive. For more insight, a review of economic theory regarding technology adoption in a duopoly was conducted in § 2.1.4.

Summary of Key Observations:

Strategy Option: New Design One way to gain a competitive advantage is to develop a new design that utilizes one to several new technologies. However, this should not be done without consideration toward a competitor and their possible strategies involving technologies, which only further increases the uncertainty of this problem. However, by considering a competitor and their possible design alternatives, an OEM may be able to identify a design-strategy combination that is more robust to competition.

1.3.2 Motivating Example: Boeing B737MAX and Airbus A320NEO

As previously stated, aircraft OEMs do not only compete by bringing forth new geometric design alternatives with infused technologies. Sometimes aircraft OEMs are able to replace the engine of an existing design with a more efficient alternative. This is not necessarily true for all aircraft designs and only applies to designs that are currently in the market. Two recent examples of this strategy being used are with the Boeing 737MAX [26, 25] and the Airbus A320NEO [4]. These two aircraft are shown in Figure 7. These two aircraft are considered derivative aircraft as opposed ot the previous example with the Boeing B787 and Airbus A350.

Boeing B737MAX Airbus A320NEO

Figure 7: Photographs of Boeing 737MAX [25] and Airbus A320NEO [4]

This type of strategy option has several benefits and shortcomings associated with it. To help visualize these, Figure 8 shows notional CCF for both new commercial aircraft and derivative aircraft.[110] Firstly, there are lower costs because there is less RDT&E costs and drastically reduced certification costs. These lower costs translate to a lower amount of risk for the aircraft manufacturer. However, one of the major drawbacks of these derivative designs is that they tend to have lower potential profits based on historical data collected by NASA Ames [110]. Another major benefit of NEO strategies is that aircraft OEMs can incentivize competition amongst engine manufacturers.

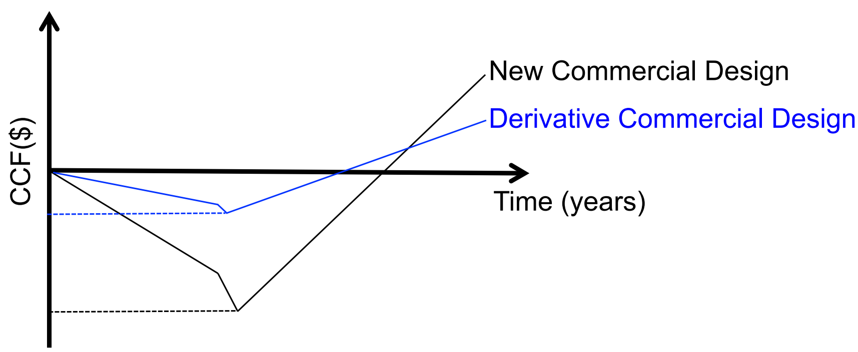

Figure 8: Notional Manufacturer CCF for new design alternatives versus derivative design alternatives – adapted from data from NASA Ames and presented by Mavris [110]

Besides the NEO strategy, there are other ways OEMs can modify their aircraft without having to examine a new geometric alternative. One of these options is the use of winglets or similar devices such as end plates that attach to the tip of the wing. The purpose of these devices is to decrease fuel consumption decreasing the amount of lift-dependent drag. These devices were commonly deployed in the same manner as a NEO – they would be integrated into an aircraft that exist in the market without significant changes to the geometry. However, sometimes the use of these devices is incorporated with other strategy options like the NEO. Both the Boeing B737MAX and Airbus A320NEO utilize a form of these devices: the B737MAX has a split-tip winglet[26, 25] and the A320NEO has a “sharklet” (blended winglet). [4]

Summary of Key Observations:

Strategy Option: Derivative Design While some may consider competition between aircraft OEMs to consist of new geometrically-designed aircraft, that is not always the case. It can be significantly less costly and less risky to infuse new technology into an existing design.

1.3.3 Motivating Example: Boeing Enterprise Solutions

Technology infusion is not the only strategy that has been used by OEMs to make their aircraft more competitive. Several OEMs have began looking at other strategy options besides new or modified products. This is an important transition because it shows that OEMs are seeking to earn revenue at different stages in an aircraft's life-cycle. Implementation of these strategies is commonly referred to as *enterprise engineering*, which “can be defined as the art of understanding, defining, specifying, analyzing, and implementing business process for the entire enterprise life cycle, so that the enterprise can achieve its objectives, be cost-effective, and be more competitive.”[170] To summarize, Enterprise Engineering can be thought of as transitioning from the approach of solely designing a product to focusing on that product's life cycle to see if there are aspects that can make that product more competitive. An example of an aircraft OEM that utilizes these techniques is Boeing, which has invested heavily into various initiatives to increase the competitiveness of their products. Two key areas specifically discussed in this subsection involve manufacturing and maintenance.

Manufacturing:

While keeping costs low has always been a priority for any manufacturer, there has been many initiatives that have been embraced by aircraft OEMs in recent decades.

One of the earliest techniques was pioneered by Taguchi [157, 158], but since his seminal work many other initiatives have been implemented. Boeing has specifically utilized techniques from Product Lifecycle Management[154], 6σ [139], Integrated Product and Process Design & Lean Aircraft Initiative [167, 83], and more recently Manufacturing Influenced Design [147, 156, 34, 98, 146]. All of these initiatives are focused on reducing the costs of manufacturing by decreasing defects, decreasing labor, reducing waste (i.e., effectively lowering raw material costs), and/or reducing the time to manufacturer. By implementing these initiatives, Boeing has reduced the costs associated with manufacturing some of the most technologically advanced systems in the modern world. By keeping their manufacturing costs low, Boeing is able to remain more competitive by offering their aircraft at a lower price to airlines. For this reason, these manufacturing initiatives can clearly be classified as enterprise engineering solutions.

Maintenance:

Maintenance has always been a concern for the aviation industry. Historically, maintenance would be performed by a third-party company or the airline's maintenance division. This has not been the case for aircraft engines, which have followed a razor-razor blade model [162] for many decades. The razor-razor blade model can simplistically be described as giving customers free razors, but charging for new razor blades. Similarly, "jet engines for commercial aircraft are priced the same way – manufacturers know that engines are long lived, and maintenance and parts is where Rolls Royce, GE, Pratt & Whitney and others make their money" [162] In recent years, there has been a shift in the business structure of aircraft airframe maintenance. Following engine manufacturers, airframe manufacturers are trying to increase profits by capturing the maintenance of the aircraft. "[Boeing's maintenance program] GoldCare has been expanded to include Next Generation B737 and the B747-400 ...

Boeing is developing GoldCare offerings for the B777 and the B747-8." [24] This transition from a product-based firm to a service-based firm has been advocated by literature [129] and can be considered an enterprise engineering solutions.

This initiative may be especially well-received by airlines, specifically those that are seeking to remove their own maintenance units, to reduce overhead (in terms of employees, facilities, and equipment) costs. Boeing advertises that strategy to airlines with their GoldCare service, stating: "Boeing is uniquely positioned to bring advantages to your operations so you can focus on what matters most to you–serving your customers...Boeing can focus on keeping your airplanes where they belong; in the air." [24]

Summary of Key Observations:

Strategy Option: Enterprise The aircraft should not be thought of as just a design, but a product. One should examine enterprise strategies that can be used to make an aircraft more competitive by focusing on various aspects of its life cycle beyond the physical design.

1.4 Layout of Remaining Chapters

This chapter has provided the motivation for this dissertation work. The motivating examples not only demonstrated a need for an approach to analyze competitive strategies, but also provided specific examples of strategies that OEMs use when designing aircraft. While these examples helped provide guidance to competitive strategies, they did not account for all of the competitive strategies. The following chapter examines general economic theory related to competition in order to determine other general forms of competition that may be applicable to aircraft manufacturers. Specific descriptions of these competitive strategies is provided in § 2.2. Based on these insights, relevant approaches to analyzing competition were examined. Identification of a gap in the ability to analyze aircraft OEM competition lead to the formulation of the Research Objective, which is stated in § 2.4.

Chapter 3 explores the technical formulation of a proposed framework necessary to satisfy the Research Objective. This chapter describes the specific actions that are taken during each step of the proposed framework. To address the specific needs of this framework the requirements of an acceptable modeling and simulation (M&S) environment were defined. Since subject matter experts (SMEs) may also be used in conjunction with or instead of an M&S environment, considerations for using SMEs was also presented in this chapter. Relevant research questions were also discussed in regards to addressing the competition element of this dissertation research. Chapter 3 concludes by presenting relevant background information necessary to address these research questions.

Chapter 4 describes the selection and modification of an acceptable M&S environment described in Chapter 3. This chapter also describes three experiments that addressed specific elements from the research questions. The results of these experiments are used to further refine the proposed framework.

Chapter 5 examines three specific *use cases* to examine the capabilities of the proposed framework. These *use cases* examine exploratory and normative forecasting approaches that can be analyzed with the proposed framework. The third *use case* examines a hypothetical scenario of two OEMs examining strategies to enter the Asian market with a narrow-body, single-aisle aircraft design.

Finally, Chapter 6 summarizes the contributions from this dissertation by examining the results of the experiments and outcomes from the *use cases*. This chapter concludes with suggestions for future work.

CHAPTER II

BACKGROUND

"As far as the laws of mathematics refer to reality, they are not certain; and as far as they are certain, they do not refer to reality."
Albert Einstein [57]

Chapter 1 provided motivating examples to properly frame this dissertation work. This chapter seeks to provide the appropriate background information and formal research objective, which is stated in § 2.4. Since the main subject of this dissertation focuses on the competitive nature associated with designing an aircraft, the first section of this chapter explores economic theory related to competition. This section includes descriptions of monopolistic, duopolistic, and perfect competition. From that information, a more detailed analysis of how aircraft OEMs compete was conducted in § 2.2. By combining those two sources of information, relevant methodologies were examined to see which ones may be best suited for analyzing competition amongst aircraft OEMs. By synthesizing insights from these sections, the research objective is formally stated and relevant questions that need to be addressed were posed.

2.1 Relevant Economic Theory

There are four basic types of competitive environments that are commonly studied in the field of economics. These include: monopolistic competition, duopoly competition, oligopoly competition, and perfect competition. When examining aircraft manufacturers, the main competitive environments are duopoly and oligopoly. The competitive markets that define aircraft manufacturers depend on the specific market segment served by those manufacturers. For example, small aircraft with less than 100 passenger capacity would be considered an oligopoly because Boeing, Airbus, Embraer, Bombardier, and Comac currently have designs in this category. When considering large aircraft with 150+ passenger capacity, there are currently only two manufacturers: Airbus and Boeing. The specific competitive environment that an aircraft manufacturer operates has a large influence on their behavior. To better understand this, it is necessary to examine economic theory related to these various forms of competitive environments. The following sections examine monopolistic, duopolistic, and perfect competition in order to highlight the different behaviors characteristic of each. While the following sections explore economic theory related to several competitive environments, a quantitative example directly compares these competitive environments in Appendix A.

2.1.1 Monopoly Competition

A monopoly exists when there is only one producer of a certain product. Monopolies offer many benefits from the perspective of the producer, but not necessarily to the customers. This is because monopolies are considered to be *price setters.* This is shown in Figure 9. Since they are the only manufacturers of a product then they can choose the price to sell it; however, they cannot ignore the basic fundamentals of the law of demand, which loosely states that quantity demanded is inversely related to the price of that product (i.e., a higher price means consumers will demand less of that product). This trend is shown by the market demand line (D^M) in Figure 9. This figure also has lines of Marginal Revenue (MR), Marginal Cost (MC), and Average Cost (AC). MR is defined by the amount of revenue achieved by selling the next unit of a good, whereas MC is the cost associated with producing that next unit. AC is defined as the total cost divided by the cumulative number of units produced. The curves shown in Figure 9 are notional representations.

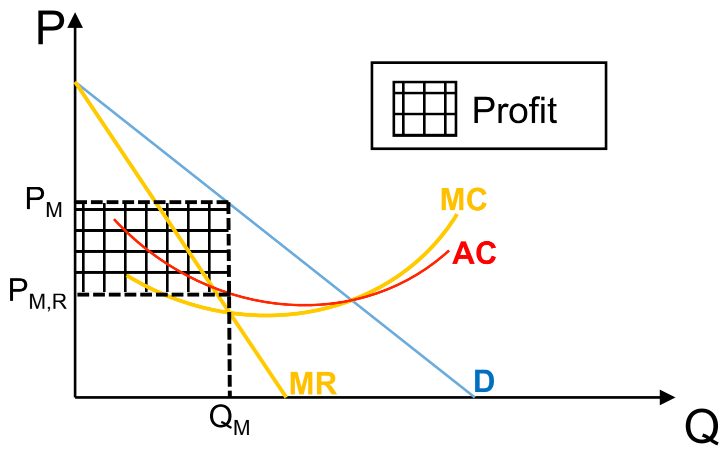

Figure 9: Notional graph of monopolistic competition where firms set the price of their product.

A monopoly is a price setter because they first determine the quantity to manufacture (Q_M) by finding the quantity that causes MR=MC. By examining Figure 9, the D line lies above the intersection of MR and MC, which means that the monopoly can charge a higher price – this is denoted by P_M. Since the AC curve also lies below the D line at this point, the firm earns a profit.

Because monopolies utilize this strategy, they are able to use variable prices as a competitive strategy. This reduction in price causes consumers to purchase the lower-priced good, which can prevent other firms from entering the market if they cannot offer the same goods at a lower price. In fact, the minimum price a monopoly can charge without suffering a loss is often referred to as a reservation price for a monopoly ($P_{M,R}$). This point occurs when Q_M intersects the AC curve. The ability to charge different prices as a competitive strategy is not unique to only a monopoly, but directly shows how the type of competitive environment influences the way in which firms can compete.

2.1.2 Duopoly Competition

A duopoly is a special case of an oligopoly where there exist only two firms; this dissertation does not examine the economic theory related to oligopolies because duopoly competition seemed more appropriate when first constructing a competitive framework. The field of duopoly competition has been studied for well over a century, and there are two leading theories. The first theory was presented in 1838 by Antoine Cournot, with the basic argument that firms in a duopoly fix the quantity to produce and then determine the price from this quantity.[42] In 1883, Joseph Bertrand suggested a different model of duopoly competition that said firms fix the price, then determine the quantity to produce and sell at that price.[19, 20] It is important to note that Bertrand's theory lacked a firm mathematical underpinning until 1889, when Francis Edgeworth closely examined decreasing marginal returns (MR). [55, 56]

Both Cournot's model and Bertrand's model of duopoly competition have similar assumptions, with the main two being that both firms are identical and produce goods that are perfect substitutes. Each of these models further reasons that firms do not act independently of each other, but instead *react* to the other firm's actions.* To understand this behavior, Figure 10 shows how each firm reacts – R_1 represents the *reaction* of Firm 2 to the behavior (i.e., quantity produced) by Firm 1. R_2 represents similar behavior, of Firm 1 to the behavior of Firm 2. The intersection of these two lines represent quantity that each firm should produce, which are given by $Q_{1,C}$ and $Q_{2,C}$ for Firms 1 and 2, respectively. Since both firms are assumed identical, which is why their reaction curves are symmetrical about a 45^o line from the origin, $Q_{1,C}$=$Q_{2,C}$.

Bertrand's model of duopoly competition arose from the insight that competing firms would try to undercut each other in terms of price so that consumers would buy

*One should note the similarity between these models and Nash Equilibrium discussed in § 2.3.3 because Nash used insights from Cournot and Bertrand in developing his formulation.

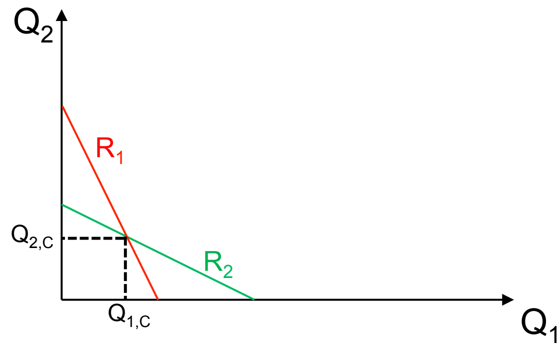

Figure 10: Cournot's model of a duopoly: two firms that react to each other and set a quantity of production, then determine the price based on a market demand.

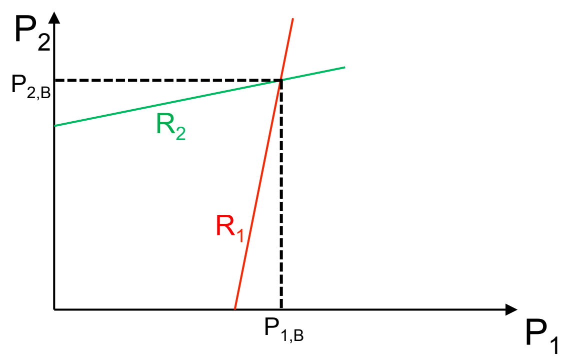

Figure 11: Bertrand's model of a duopoly: two firms that react to each other and set a price of goods being sold to, then determine the quantity of production based on market demand.

their product and not their competitors. Further assuming no collusion, this could be extended all the way until both firms earn no profits because they are both selling their products at the average cost required to produce them for that quantity. However, the main takeaway is that both firms are reacting to the actions and strategies of the other firm. This is shown in Figure 11. The firms' reaction lines are not the same as they appear in Figure 10 because they represent the price firms will charge. When the curves intersect, the prices of $P_{1,B}$ and $P_{2,B}$ are set for each firm; since both firms are assumed to be identical, $P_{1,B}$=$P_{2,B}$.

Regardless of the model being examined, both of these models have implications when compared to the monopoly model presented in Figure 9. This is best illustrated by directly comparing the monopolistic competition model to the duopoly competition model, which can be seen in Figure 12. One of the first things to notice in this model is that the quantity produced in a duopoly (Q_D) is higher than the quantity produced in a monopoly; however, it should be noted that this is the market quantity produced – each firm would produce half of amount based on previous assumptions. Furthermore, the price being charged in a duopoly (P_D) is lower than P_M. Each firm would now earn a lower profit than either firm would earn in a monopoly because the profit shown in the figure represents the total profit for both firms. It should also be noted that the quantity produced occurs where the MR curve intersects the horizontal axis – if firms produced a quantity greater than Q_D, their profits would decrease because this quantity of production represents maximum profit.

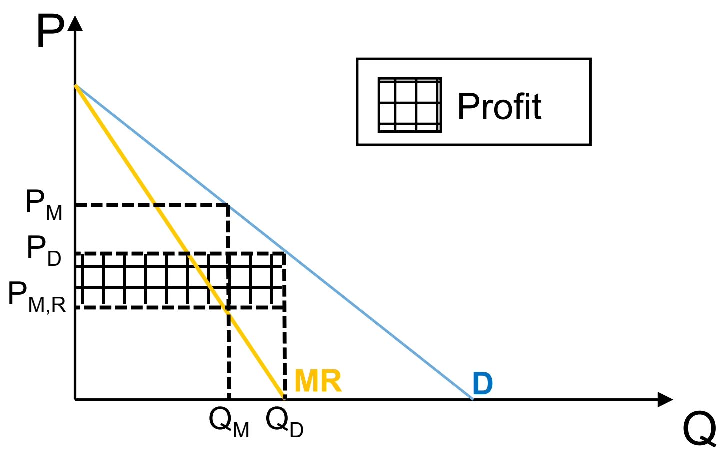

Figure 12: Notional comparison between monopolistic competition and duopoly competition.

While the applicability of the Bertrand and Cournot models of duopoly competition vary depending on the industry, neither is completely accurate to describe aircraft manufacturers of large commercial aircraft. The main reason is that neither Boeing nor Airbus could be assumed to be identical firms. However, research in recent decades has shown the applicability of Bertrand/Cournot models even when the firms are differentiated.[148] Furthermore, insight into differentiated duopolies has shown that market barriers can exist and be exploited by firms already established in the market (i.e., incumbents).[52] These effects seem more applicable to the aircraft manufacturing industry because of their use of competitive strategies involving price differentiation and derivative designs, which were discussed in § 2.2 and § 1.3.2, respectively.

2.1.3 Perfect Competition

While Perfect Competition does not exist amongst aircraft manufacturers, there are some general insights that can be gained by examining the underlying economic theory. Since firms in perfect competition are assumed to produce identical products, the market sets the price using the fundamental laws of supply and demand. One of the main insights from perfect competition is the idea that firms are not price setters, but rather *price takers*. The specific characteristics of each firm determine whether or not they will make a profit. This is illustrated in Figure 13. It is important to note that in perfect competition it is assumed that D = MR = AR (Average Revenue) for each firm and is determined by the intersection of the demand line (D^M) and supply line (S^M) for the market. In this figure, three types of a notional firm are examined in each row A, B, and C. In each row, the firm will produce the quantity where their MR = MC (for simplicity, each type of firm was assumed to have the same MC curve, although this would not be the case with real firms). In row A, this intersection occurs at the same point as average cost (AC), which means that the firm makes no profit. In row B, the AC curve is below that intersection, which means that the firm will make a profit. In row C, the AC curve is above the intersection, which means that the firm will suffer a loss. This highlights the need for firms to keep costs as low as possible in order to achieve a positive profit.

It is important to note that the laws of supply and demand dictate that over

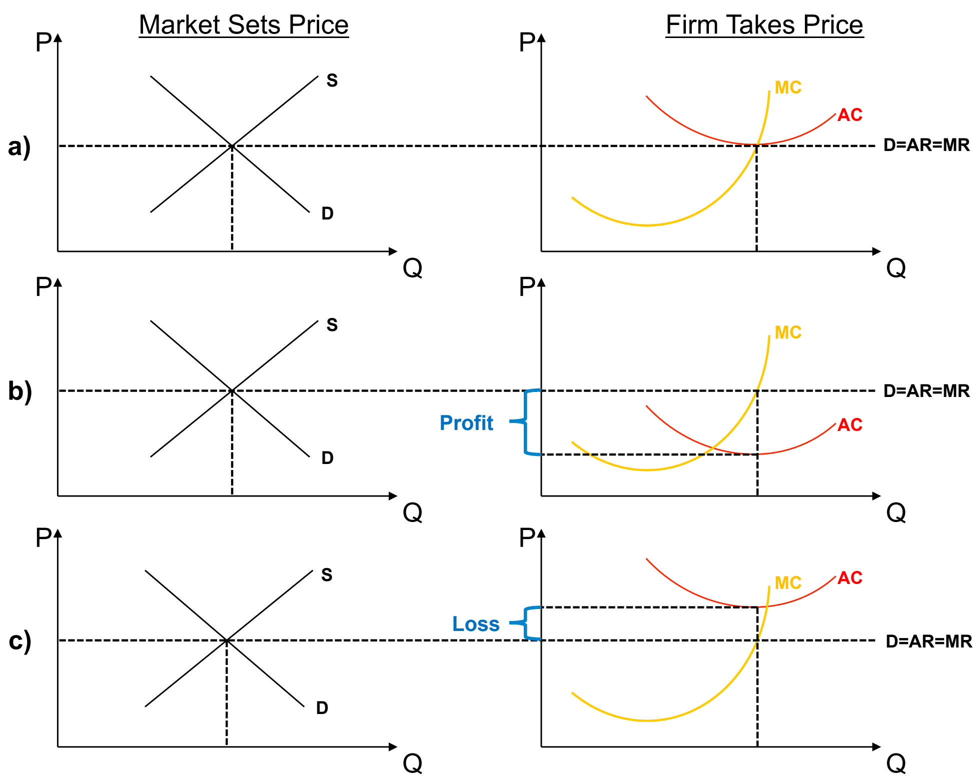

Figure 13: Notional figures of perfect competition where the market sets the price and the individual firms take the price.

time all firms will earn zero profit in perfect competition. This occurs because firms suffering a loss will go out of business, or firms earning a profit will produce more goods causing the supply line of the market to shift.[102] This shift will further drive down the price of goods until a scenario similar to the one presented in row A of Figure 13 occurs – where no firms earn a profit. A general heuristic that can be derived from this analysis is that the firm that produces a desired product at the lowest cost will survive, while other firms are forced to exit the market – this also suggests rationale for how some industries can shift from a competitive environment similar to perfect competition to one that is largely considered oligopolistic, duopolositic, or monopolistic.

2.1.4 First-mover Advantage

This section seeks to provide economic theory related to the motivating example of the Boeing B787 versus the Airbus A350 discussed in § 1.3.1. That example discussed the adoption of a technology that preempted the competitor's adoption of a similar technology. Several authors have shown that a company's adoption of a technology would be influenced by the type of competitive market. Fudenberg and Tirole's work focused on whether a company should be the first adopter of a technology, which is often referred to as a first-mover advantage†. [64] Fudenberg and Tirole showed that a first-mover advantage may not be preferred in an duopoly. [64] This is best illustrated by examining Figure 14 and Figure 15. [64]

†The first mover gets to enjoy high profits while their competitor(s) are still maturing the technology.

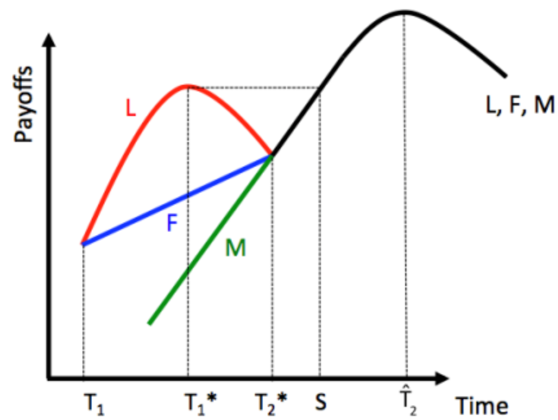

Figure 14: Joint adoption model showing notional payoffs for Leader (L), Follower (F), and Mutual (M). [64]

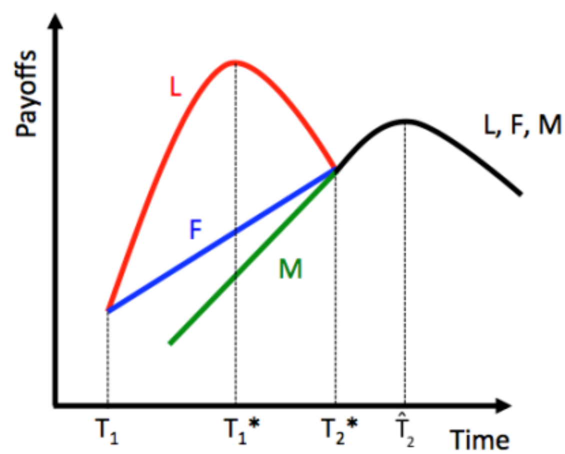

Figure 15: Diffusion model showing notional payoffs for Leader (L), Follower (F), and Mutual (M). [64]

In Figure 14, there is no first mover advantage; this is referred to as the *joint adoption model*. In this figure, the leader makes more profit than the follower, but would not earn more profit with simultaneous adoption. The opposite of this is true in Figure 15, where an obvious first-mover advantage occurs in the *diffusion model*. When looking at both of these figures, one should note that mutual adoption before time T_2^* results in both firms achieving lower payoffs by being on the mutual adoption curve. While these models offer valuable insight to be gained into the adoption of a technology there exist some obvious concerns. One of these concerns is inability to easily classify a technology as following one model or the other. Another issue arises with regards to the example presented in this section, which described a perceived first-mover advantage for Boeing.

The reason for the different outcome in this section's example may be influenced by several assumptions of these models, including perfect information and identical firms; however, if a preemption in the adoption of a technology would result in large profits, each firm would have incentive to preempt the other. These factors would result in firms adopting simultaneously when the technology was initially matured. This distinction suggest that the large aircraft manufacturer duopoly market follows more of a diffusion model with technologies, which means that a first-mover advantage may exist in this market. This may be the case when considering short-term profitability, but in the long-term the second mover may be able to capitalize on information from the first-mover.

Based on the economic theory about preemption in a duopoly and an oligopoly, there may be more information to be gained from the industry example of the Boeing B787 and Airbus A350 presented in § 1.3.1. A major risk associated with an aircraft that is largely composite is that the certification standards were written for mostly metallic aircraft. [60] This proved to be an issue for Boeing because the composite wings could not initially pass the 150% deflection test. In order to meet certification requirements, Boeing had to install titanium spars [127]. Boeing was able to pass the wing deflection test in November, 2008 [127]; however, additional costs were incurred and the full benefits of the composite technology were not realized. The insight gained from Boeing moving first suggests that Airbus may be able to capitalize on this information, which may reduce the A350's certification and design costs. This insight further casts doubt on whether a large aircraft manufacturer would prefer to be a first mover.

However, the fact that Boeing was the first to market with this technology allows for them to earn income while Airbus is still developing/certifying their aircraft. The long-term impact on total profit that these diverging ideas present about preemption versus joint adoption will not be known for many years. An article published in February of 2016 states, "the 787 is close to the point where it is no longer losing money on each jet delivered, but its not quite there and certainly will not be making significant profits for a long time." [68] Furthermore, Boeing has recently announced that it will be eliminating approximately 8,000 jobs (which represents approximately 5% of their total workforce and may reduce some business units by up to 10%) in 2016. [67]. It cannot be assumed that these layoffs are specifically related to the B787, but another article offers the following insight:

> "Teal Group analyst Richard Aboulafia said that to cover the recurring cost of producing all its 787s and eke out an overall profit, Boeing will have to build future 787-9s at an average cost of $91 million each – compared with an estimated cost of $140 million each in the fourth quarter of 2015 ... [a] 787 engineer said older employees were not surprised by the news of job cuts, which he attributed at least partly to the money pit that is the [B787] Dreamliner program." [68]

Based on the economic theory and analysis of the industry example, the following insight regarding preemption versus joint adoption was assumed:

Preemption v. Joint Adoption This decision may be sensitive to factors such as quality and availability of information. It may be difficult to truly capture these effects without very clear insight and specific details regarding both aircraft OEMs.

2.2 How OEMs Compete

The previous section explicitly described three distinct approaches regarding competition amongst aircraft OEMs. The strategy of infusing technologies into the design of a new aircraft concept was described in § 1.3.1. The strategy of developing a derivative aircraft was explained in § 1.3.2. And § 1.3.3 discussed the departure from the paradigm that an aircraft is solely a design and focused on the business aspects of the aircraft throughout its life cycle. By examining all of these strategy options during the conceptual design phase more information can be provided to a decision-maker.

The previous section also implicitly defined another form of competition amongst aircraft OEMs. This form of competition involves the way in which decision-makers interpret market data. While the aircraft described in § 1.3.1 and § 1.3.2 were examples of designs competing in the same market segment, not all of the aircraft presented in Chapter 1 were focused on the same market segment. This differentiation in aircraft designs for different market segments arises for multiple reasons. One of the main factors is the needs of the customer – airlines have different business models, and it is economically rational for OEMs to recognize those unique needs. Secondly, having multiple aircraft that are each focused on different market segments is a good way to mitigate business risks and has been suggested to be a robust approach for designing aircraft. [39] Finally, aircraft differentiation can occur simply because separate decision-makers may not arrive at the same conclusion even though they are both examining the same data. This final reason may best be illustrated with an example described in a Forbes article with the following quote:

> In todays marketplace, distinct differences in the way competitive products work have become increasingly rare. But functional product differentiation is exactly what the rivalry between the Airbus A380 and the Boeing 787 Dreamliner is all about: Two companies with fundamentally

> different products, based on diametrically opposite visions of the future, engaged in a Hatfields versus McCoys battle with billions of dollars at stake. [11]

The "diametrically opposite visions of the future" in that quote truly captures the essence of this specific rationale into product differentiation. Technologies and business strategies aside, Airbus and Boeing have created different visions (i.e., models) of the future, which means that neither company pursues the same type of basic design for a new aircraft. It is reasonable to assume that both Airbus and Boeing had access to the similar raw data regarding current market trends, but both firms arrived at different conclusions. The underlying reasons for this result is too difficult to discern, which makes this form of competitive analysis very difficult to model and analyze a priori. However, the Forbes article points out, "both Airbus and Boeing have a hedge in their back pocket. To compete directly with the A380 [Boeing is developing the Boeing] 747-8 ... To counter the [Boeing] 787, Airbus is offering a white elephant called the A350." [11] While hedging is a common business practice, in many industries, there can be a significant increase in costs, especially when the product is as expensive to design and produce as an aircraft.

Another way that OEMs compete, which is common in most industries, is by offering price discounts on aircraft. A recent Wall Street Journal article describes this competitive action with the Airbus A380: "having given large price discounts to the A380's first customers and those that bought large numbers – which is typical in the aviation industry – Airbus now has to try to sell A380s at high prices." [173] Based on general economic theory, offering a product at a lower price can increase the demand for the product; however, this means that more of the product must be sold to reach the breakeven point or return a profit. In fact, the price that is often stated publicly for an aircraft is not the price that is paid by airlines:

> Discounts seem to vary between roughly 20% and 60%, with an average

> around 45%. Savvy buyers don't pay more than half the sticker price, industry veterans say. But deal specifics differ greatly. Part of the reason prices vary so much and are hard to pin down is that airplane contracts are complex ... airlines also generally order lots of planes at once for delivery over many years ... [and] psychology: Less-experienced plan buys like to think they got a bargain ... more-seasoned plane buys also know that bragging about discount specifics would anger Airbus, Boeing or other producers and hurt the chances of striking a sweetheart deal again. [118]

A major insight that can be gained from this competitive strategy is the need to analyze aircraft being sold a range of prices instead of a fixed price – this will allow a decision-maker to more accurately assess the profitability of an aircraft during early phases of design.

Based on these descriptions of how aircraft OEMs compete, the capabilities of an appropriate framework to address the research objective can be more accurately defined; this mapping is shown in Table 2. For example, the color of the carpet being used in the aircraft would not be a top priority for a decision-maker during the conceptual design phase. Alternatively, the choice about whether or not to fund research into a given technology for infusion on an aircraft would be of more importance to a decision-maker at this phase in the design process. Based on these characteristics, various techniques/approaches that have been used to account for competition are examined in the following section.

Table 2: Summary and implications of how OEMs compete during the Conceptual Design Phase

How OEMs Compete	Implications for Proposed Framework
Infuse Technologies into New Design	Must be able to examine physical impacts of technologies and the increase cost of developing those technologies to maturation
Infuse Technologies into Derivative Design	Must be able to account for decreased costs associated with modifying an operational aircraft
Enterprise Solutions	Must be able to account for various business strategies that occur in other phases of the aircraft's life cycle besides design
Different Passenger Class Designs	Must be able to analyze a variety of different types of aircraft (i.e., should not just interpolate between known designs of one passenger class) and account for segmented market with different expectations
Hedging Designs	Must be able to account for head-to-head comparisons of designs in the same passenger class
Price Fluctuations	Must be able to account for variable prices charged for the same design and/or strategy alternative

2.3 Applicable Design Methodologies/Approaches

Competition is basically defined as a contest between individuals, companies, organisms, etc. seeking to gain some benefit, whether it be food, mate, market share, resources, etc. However, in the context of this dissertation, the term competition involves the interactions between competing firms over market share based on the proposed design and strategy for a given aircraft. While many ad-hoc approaches have existed throughout the millennia to address various competitive situations, a more formalized approach was desired. The idea about strategically allocating resources is paramount to conceptual design – this sentiment was captured by Hazelrigg by stating, "design is, essentially, the effective allocation of resources. The allocation of resources is, by definition, decision making."[73]. As stated in § 1.1, these decisions should be made as early as possible in the conceptual design phase when it is easier and less costly to make design changes.

Although multiple formalized techniques exist for exploring competitive strategy development/evaluation, they may not be well-suited for this design problem. To this end, it was necessary to examine and critically evaluate the various techniques in order to determine which is most appropriate. Several qualitative techniques were examined, many of which are popular amongst a large number of companies today. The concept of game theory, which has been used to analyze many similar duopoly problems, was explored, but several key issues were raised that limit its applicability to the proposed framework. Due to those reasons, which are discussed in more detail in § 2.3.3, the work in this dissertation can be viewed as a necessary step to be able to utilize the well established mathematical framework of game theory more concretely in aircraft design.

Even though game theory cannot currently be used at an acceptable level for this problem, that does not eliminate the need to examine how a competitor's design and strategies can influence design decisions. In order to gain insight into this competitive nature of the problem, a general decision making method was adopted and expanded to explicitly account for duopolistic competition.

2.3.1 SWOT Analysis

SWOT analysis is a common analysis technique that stands for Strengths, Weaknesses, Opportunities, and Threats. This technique was proposed by Humphrey in 1970 [76] as an effective means for companies to determine the appropriate business strategies to pursue. This can be especially useful when analyzing the impacts of a competitor because their actions/strategies can seen as threats. While there are multiple ways to conduct SWOT analysis, the two most prevalent approaches involve a single decision-maker or a group brainstorming. Regardless of the specific approach chosen, the basic steps remain the same.

These steps are divided into two main categories: internal and external assessments. The internal assessments concern the strengths and weaknesses. A strength could be thought of as something that gives the company a competitive edge, whether it involves intellectual property, physical assets, proprietary designs, etc. A weakness is best described as an area that is lacking in the company. Some examples of weaknesses could include: lack of appropriate information technology infrastructure, inefficient workforce, bad geographical location, etc. After assessing these internal attributes, the external possibilities (opportunities and threat) are then examined. An opportunity is an area that a company could easily expand to based on the companies current resources and the state of the marketplace. Similarly, a threat is something, whether entity, product, market trend, revolutionary technology, etc., that could harm business operations by a reduction in market share or loss in profit.

After enumerating these elements, some form of qualitative analysis is often used to interpret the data. This means that this approach is highly subjective and can suffer from many of the drawbacks associated with qualitative analysis. However, the decision-maker would typically be considered a subject-matter expert (SME) when it comes to evaluating the company. While the results of the SWOT analysis may be useful at a high-level of analysis, they may lack the traceability to lower-level actions. To illustrate this point, consider the following notional example:

Notional Example: Company A classifies a Company B's development of a structural technology as a threat because it can reduce fuel burn by up to 5%. Company A classifies their completed development of a structural technology that increases utilization by at least 3% as a strength. Should Company A look to develop another technology to compete with Company B? Or should Company A examine other aspects feeling confident that the threat is neutralized by their strength? Without a way to further examine the threat and strength and directly compare their impacts on the aircraft, there is no way for Company A to defensibly know which is the appropriate action to take.

2.3.2 Other Subjective Competitive Assessments

In addition to SWOT analysis, there exist several other subjective techniques that mainly rely on qualitative assessments by a decision-maker or group brainstorming. Each of these techniques can offer unique insights. Preferences for a technique are dependent on the individual(s) and the situation being assessed. While obvious synergy exists when multiple subjective techniques are combined, it was not possible to determine the extent that this is prevalent in industry.

Political, Economical, Social, and Technological (PEST) can be a useful tool for assessing the competitiveness of a company in a constantly changing market. This technique was proposed by Narayanan and Fahey in 1994. [123] The main benefit of this technique is that it allows for analysis of four key factors that can drastically alter a company's external environment. The applicability of this technique to a complex design problem seems to be limited; however, this technique may be useful for helping develop future scenarios that may occur during a system's life cycle. While PEST is more focused on the environmental factors in which a company operates, the GE/McKinsey Matrix focuses more on internal business units.

The GE/McKinsey Matrix was developed in the 1970s by McKinsey & Company's consultant work at General Electric (GE). [168, 135] This approach is most useful for evaluating various business units (i.e., separate entities under control of a central company), but similar analysis may be applicable to other situations. The basic principle of the GE/McKinsey Matrix is a 3x3 matrix used to evaluate Business Unit Strength vs. Market Attractiveness based on a qualitative scale of Low, Medium, and High. Figure 16 shows a notional GE/McKinsey Matrix. In these matrices, the size of the circles represents the market size, the pie chart represents the market share,

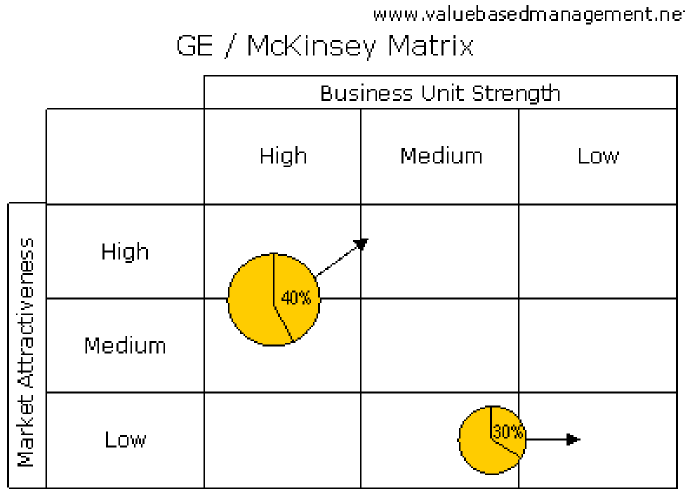

Figure 16: A notional GE/McKinsey Matrix, which may be applicable to more than just business unit evaluation. [168]

and the arrow points to the expected future position. This could be thought of as an extension on Boston Consulting Group's Growth Share Matrix, which was first described by Bruce Henderson in 1970. [104] The Growth Share Matrix categorizes ideas into one of four categories: star (amazing performance), cash-cow (long-term earnings, but not high growth), dog (bad investment), or question mark (need more time and/or information to decide).

While these techniques are useful to many business, they suffer from the same shortcomings as the SWOT analysis. The qualitative nature of these techniques means they may lack repeatability because of their subjective evaluations. However, these techniques may be useful in situations where quantitative physical/virtual analysis cannot be conducted, and the only sources of information are SMEs.

2.3.3 Game Theory

Game theory was first introduced by John von Neumann and Oskar Morgenstern in 1944 [172] and pioneered the field of interactive (competitive) decision making. Game theory has been defined by Hazelrigg as "any activity that involves more than one individual, where the actions of each individual in the game affects others who are also in the game." [73] At a basic level, game theoretic analysis requires four "items":

1. The players
2. The strategy space
3. The sequence of decisions/actions
4. The payoff structure for all the possible actions in the strategy space

This ability to reduce a complex problem to four dimensions was noted in 2004 by Smit and Trigeorgis. [151] The ability to shrink the dimensionality of the problem greatly increases the desirability of using game theory, which was also noted by Briceno [29]. By shrinking the dimensionality of the problem, it can become easier to perform useful analysis based on the type of game being analyzed. *Cooperative* and *noncooperative* games are the most common approaches to modeling interactive behavior. [73] and are described as:

cooperative game "any game in which players can make binding commitments." [73]

noncooperative game "any game that is not a cooperative game, this is, a game in which the players are not permitted to make binding commitments." [73] These games can also include games in which the players can break binding agreements.

While a cooperative solution can easily be described as the solution that maximizes reward for all of the parties, the non-cooperative solution is more complicated. The non-cooperative game is also the format required to analyze competition between aircraft OEMs because collusion amongst them is illegal‡. The non-cooperative solution can be thought of as:

‡Aircraft OEMs cannot agree to adhere to a specific competitive strategy because that would unfairly hurt the customers. Most countries have specific legislation preventing this behavior.

> "the strategy of [a] player [that] yields the highest obtainable [payout] for its player against...strategies of the other players. A self-countering [set of strategies amongst players] is called an equilibrium point." [124]

This is commonly referred to as the Nash Equilibrium (NE). Mathematically, an NE of *pure strategies*[§] is defined if a set of actions (a_1^N, a_2^N) that meet the conditions in Equation 1, where U[¶] represents the payoffs for a given player:

$$
\begin{aligned}
&U_1(a_1^{NE}, a_2^{NE}) \geq U_1(a_1, a_2^{NE}) \text{ for all } a_1, \text{ and} \\
&U_2(a_1^{NE}, a_2^{NE}) \geq U_2(a_1^{NE}, a_2) \text{ for all } a_2
\end{aligned}
\tag{1}
$$

There exist several, well-defined approaches for determining the NE of a game, including dominated strategies and best response analysis [174]. Both of these techniques can guide one to finding a pure-strategy NE in a game (assuming that one exists), and often the technique used depends on the preferences of the one analyzing the game. The best response technique basically employs a dynamic programming framework to solving the problem. This technique seems rather intuitive because it requires identification of each player's best response given the other player's actions. While implementing this best response technique is rather easy for normal form games with complete information, this type of game does not fully capture the intricacies of a competitive aircraft design problem. When considering a competitor, the uncertainty of the problem can increase exponentially because of the difficulty in predicting the decisions they may make.

Shortcomings of Game Theory:

Several authors have criticized game theory for a variety of reasons. One of the major

[§] *Pure strategies* refers to selecting only one strategy option to be used throughout the game.
[¶] The notation U is used because economists traditionally deal with utility values

elements of these criticisms is underlying human behavior; Hagen and Hammerstein addressed this and other issues in a paper highlighting theoretical game theory's inability to match the results of several experiments. [70] A quote that summarizes many of the issues with game theory comes from John Williams‖:

> [Game theorists] are often viewed by the professional students of man as precocious children who, not appreciating the true complexities of man and his works, wander in wide-eyed innocence, expecting that their toy weapons will slay live dragons just as well as they did inanimate ones. [33]

That quote (and other critiques) highlights two of the key aspects that limit the practicality of game theory when dealing with complex design problems. Firstly, game theory assumes that all decision-makers are rational and seeking to maximize utility (either with regards to another player's actions or independent of other players). That assumption has two major concerns: 1) it may be difficult, if not impossible, to accurately describe a utility function (or all of its elements) for an individual and/or firm [87], and 2) decision-maker's preferences may change during the design process and/or their preferences may not be accurately known. While assuming a firm is profit maximizing does mitigate some of these concerns, it does not completely alleviate them.

Furthermore, the problem of uncertainty has long been an issue for not only game theory, but many other fields. While several specific forms of game theory (e.g., games with incomplete information [71, 174], signaling games with asymmetric information [153, 126]) have attempted to mitigate these concerns, they still cannot fully eliminate

‖John Williams wrote texts on game theory and "provided the initial impetus and intellectual (and financial) support for most of the mathematical work underpinning the entire edifice of the theory of games." [33]

all the issues that arise with uncertainty and are often limited to only exploring high-level actions. Also, these techniques are not well suited for problems with multiple sources of uncertainty – as the number of sources of uncertainty grow, there is an exponential growth in the level of difficulty associated with modeling and accounting for these sources.

Due to these limitations, this dissertation work did not seek to implement game theory for the competition problem being addressed. Instead a framework was developed in order to gain more insight into the competition problem by allowing for games to be played (i.e., various actions and strategies can be implemented to see how they might impact the final result). This proposed framework was seen as a necessary first step towards being able to implement game theoretic analysis. For this reason, a generalized decision making approach needs to be adopted to further explore this competition-influenced design problem.

2.3.4 Top-Down Design Decision Making

The top-down design decision support process is a general methodology to allow for increased traceability in decisions. The general applicability of this approach allows for it to be applied to a large variety of problems. Figure 17 shows the steps that are used; these specific steps are taken from the Integrated Product and Process Design methodology proposed by Mavris et al. [111] However, many other decision making techniques follow similar steps. For example, Gass defines decision making as, "recognizing that a problem exists, identifying possible causes, developing alternative solutions, choosing among alternative courses of action"[66], which are very similar to the steps shown in Figure 17.

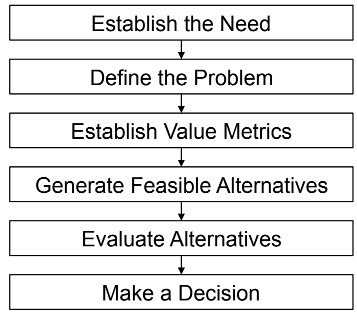

Figure 17: Top-down Design Decision Support Process [111] that is generally applicable to most decision making problems.

The generality of this top-down design decision support process lends itself well to the competition problem being analyzed. The one element that is missing involves the act of competition, which should be explicitly stated and not lumped into the step of evaluating alternatives. By explicitly analyzing competition separately from evaluating feasible alternatives, a decision-maker may be able to gain more insight into which aspects should be further investigated to improve a design's competitiveness.

2.4 Research Objective

Each of the examples from industry presented in § 1.2 and § 1.3 provided motivation for the research objective of this dissertation. As a reminder, Table 3 provides an overview of some key observations and where they were discussed.

The information presented in Table 3 also highlights some of the approaches that

Table 3: Restating of observations from the industry examples that motivated this research.

Section 1.2.1	Uncertainty	Economic Viability
	Long Life-cycle	
Section 1.2.2	Market Penetration	Market Volatility
Section 1.3.1	Strategy Option: New Design	
Section 1.3.2	Strategy Option: Derivative Design	
Section 1.3.3	Strategy Option: Enterprise	

aircraft OEMs use to compete; a more complete listing of these approaches is shown in Table 2 of § 2.2. By compiling the information in those tables, one can begin to understand the large range of possible competitive strategies that exist, especially since multiple strategies may be used simultaneously. Even though there is no way to analyze every possible permutation and combination of possible competitive strategies, a framework could be developed that allows for various *games* to be played. However, based on the motivating examples presented in § 1.2 and 1.3 coupled with the economic theory presented in § 2.1, several key elements need to be addressed:

Flexibility The framework should allow for various strategies to be used. Furthermore, the framework should be adaptable to the preferences of the decision-maker and allow for the specific approach to be adopted based on the specific problem being analyzed.

Uncertainty Mitigation When designing a product with a long life cycle, like an aircraft, the large amounts of uncertainty can drastically reduce the confidence of one's decisions. The proposed framework must provide a process to mitigate the impacts of uncertainty.

Sensitivities Since decision-makers may not fully know their preferences and/or their preferences may change over time, the framework should focus on the sensitivities related to decisions, not just a final decision based on assumed/inputted preferences.

Direct Comparison One of the major strengths of Game Theory is that it directly accounts for the actions of the competitor. This direct comparison should be used in the framework in order more robustly account for possible strategies of a competitor.

As discussed in the previous sections, techniques that have traditionally been used to analyze competition cannot be applied to this specific problem. However, modifications to the Top-Down Decision Support Process can be made to construct a framework that would allow a decision-maker to analyze *games* of interest.

> **Research Objective:** Develop a framework to aid in the conceptual design of aircraft by parametrically accounting for uncertainty from the economic market and competitive environment through an integrated and interactive design approach. This approach should allow for analysis of various strategies (e.g., technology and enterprise-based) that can be used by the designer or the competitor. Furthermore, this framework should allow for a direct comparison between proposed solution(s) and possible competitors solution(s).

Chapter 3 focuses on the formulation of the proposed framework. This formulation addresses the key elements that were previously stated. *Flexibility* is addressed throughout the development of the framework by allowing various paths to be taken depending on the problem being analyzed. Since it has been shown that the *uncertainty* of the market and competition can affect the success of a design alternative, there is a need to further explore the impacts of uncertainty. Assuming that the uncertainty reduces the ability to make decisions with confidence, then there will be a need to introduce a mitigating strategy. These impacts are further discussed in § 3.6, but they also propagate to the other key elements of *sensitivities* and *direct comparisons*. Both of these are directly related to decision making. While a large variety of decision making techniques exist in the literature, some are not applicable to this design problem. This occurs for two reasons: 1) as previously stated, a decision-maker's preferences may be unknown or may change, and 2) there needs to be a direct comparison between a proposed alternative and a competitor's design that leverages this decision making technique. To address the first point, it was necessary to implement an approach that allows for a decision-maker to easily examine how changes in their preferences can affect the preferred decision. To address the second point, a selected decision making technique should be applicable to both the proposed design and the competitor's design. Both of these elements are examined in further detail in § 3.7.

The formulation of the proposed framework resulted in several concerns regarding the implementation of the specific approaches for a given problem. One of the concerns arose due to the specific impacts of uncertainty and a mitigating strategy is examined in Chapter 4 – this experiment includes a sensitivity analysis on the sources of uncertainty and examines the effectiveness of mitigating strategies. Furthermore, the impacts of uncertainty and implementation of a mitigating approach could impact the ability to apply various decision making techniques. To this end, Chapter 4 also examines an experiment to compare decision making approaches that are formulated in § 4.3. Based on the results of these experiments, several *use cases* were then examined in Chapter 5 using the proposed framework in order to demonstrate its capabilities.

CHAPTER III

TECHNICAL FORMULATION

> "Human decisions affecting the future ... cannot depend on strict mathematical expectation, since the basis for calculating such calculations does not exist; ... it is our innate urge to activity which makes the wheels go round, our rational selves choosing ... but often falling back for our motive on whim or sentiment or chance."
>
> John Maynard Keynes [89]

This chapter sought to explicitly define the proposed framework and elaborate on the steps necessary for it to be effectively used. The general framework can be described by adopting an approach similar to the Top-Down Decision Support Process presented in § 2.3.4. However, the application of this process to the specific objective of this dissertation required elaboration of the various tasks performed throughout each step. Some of these tasks were answered from the literature, but when the literature did not highlight a clear approach research questions were posed to determine which technique was best suited.

3.1 Overview of Proposed Framework

While the Top-Down Decision Support Process, which is shown in Figure 17, is generally applicable to most problems of interest, there are some obvious modifications that were needed to account for competition. The major deficiency of the Top-Down Decision Support Process in analyzing competition is that there is not an explicit step for comparing a design to a competitor's design. This modification creates the backbone of the proposed framework, which is referred to as the Competition-influenced Decision Support (CoDeS) Framework and is shown in Figure 18.

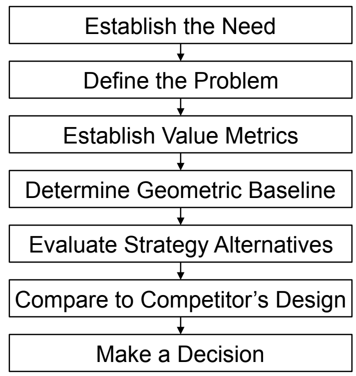

Figure 18: General steps of the proposed Competition-influenced Decision Support (CoDeS) Framework.

The generality of these steps results in the benefit of the CoDeS Framework being flexible to handle a variety of competitive situations that may be of interest to a decision-maker. The steps of the proposed framework are not specific to one type of competitive strategy, but can be adapted to almost all of the types described in § 2.2.

By directly comparing a proposed design to a competitor's design, one of the major aims of this research was addressed; however, the steps of the CoDeS Framework as shown in Figure 18 are not particularly useful. More information about the specific processes that should be taken during each step are needed to allow for beneficial analysis. In its current form, the CoDeS Framework suffers from being too flexible because guidance is not offered on how to accomplish the various steps. To this end, the following sections seek to more explicitly define the required steps of the proposed framework.

3.2 Step 1: Establish the Need

Establishing the Need is one of the most important and possibly time-consuming steps for any decision making process, especially related to designing a product for a customer. The reason this step is so crucial is because without a correctly and properly defined need, the remaining steps may be executed and result in a final product that is neither desired or purchased. The need identification is crucial because it lets the producer know which product to design. From this step, requirements can be properly defined, which were discussed in § 1.1. While these requirements can come from a variety of stakeholders, this dissertation focuses on the concerns of the customer (i.e., airlines) because of their importance during the conceptual design of commercial aircraft. [36, 117, 128] This is summarized with the general sentiment, "in the commercial sector, the voice of the customer is critical."[117] To further this point Anderson states, "The design process starts with a set of specifications (requirements) for a new airplane ... there is a rather concrete goal toward which the designers are aiming." [8]

While this step is important and lays the foundation for all of the future steps, it is not considered a thrust of this dissertation research. This is justified for two reasons stated in § 2.4: 1) it is difficult to model competition between aircraft manufacturers that are pursuing different needs in the market, and 2) most of the time, aircraft manufacturers will hedge their interpretation of market needs by having designs that directly compete in the same market [11]. For these reasons, the CoDeS Framework was constructed assuming that all customers have the same need (i.e., aircraft manufacturers are competing in the same market).

By assuming that the need is the same for the competing aircraft designs, the design mission was also assumed to be identical. This means that aircraft manufacturers are not competing by trying to gain extra range, endurance, or other performance-specific metrics. Instead aircraft designs were evaluated using the same metrics of value in an "apples to apples" comparison. However, before discussing the selection of value metrics the aspects of the specific problem need to be defined.

3.3 Step 2: Define the Problem

While *Establishing the Need* directly leads to a description of the requirements and outlines the basis for undertaking the design problem of interest, it only serves as a starting point of analysis. To fully understand the requirements of a design, one needs to *Define the Problem*, which consist of several important elements. These elements are necessary to conduct meaningful analysis in the following steps of the CoDeS Framework and are shown in Figure 19. Each of these elements is discussed in more detail in the following sections:

§ **3.3.1** Define the Competitive Environment

§ **3.3.2** Define the Geometric Variables and Their Ranges

§ **3.3.3** Define the Competitor's Geometric Baseline and Variable Ranges

§ **3.3.4** Define the Economic Noise Variables and Their Ranges

§ **3.3.5** Define the Strategy Variables and Their Ranges

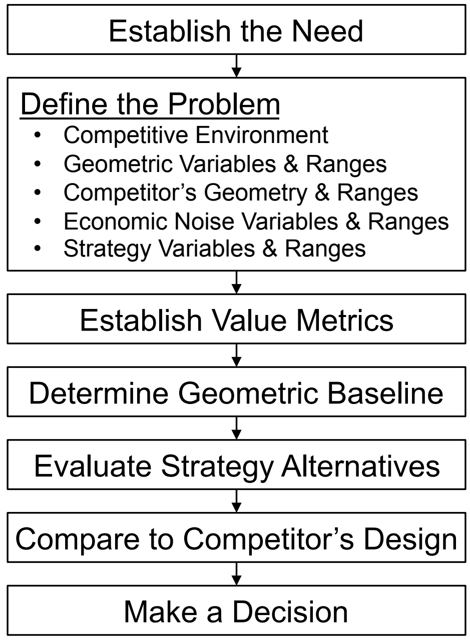

Figure 19: The CoDeS Framework with specific elements of the *Define the Problem* step.

3.3.1 Competitive Environment

§ 2.1 described different competitive environments and the implications of each. While the CoDeS Framework allows for any type of competitive theory to be analyzed, the remainder of this dissertation focused on duopoly competition. This was because it was believed that most traditional aircraft design methods implicitly assume the aircraft is operating in a monopoly – a duopoly would represent a logical step and insights gained from a duopoly-model could be extended further to account for oligopoly competition. Furthermore, the aircraft manufacturing industry is not indicative of perfect competition. However, aircraft manufacturing can not be completely described by Bertrand or Cournot duopoly competition theory either. However, Singh and Vives showed that in a differentiated duopoly, it is a preferred strategy to fix the quantity of the good produced and then determine the price to charge if the products are substitutes.[148]

3.3.2 Geometric Variables & Ranges

When considering a large, commercial aircraft there are thousands of possible variables that impact the geometry of the design. However, the importance of these variables is dependent on the phase of design. This dissertation work sought to address competition during the early part of the conceptual design phase. In order to determine the necessary variables to be considered, it was necessary to consult the literature. Anderson defines conceptual design as, "within a certain somewhat fuzzy latitude, the overall shape, size, weight, and performance of the new design [is] determined."[8]. Raymer suggest that conceptual design should answer "the basic questions of configuration arrangement, size and weight, and performance."[137] With these considerations in mind, it was necessary to determine the key geometric variables that should be considered.

In order to determine geometric variables, an architecture for the design needs to be determined. During the early conceptual design phase, the architecture basically describes the overall physical configuration of the aircraft. One way of visualizing the various possibilities of different architectures is through a Morphological Matrix, which can be seen in Figure 20, where the yellow boxes represent the selection of a notional architecture. In this figure, each row corresponds to a different physical characteristic and the columns represent different options. This particular Morphological Matrix has 1,007,769,600,000 unique combinations of architectures. If it were possible to analyze one combination every second, it would take over 31,934 years to explore all of the combinations. Further complicating the issues is that there is no reason to assume that the geometric variables are the same between different architectures.

Once an architecture is decided for the aircraft being analyzed, then the geometric design variables of interest can be determined. For conventional aircraft configurations, which are common throughout today's markets, the architecture would be

Design Attribute	Option 1	Option 2	Option 3	Option 4	Option 5	Option 6
Number of Passengers	75	150	225	300	400	
Body Style	Conventional	Blended-Wing Body	Flying Wing	Truss-braced		
Tail Configuration	Conventional	T-tail	H-tail	Triple-tail	Other	
Cruise Speed	Subsonic	Transonic	Supersonic			
Range	Short Domestic	Medium Domestic	Long Domestic	Medium International	Long International	
Sweep	No Sweep	Low Sweep	Medium Sweep	High Sweep	Reverse Sweep	
Taper	No Taper	Low Taper	Medium Taper	Higher Taper		
High-lift Devices	Flaps	Slotted Flaps	Double Slotted Flaps	Slats	Combination	
Number of Engines	1	2	3	4		
Engine Type	Propeller	Turboprop	Turbofan	Turbojet	Open-rotor	Hybrid
Wing Material	Aluminum alloy	Composite	Combination			
Body Material	Aluminum alloy	Composite	Combination			
Tail Material	Aluminum alloy	Composite	Combination			
Wing Tips	None	Endplate	Winglet	Angled Winglet	Swept Winglet	Rounded
Aspect Ratio Wing	Low	Medium	High			
Aspect Ratio Horizontal Stabilizer	Low	Medium	High			
Aspect Ratio Vertical Stabilizer	Low	Medium	High			
Wing Mount Location	High Wing	Mid Wing	Low Wing	N/A		
Engine Location	Under Wing	Over Wing	Tail	Combination		

Figure 20: Morphological Matrix allows a way to visualize the various architectures for the design of an aircraft. A notional architecture is highlighted in yellow.

similar to the notional architecture highlighted in Figure 20. Assuming this architecture was selected, some of the key geometric variables during the early phases of conceptual design would include:

Wing Area The wing is the main source of lift for an aircraft and the amount of lift produced is directly related to the size of the wing.

Thrust-to-Weight Ratio This ratio considers the thrust of the engines and the amount of weight that must be lifted.

Aspect Ratio, Wing The Aspect Ratio relates the area of the wing to the span of the wing. This parameter is important in determining the efficiency of the wing.

Thickness-to-Chord Ratio, Wing This parameter accounts for the rigidity and weight of the wing.

Sweep, Wing This parameter is important for drag considerations, especially considering the operating speed of most commercial aircraft during their cruise segments.

Control Surfaces At these early phases of design, it is only necessary to examine the general characteristics of the vertical and horizontal tail, which are similar to those of the wing.

After identification of the key geometric variables, the ranges for each of these variables need to be determined. These ranges can be influenced by: manufacturing considerations, safety considerations, airport operations, etc. After the ranges are defined for each geometric variable, analysis can begin on performance and economic considerations from combinations of these geometric variables. The process for conducting this analysis is further discussed in § 3.5.

3.3.3 Competitor Geometric Baseline & Ranges

There is a need to determine the details of the competitor's aircraft, whether that design is in the market or still being developed. There are many legal means that a company can employ to gain this insight into their competition. These techniques include: reverse engineering, interviews with customers, interviews with suppliers, examining paperwork filed with regulatory agencies, examining patents filed, etc. The appropriate technique depends on the specifics of the scenario. For instance, one could not reverse engineer a design that has yet to be manufactured.

If the competitor is using the same basic architecture for their design, then the same geometric variables should be used to define their design. By using the same variables to describe these two aircraft, it is more intuitive to make a direct comparison between them. However, it is important to note that there is more than just the geometry of the vehicle that will affect its economic success. An example of one of these factors is the overall cost required to produce that design, which may be dependent on information regarding the competitor that may not be known. Regardless, estimations of these factors, even if described by a range of possible values, would provide valuable insight.

3.3.4 Economic Noise Variables & Ranges

There are a large number of economic noise variables that could impact the design of an aircraft; however, it is important to only examine key variables that can easily be mapped to an aircraft designs. For instance, the valuation of the Euro relative to the Dollar has impacts on which aircraft are purchased, but this variable might over-complicate the analysis and not provide significant insights into the problem. Instead of currency rates, it might be easier to vary the number of aircraft purchased in order to see how quantity demanded and manufactured impact the profitability of a design. While the CoDeS Framework has the flexibility for a decision-maker selecting noise variables that are deemed important, the remainder of this section suggest a few key variables.

As a manufacturer, there are a couple key variables that can greatly impact the profitability of a design. As previously stated, the *number of aircraft sold and produced* can have significant impacts for two reasons: 1) it significantly influences average costs, and 2) learning curve effects. Average costs have been discussed in § 2.1 and since aircraft manufacturers exercise some control over the price of an aircraft it is important to keep these costs as low as possible. Learning curve effects refers to the fact that it often becomes less expensive to manufacturer a large number of an item than it is to manufacturer a small quantity. This is often modeled using an exponential relationship as described by Equation 2; in this equation, γ represents the cost to produce the xth unit, a is cost to produce the first unit, x is the cumulative number of units produced, and b is a learning curve parameter used to account for the reduction in costs as production quantity increases. Of these parameters, b is often the most difficult to estimate a priori – often this parameter is estimated from historical data, but obvious errors can occur when trying to extrapolate historical data to apply to new aircraft.

$$\gamma = ax^{-b} \tag{2}$$

There are two main reasons that the *learning curve* often causes a decrease in the average cost as production increases. Firstly, a large amount of cost exist in the *production facilities and equipment* needed to manufacturer, which includes tooling. Secondly, as the number of units increases, the workforce gains more experience and can then produce them more rapidly, which directly translates to lower costs. The later effect dominates the learning curve in aircraft manufacturing because it is highly labor-intensive and production rates are low. [18] In 1936, it was estimated by Wright that aircraft manufacturing costs decreased by 20% for every doubling of quantity. [178, 18] This reduction would correspond to $b = 0.8$ using Equation 2. But in

1963, Alchian conducted analysis on twenty-two aircraft from World War II, and noted that the exact value varies based on the aircraft.[7] Regardless, the estimate of approximately 20% reduction does have wide-spread acceptance when no other information is known. [18].

While the previous discussion of economic variables has focused exclusively on factors that can influence the aircraft manufacturer, there is a need to also account for the customer. As shown with industry examples in Chapter 1, the airlines have to purchase the aircraft in order for it to be a successful design. For this reason, it makes sense for an aircraft manufacturer to account for factors that affect airlines when evaluating design alternatives. One of these factors is *fuel costs*, which have been very prevalent in the news in recent years. One report stated that Delta earned a record $4.5 Billion in profits for 2015 even though operating revenue decreased by 2%. [164] These large profits were due to the significant drop in fuel prices in the last several years. Other factors that influence an airlines decision to purchase aircraft include the *price* and the number of people that desire to use air travel. The number of passengers expected to travel by aircraft in the next twenty years is expected to grow by an average of 4.1% annually according data released by the International Air Transport Association.[81] Based on these forecasts, it may be more beneficial to examine how efficiently airlines are able to fill their aircraft since it seems that the number of passengers will be increasing for the foreseeable future. This efficiency is dependent on many different sources, but can often be summarized by the metric of *Load Factor* (LF), which is used to quantify the percentage of seats occupied on a flight.

One last factor to consider that affects both airlines and aircraft manufacturers is *inflation rate*. Inflation is basically a reduction in the purchasing power of money. There are many ways to estimate inflation and a large number of economist use the Consumer Price Index as general measure of inflation for consumers throughout all industries. However, inflation does not have to be uniform throughout industries. In fact, the Bureau of Labor Statistics releases regular reports on the Producer Price Index (PPI), which tracks inflation in various industries. [30] This data can be used to more accurately track how inflation affects aircraft manufacturers, and can be used as an estimate the inflation rate experienced by airlines.

The following list summarizes some of the suggest key economic noise variables for both aircraft manufacturers and airlines.

- Manufacturing Learning Curve
- Production Facility and Equipment Costs
- Number of Aircraft Produced/Purchased
- Price of Aircraft
- Price of Fuel
- Load Factor
- Inflation Rate

3.3.5 Strategy Variables & Ranges

The specific strategy variables and their ranges depends on which strategies are analyzed. A list of major strategies that OEMs use during the conceptual design phase is presented in Table 2 of § 2.2. The process of determining specific variables and their ranges for a given strategy is largely dependent on understanding the specific parameters affected by a strategy. This understanding can often be gained through a literature review of that specific strategy.

Consider a manufacturing strategy, like the ones discussed in § 1.3.3: Product Lifecycle Management[154], 6σ [139], Integrated Product and Process Design & Lean Aircraft Initiative [167, 83], and Manufacturing Influenced Design [147, 156, 34, 98, 146]. These manufacturing initiatives are not focused on reducing the cost to produce the first unit, but are often focused on affecting manufacturing costs of the following units. While there are a large number of specific variables that could be impacted by these different manufacturing initiatives, there may not be a need to model all of these details during the early phases of conceptual design. Instead, one could alter the learning curve parameter, b in Equation 2, to capture the benefits/costs of these initiatives.

This is similar to an approach adopted by Kirby for technologies. [91] This approach is further discussed in § 3.5.1. If no equations exist, then one could use SMEs to help estimate the impacts on top-level metrics. The use of SMEs is further discussed in § 3.5.2. Regardless of the strategies that are used, a decision-maker evaluates them based on their impacts on the selected value metrics of interest.

3.4 Step 3: Establish Value Metrics

The choice of value metrics depends on the preferences of the stakeholder and this can affect the result of the analysis. Since a variety of value metric may be chosen, flexibility was built into the CoDeS Framework. However, for this dissertation work, two main value metrics were used. One metric was meant to capture the competitive interactions between aircraft manufacturers and the other metric was meant to capture the desirability of an airline to purchase a particular aircraft. These metrics were *normalized profit* and *normalized average required yield per revenue passenger mile ($/RPM).*

Profit:

Profit makes sense as a value metric because an aircraft manufacturer is a profit maximizing firm. To maximize their profit, an aircraft manufacturer would not only want to minimize their costs, but also sell as many aircraft as possible at as high of a price as possible. While profit is a good metric for examining an aircraft, it does not provide information about risk, return on investment, or the amount of time required to recoup that investment.

To provide more insight into the economic performance of an aircraft, one might consider the manufacturer's cumulative cash flow (CCF) defined by Equation 3, which shows how yearly incomes (I_t) and yearly costs (C_t) propagate throughout an aircraft's life cycle. Within these curves, there is a wealth of information that could be useful to a decision-maker. A notional example of a manufacturer's CCF curve is shown in Figure 21. The first segment of this curve, from *Research, Development, Testing, and Evaluation (RDT&E) Begins* to *production begins* represents the initial investment and conceptual exploration of a possible design. All design (conceptual, preliminary, and detailed) occurs during this first segment of the CCF curve. At the point *production begins*, all of the design considerations should be finalized and manufacturing occurs. The start of this activity causes a change in slope of the following line segment until *maximum sunk cost*, which marks the point where incomes from aircraft sales are greater than the costs associated with producing those aircraft; therefore, the slope of the CCF curve changes from negative to positive. Notionally, this line segment continues until the end of the manufacturing life cycle for that particular design of aircraft. When that line segment crosses the horizontal axis (which indicates when CCF is equal to zero), the design is said to have reached its *breakeven point* – at this time the manufacturer has recouped their investment in the aircraft. All net earnings after this period of time are considered *profit (*Π*)* for the aircraft manufacturer.s

$$CCF_i = \sum_{t=1:i}^{N} I_{1:i} - C_{1:i} \tag{3}$$

For any year i

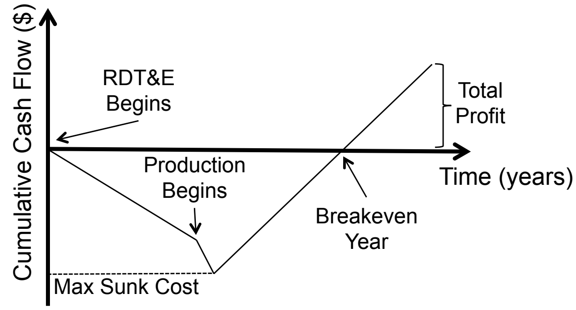

Figure 21: Notional Manufacturer's Cumulative Cash Flow curve, highlighting points of interest.

There are many interesting points on a manufacturer's cumulative cash flow curve, and several metrics can be further analyzed to provide additional insight into an aircraft design's economic performance. For example, the Return on Investment (ROI) for a design can be calculated by using the formula in Equation 4 and data taken from the manufacturer's CCF curve. Although the notional figure assumed that all of the line segments were linear, this may not be the case. Not only is the slope of the line affected by the number of aircraft sold in a given year, there are external factors that can influence these curves such as the factors described in § 3.3.4. The combination of these factors introduce economic uncertainty into the design of an aircraft, which can be visualized in the CCF curve. Instead of being approximated as a single curve, it may be more accurate to visualize the boundaries of the CCF curve caused by economic uncertainty, which can been in Figure 22. This figure not only highlights potential upper and lower ranges of the manufacturer's CCF, but it also explicitly shows a potential distribution on the breakeven year. Distributions like those could also be created for ranges of profit and ranges of maximum sunk cost, which could provide more insight into potential risks of design alternatives given an amount of economic uncertainty.

$$ROI = \frac{\Pi}{\text{Max Sunk Cost}} \tag{4}$$

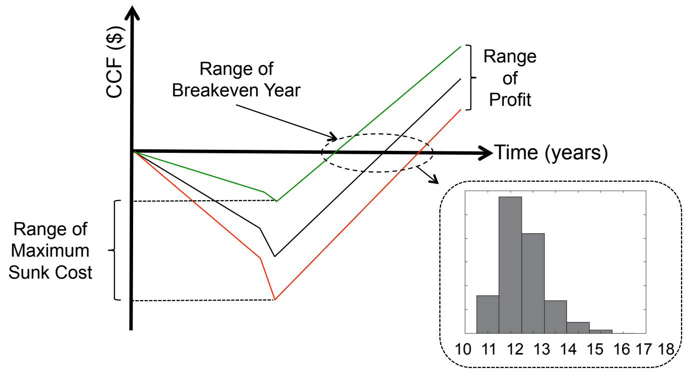

Figure 22: Notional Manufacturer's CCF ranges with uncertainty. A notional distribution of the possible breakeven year has been highlighted.

While the manufacturer's CCF curve does provide large amounts of information about a design, the single metric of profit may be more useful in comparing designs at this early stage of conceptual design. However, by keeping track of the CCF values throughout the years, the final profit can be calculated. Furthermore, by keeping track of the CCF yearly values, a decision-maker has more tools available to make a decision. Suppose two strategies had the same expected profit, but one strategy had a breakeven year that was expected to occur 1-2 years before the other – the decision-maker would probably choose to go with the strategy that had the earlier breakeven year, especially considering the demands of investors, which was discussed in § 1.2.2.

$/RPM:

As stated earlier, this metric serves as a surrogate to represent the desirability of airlines to purchase a given design alternative. Like aircraft OEMs, airlines seek to maximize their profit as well. This is accomplished by purchasing aircraft at a low price and keeping operating costs low, which usually occurs from having efficient aircraft. To fully understand how $/RPM captures these interest of an airline, it is necessary to examine the various factors that constitute $/RPM. Firstly, it is a function of total operating costs (TOC), number of seats on the aircraft (N_S), LF, and the length of trips flown throughout its life cycle ($L_{Tot,LC}$). Before defining the exact equation for $/RPM, it is necessary to identify the factors that comprise TOC, which are broken into two categories of Direct Operating Costs (DOC) and Indirect Operating Costs (IOC). DOC are costs that are required to operate the aircraft, and IOC are cost related to running the aircraft. According to the Federal Aviation Administration, DOC account for approximately 52% of the total operating costs for major passenger air carriers. [61] To better illustrate this distinction, the common elements of DOC and IOC are:

- **DOC:**
  - Flight Crew
  - Fuel Costs
  - Maintenance
    - Aircraft
    - Engine
    - Burden
  - Ownership
    - Depreciation
    - Insurance
    - Financing
- **IOC:**
  - Cabin Crew
  - Landing Fees
  - Control & Communication

– Ground Handling

– Ground Property

– General & Administrative Fees

Since these operating costs will occur throughout the life cycle of the aircraft, their values will change based on the inflation rate.* In order to account for this variation in the quantity of cash needed throughout the years, a net present value (NPV) formulation of the TOC should be used; this formulation is applied by using Equation 5. In this equation, P_i represents the amount of cash in year i and f represents the inflation rate. To quickly illustrate how NPV works, consider an example where \$100 was received each year for three years with a constant 5% inflation rate. At the end of three years, there would be a quantity of \$300, but it would only have the purchasing power of \$272.32 in today's dollars.

$$NPV = \frac{P_i}{(1+f)^i} \tag{5}$$

Using a NPV formulation, the various operating costs throughout the years can be converted to a common year's dollar value. Furthermore, this formulation allows for the \$/RPM metric to be less sensitive to inflation. But the value of \$/RPM would still change if estimation of the costs increase or decrease. The formula for calculating \$/RPM is given by Equation 6.

$$\$/RPM = \frac{\mathrm{NPV}(TOC)}{(LF)(N_S)(L_{Tot,LC})} \tag{6}$$

One of the key benefits of using \$/RPM as a surrogate metric for desirability to purchase an aircraft is that it is intrinsically linked to Profit for an OEM because one of the elements of DOC is *financing*, which relates to the acquisition price of the aircraft. The significance of this linkage between value metrics, becomes more apparent by explaining the rationale for normalizing them.

*Since inflation reduces the purchasing power of money, a larger quantity of money will be needed in future years to achieve the same level of service/benefit.

Normalizing the Metrics:

This need arises for two main reasons: 1) it provides more context for the gains/losses of a possible strategy compared to the strategy of doing nothing, and 2) it allows for a more direct comparison to the competition. The first reason has to do with the cognitive processing of humans – by showing both metrics on the same scale and in terms of percentage change from a baseline, it is easier to intuit the net improvement/detriment of a given strategy. Furthermore, it is also easier to evaluate possible strategies relative to a competitor. For example, consider the direct comparison between aircraft in Figure 23 where i represents the initial location of the aircraft and f represents the final location given market behavior and/or strategy option. If the red square represents a competitor's aircraft and the green circle represents the proposed design alternative, it is easy to see that the competitor has a lower *normalized $/RPM* value, which may cause more aircraft to purchase their aircraft than initially estimated. This behavior is shown in Plot A of Figure 23. If more of the competitor's aircraft was purchased then the red square would shift to the right (i.e., obtain a higher normalized profit) and the green circle would shift to the left (i.e., obtain a lower normalized profit). Since the profit values have been normalized, it is easy to directly relate the changes in *normalized profit* to market share if the a direct relationship between $/RPM and quantity demanded by airlines was known. Plot B shows a different result because the green circle implemented a price cutting strategy that caused a reduction in the *normalized $/RPM* value and a reduction in the *normalized profit*; however, the reduction in *normalized $/RPM* value could cause more airlines to purchase that design of aircraft which would increase the *normalized profit*. Again, if a relationship between $/RPM and quantity demanded was known, then the percentage change in market share could be quantified. It is important to note that this is analogous to the typical price versus quantity relationships often seen in

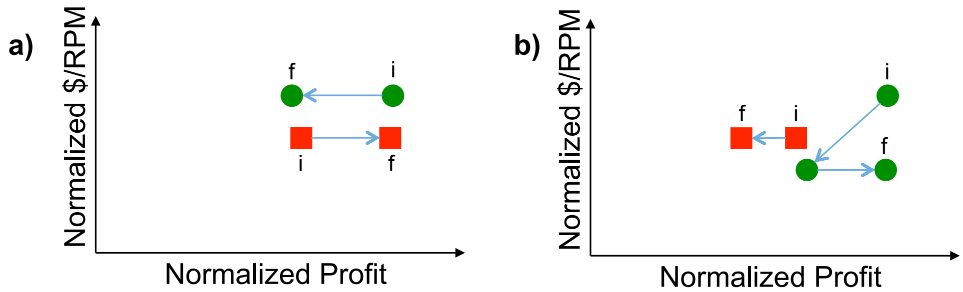

Figure 23: Notional plot showing the benefits of using normalized value metrics. Plot A shows how market share could be reduced due to a higher *normalized $/RPM*, and Plot B shows how a price-cutting strategy could help increase market share.

economics. General theory states that the quantity demanded of a good/product has an inverse relationship between price and quantity – as the price of a good increases, the quantity demanded decreases.

While the exact relationship between $/RPM and quantity of aircraft demanded by airlines is not publicly available, one would expect that aircraft OEMs would have estimations of this relationship based on their past experience with customers (i.e., airlines). Since this information could not be used in this dissertation, *normalized profit* served as a surrogate metric to approximate changes in market share.

Even though this dissertation work used *profit* and *$/RPM* as the value metrics, the CoDeS Framework is not limited to these metrics. While this flexibility does exist, there are benefits that come to using these economic-based metrics. The main benefit is that it allows for the engineers/designers and the decision-maker(s) to "speak the same language" when evaluating designs – the need for clear communication within and between engineering teams and decision-makers has been cited as being a critical element for effective designs. [74, 12, 41] For this to occur, appropriate relationships between design, economic noise, and strategy variables need to be mapped to the value metrics of interest using a defensible approach.

3.5 Step 4: Determine Geometric Baseline

Geometric Baselines need to be established for both a proposed design alternative and a competitor's design. This need exist for several reasons. Firstly, it is necessary to separate the geometry considerations from the strategy considerations in order to fully understand the impacts of each – this is similar to the approach adopted by Kirby where she separated geometric optimization from technology implementation in her Technology Identification, Evaluation, and Selection (TIES) methodology. [91] It is important to note that Kirby did adopt an iterative approach where the geometry was re-optimized after a technology was selected in order to realize the full benefits of the technology. Secondly, it is important to have a baseline vehicle design in order to easily make comparisons; this was discussed in the previous section (§ 3.4) when it was suggested that the value metrics should be normalized. While these two reasons highlight the importance of having baseline designs, they do not address how they should be constructed or evaluated.

When thinking about constructing models of geometric baselines of a proposed design and a competitor's design, one can easily imagine two distinct approaches. One of these approaches is to create models of the designs in parallel to each other (i.e., create both geometric baseline models simultaneously) and the other is to create these models in series (e.g., create a model of the competitor's geometric baseline and then create a model of the proposed geometric baseline). The former approach may be preferred if both aircraft OEMs are seeking to enter the market simultaneously and there is little information known about the competitor's design. This approach may also be ideal if the aircraft OEM has enough resources for two design teams to independently model each design. The latter approach may be preferred if the competitor's design is already in the market; if this were the case, then there would be a large amount of information that could be gathered about the competitor's design in order to create an accurate representation of it. Furthermore, this approach may

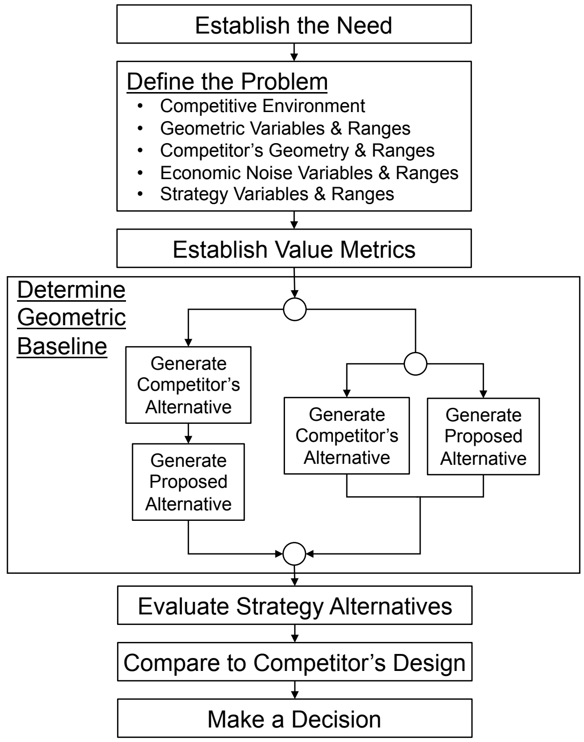

Figure 24: The Geometric Baseline for the proposed design and competitor's design can be established either in series or in parallel.

also be preferred if there are limited resources to model both designs simultaneously. The approach adopted in this dissertation was to model the competitor's design and the proposed design in series. These two approaches are shown being incorporated in the CoDeS Framework in Figure 24. It is important to note that the ability to adopt either approach increases the flexibility of the CoDeS Framework.

While it may not be difficult to determine which approach should be used in creating models of the geometric baselines, there may be considerable difficulty in ensuring that the models provide reliable and relevant information to the decision-maker. In order to have confidence in the results, an ad-hoc approach should not be used in establishing the geometric baseline for aircraft. Furthermore, this approach should be defensible, repeatable, traceable, and also applicable to strategy evaluation in order to maintain consistency in the analysis. For mapping design variables to performance characteristics, the ideal solution would be using a validated physics-based analysis tool. This would allow for changes in various design variables to propagate through the system using a proven mathematical framework. For capturing how these performance characteristics and manufacturing considerations would map to economic value metrics, an ideal solution would be using an activity-based costing tool. However, the use of these tools may not always be possible.

The inability to use these tools could occur for several reasons. Two of the possible reasons for this include the proprietary nature of these tools or because alternatives are being analyzed where the physics or cost-basis are not fully understood. While the lack of proprietary tools may limit analysis in this dissertation, it would not affect an OEM's ability to apply the CoDeS Framework to their design. However, when trying to analyze situations where the physics or cost-bases are not fully understood, it may be better to use SMEs. It is not advisable to use a database that interpolates between existing designs in order to estimate performance. The conceptual design of an aircraft may analyze alternatives that have never been flight-tested or manufactured, which would result in erroneous results when interpolating.

The following subsections focus on three approaches for the conceptual design of aircraft. § 3.5.1 elaborates on the requirements of an appropriate modeling and simulation (M&S) environment. § 3.5.2 describes when it may be necessary to use SMEs and how SMEs could be solicited to evaluate potential designs. And § 3.5.3 discusses how these two approaches may be used jointly in order to fully evaluate a potential design alternative.

3.5.1 Considerations for a Modeling and Simulation Environment

One of the underlying factors influencing the selection process was the availability of the M&S environment. It would be naïve to believe that OEMs do not have proprietary tools that they use for conceptual design of their aircraft; however, the proprietary nature of these tools meant that they were inaccessible for this dissertation. Other factors influencing the selection of an appropriate tool are more directly related to the research that was conducted. This section is divided into three parts: Part 1 provides an overview of the capability requirements of an M&S environment that is able to meet the needs of this dissertation research, Part 2 explains how to establish a Geometric Baseline using in M&S environment described in Part 1, and Part 3 elaborates on implications for the CoDeS Framework.

Overive of Desired M&S Environment Capabilities:

While performance characteristics were not considered to be value metrics in this dissertation, their effects on the value metrics selected should be accurately quantified. To this end, there was a need to discuss how design variables are used to determine performance characteristics in the design of aircraft. This will be discussed from a first-principles, physics-based analysis focusing on evaluations that would be typical during the conceptual design phase. This is usually accomplished through a process referred to as sizing and synthesis (S&S). Synthesis refers to the idea of bringing together multiple disciplines (e.g., aerodynamics, propulsion, structures, stability & control) in order to determine the characteristics of an aircraft (i.e., sizing) that meet the stakeholders' requirements. The basic premise of S&S is to simulate the mission, whether on a computer or paper, ensuring that at each point throughout the mission the aircraft meets stakeholders' requirements (e.g., has enough fuel, produces enough lift, maintains appropriate thrust).

A typical commercial aircraft mission consists of eight segments: 1) pre-takeoff (e.g., board, refuel, taxi), 2) takeoff, 3) climb, 4) cruise, 5) descend, 6) approach, 7) land, and 8) post-landing (e.g., taxi, deboard, unload cargo). There exist additional reserve requirements (e.g., climb, loiter, descend) that are used as a margin for safety – if the initial fuel estimates are too low, aircraft gets delayed in landing, or has to reroute due to a situation at the destination airport. While multiple other mission segments could occur, these nine (eight including the additional reserve phase) can be considered typical of a notional mission. As stated above, S&S literally examines whether an aircraft has the performance characteristics necessary to complete each segment of its mission and has enough fuel in order to safely complete the mission. An appropriate M&S environment must be able to account for these various mission segments and the key characteristics that affect the aircraft performance during each. Multiple authors, including Anderson[8], Mattingly[105], and Raymer[137] have suggested approaches for performing S&S. The following provides a brief overview of the general approach suggested by these authors; a more detailed explanation can be found in [105].

The phases of pre-takeoff and post-landing can be approximated using historical data since this dissertation does not examine any strategies involving airport operations. The other phases though can be modeled using equations. The equations presented by Mattingly focus on using two high-level scaling parameters: thrust-to-weight ratio (T/W) and wing loading (W/S_{wing}). These equations all take the general form of $T/W = f(W/S_{wing})$. In order to use these equations, specific details need to be known about the aircraft, such as: aircraft drag polar, engine characteristics, and component weights.

The aircraft drag polar is a mathematical representation of the amount of drag an aircraft experiences based on given characteristics. While the specific equation used can take a variety of forms, a common expression is described by Equation 7. In this equation, C_D represents the drag coefficient, $C_{D,0}$ represents the amount of profile drag that occurs from the shape of the body, K_1 & K_2 represent coefficients that describe the amount of lift-induced drag that occurs, and C_L represents the lift coefficient. C_L and C_D are directly proportional to the amount of lift (L) and drag (D) experienced by the aircraft. Formulas for L and D are shown in Equations 8 and 9, respectively; in these equations, q_∞ represents the dynamic pressure. The other parameters, $C_{D,0}$, K_1, and K_2 are dependent on the specific geometry of the aircraft. A common heuristic used in commercial aircraft design states that the higher the lift-to-drag ratio, the less fuel will be burned during a mission. This directly relates to the cost to operate the aircraft (as seen in DOC described in § 3.4).

$$C_D = C_{D,0} + K_1 C_L^2 + K_2 C_L \tag{7}$$

$$L = q_\infty S_{wing} C_L \tag{8}$$

$$D = q_\infty S_{wing} C_D \tag{9}$$

Engine characteristics that are needed to perform S&S analysis include the amount of fuel burned for different thrust levels and how that fuel burn varies as a function of altitude. This information is necessary because S&S ensures the aircraft is producing enough thrust to overcome the drag experienced during the various mission segments. From determining the amount of thrust required, the engine characteristics can be used to determine the amount of fuel burned. This information can then be directly related to the costs of operating the aircraft.

Finally, the component weights need to be taken into account. This is because the amount of lift required, is directly proportional to the weight of the aircraft at that phase in the mission. While fuel will be burned throughout the mission, which causes the weight to decrease, a commercial aircraft should not have any other changes in weight[†] associated with completing its mission. While historical estimates could be used to approximate the weights of various components, it may limit the capability of examining how changes in those components affect the total weight. For this reason, it would be better to use an M&S environment that is capable of converting

[†]Some missions for military aircraft include a payload drop.

geometric descriptions of components, which is comprised of a given material, to an accurate weight for that component. An example of this could be for the wing of an aircraft, where a geometric description and choice of materials are inputted to approximate the weight of the wing. This level of fidelity would allow for an accurate assessment of the amount of fuel required to complete the aircraft's mission – since it is heavily dependent on the total weight of the aircraft – the amount of fuel is directly proportional to the costs of operating the aircraft. Furthermore, if manufacturing complexities associated with constructing the desired component were inputted, then the M&S environment should be able to estimate the manufacturing costs incurred by the OEM.

Figure 25 aids in illustrating how the drag polar, engine characteristics, and component descriptions are used in S&S by illustrating Mission Analysis and Constraint Analysis. In Constraint Analysis, the characteristics of the aircraft are used to develop the various constraints for each mission segment using the $T/W = f(W/S_{wing})$ formulation for each segment. The interactions of these constraints can lead to a feasible area, which is colored green in Figure 25. All the points in that feasible area represent designs that are able to complete the mission segments based on the inputted aircraft characteristics (drag polar, engine characteristics, and component weights); however, any changes in those characteristics will cause some and/or all of the curves to shift which could increase or reduce the size of the feasible space. In Mission Analysis, the aircraft simulates completing each mission segment to ensure that it has enough fuel to complete the mission – as stated previously, the amount of fuel burned depends on the aircraft characteristics. Figure 25 also shows the iterative nature of S&S. Since Mission Analysis depends on the results of Constraint Analysis, and visa-versa, both analyses need to be iterated until a converged solution occurs. If a converged solution does not occur, then either the aircraft characteristics or the mission segments need to be adjusted.

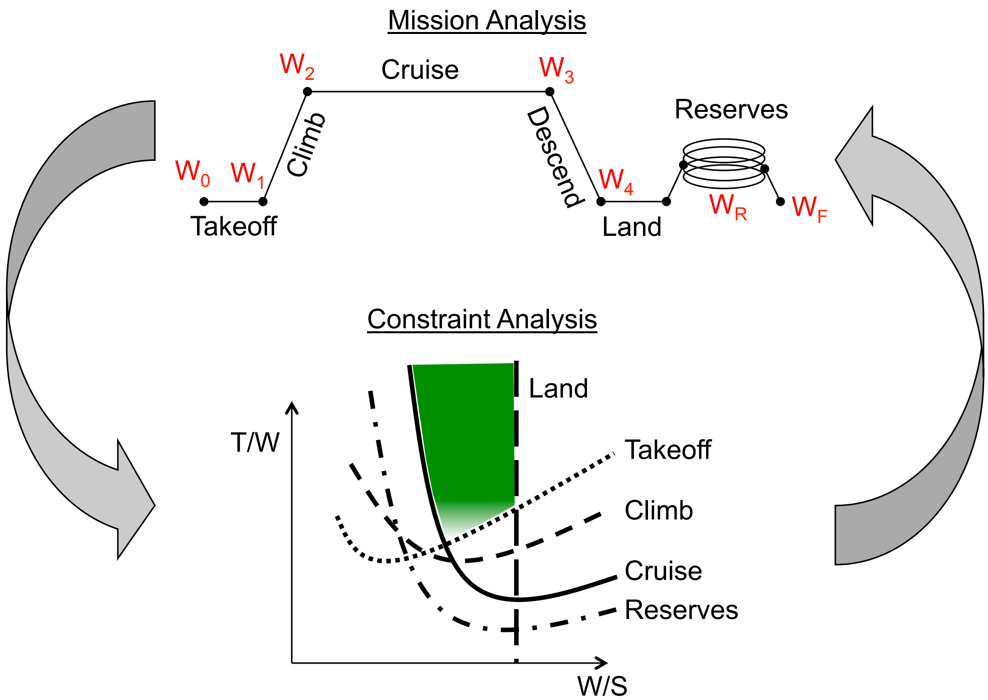

Figure 25: S&S analysis of a mission consist of iterating between constraint analysis, which yields the feasible design space, and mission analysis, which yields the weights at various mission segments to ensure adequate fuel.

The discussion on performance characteristics has focused on their relationship to operating costs of the airline, but they are also related to the profit of the aircraft OEM indirectly and directly. They are indirectly related for the same reasons that \$/RPM is used as a value metric, which was discussed in § 3.4 – the more desirable an aircraft is to an airline means that aircraft OEMs may be able to charge a higher price and/or sell more units. These performance characteristics are directly related to profit because they affect the cost of production.

The cost to produce aircraft is directly dependent on three high-level factors: RDT&E Costs ($C_{R,Tot}$), Manufacturing Costs ($C_{M,Tot}$), and Sustainment Costs ($C_{S,Tot}$). $C_{R,Tot}$ encompass all of the costs to design and develop the vehicle and components. These costs include: labor, initial tooling, experimentation (ground-based and air-based), certification, raw materials required for the initial prototypes, and technology development. $C_{M,Tot}$ account for the costs associated with producing all of the operational vehicles. These costs include: labor, tooling, raw materials, component purchasing (e.g., buying an engine from an engine manufacturer), and possible transportation costs. $C_{S,Tot}$ account for all other production costs that are not $C_{M,Tot}$. This includes: spares, facilities, initial training, ground support equipment, and technical data.

These cost elements could be modeled as only total costs accrued over the aircraft's production life cycle. However, this would limit the flexibility in analyzing data. As stated in § 3.4, a large amount of information can be gained from the manufacturer's CCF similar to the one seen in Figure 21. For this reason, it would be preferable to have an M&S environment that computes yearly values, which can then be summed to quantify total costs for the aircraft – this approach also assumes that incomes from selling aircraft would be calculated on yearly basis. The costs associated with RDT&E would occur over several years before production on the aircraft begins, but for simplicity one could model these costs as occurring over the entire life cycle of N years as denoted by Equation 10, but RDT&E costs would be equal to zero for each year after production begins. The costs for manufacturing can also be modeled as occurring each year during the aircraft's life cycle, as shown in Equation 11, but with a value of zero for each year before production begins. This same approach can be adopted for the costs of sustainment, which is captured in Equation 12. Ideally, an M&S environment would allow these costs to vary yearly depending on influencing factors (e.g., difficulty in technology maturation, production schedules, modifications to existing facilities) instead of having a fixed value from historical data that is equally distributed over the production life cycle.

$$C_{R,Tot} = \sum_{i=1}^{N} C_{R,i} \tag{10}$$

$$C_{M,Tot} = \sum_{i=1}^{N} C_{M,i} \tag{11}$$

$$C_{S,Tot} = \sum_{i=1}^{N} C_{S,i} \tag{12}$$

Some interdependencies between costs and performance characteristics are obvious based on the previous discussion. One of these is the component weights, which depend on the raw materials being used for production. Another is the engine characteristics because one would expect a better performing engine to costs more than a lower performing engine. However, several of the interdependencies are more subtle to detect. For example, improving the drag polar might require use of a new technology ($C_{R,Tot}$), more complicated tooling ($C_{M,Tot}$), and new facilities ($C_{S,Tot}$). This means that the impact on the OEMs profit is not just dependent on the technology, but also the change in manufacturing activity caused by that technology. These subtle effects may be simplified to the point of being adequately captured as learning curve effects (given by Equation 2 in § 3.3.4), but this depends on the level of granularity desired. By accurately capturing more of these interdependencies, the M&S environment can be used to explore more strategy options. An activity-based costing approach would be ideal to capture these interdependencies, if and only if it was also directly linked to the physics-based analysis described previously.

These requirements on an acceptable M&S Environment are summarized as:

- Available for use (i.e., non-proprietary)
- Capable of analyzing strategies discussed in Section 2.2
- Propagate low-level physical design and business changes to high-level metrics
- Use physics-based analysis whenever possible
- Use more than weight-based regressions/heuristics for cost-related information

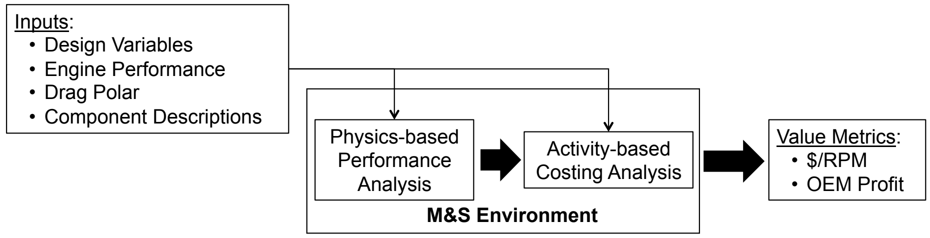

Figure 26: Notional figure of a desired M&S environment that links physics-based performance calculations to activity-based cost calculations for an aircraft.

- Analyze costs throughout the life cycle of the design – including costs related to the OEM during RDT&E, Manufacturing, and Sustainment and costs related to operations (DOC and IOC)

Ideally, an M&S environment would allow for a direct linkage between the performance characteristics and the economics related to the aircraft. As previously stated, this would allow for capturing of the interdependencies that exists between performance and costs. To this end, a notional block diagram shows this linkage in Figure 26. Using an M&S environment as described would provide confidence in accurately selecting a geometric baseline.

Selecting a Geometric Baseline:

As previously stated, if a design exist in the market, then reverse engineering can be used to determine the geometric baseline of that aircraft – this geometric baseline can then be analyzed using an M&S environment in order to create a mapping between the design variables and the value metrics. However, if the design does not exist and only a range of values for different geometric design variables has been established, then an optimization technique should used to identified a preferred geometric baseline. Based on the value metrics identified in § 3.4, a multi-objective optimization technique should be used. Several techniques were identified in the literature that could be well suited for this design problem, depending on the specific details. These techniques are: Monte Carlo Simulation (MCS), gradient-based algorithms, and evolutionary algorithms. Each of these techniques are well-suited for different types of problems – to maintain flexibility in the CoDeS Framework any of these approaches could be used. To aid in the selection of an appropriate technique, a brief description of each approach is provided.

MCS is a brute-force approach to solving problems that is best suited when an M&S environment can be evaluated many times in a small amount of time. This approach does not rely on information from previously evaluated alternatives, but instead evaluates randomly sampled combinations of design variables. For MCS to be effective a large number of evaluations must occur, which is typically greater than or on the magnitude of 10^4 alternatives – even if an M&S took only one second to execute, it would still take over 2.75 hours to analyze just 10,000 alternatives using an MCS approach. Regardless, this technique can be useful in visualizing the design space. Filtering techniques can also be applied to these results in order to identify a preferred geometric baseline. This technique is best suited for problems where the M&S environment has a low runtime and when it is not possible to apply other optimization techniques.

Gradient-based algorithms seek to minimize the number of alternatives analyzed by exploiting information regarding previous evaluations. These algorithms are more suitable for M&S environments that take longer to analyze a design alternative; however, to utilize these algorithms, the design variable inputs (and outputs) need to be continuous. While these algorithms can be used in the presence of constraints, the design space must be convex in order to ensure that global optimum is found. Furthermore, some gradient-based algorithms require the calculation or approximation of second derivatives, which can be time consuming or may not be possible for a given M&S environment. If it was assumed that a gradient-based algorithm could be used for a given M&S environment, then sequential quadratic programming (SQP) may be the preferred algorithm to use for these design problems. Details for applying this approach are discussed in several sources [21, 169] that provide a strong theoretical underpinning and worked out examples. SQP has been shown to quickly converge on optimums with a minimal number of function calls, which can be beneficial if the M&S environment is expensive to execute. The speed of convergence is dependent on the initial point evaluated, which may be randomly selected. As with other gradient-based algorithms, SQP cannot be easily applied if design variables or outputs are discretized or if discontinuities exist in the design space.

Evolutionary algorithms are well suited for handling problems with discrete inputs and/or outputs or that have a non-convex design space. These algorithms first initialize a random population of points that evaluate different alternatives and then attempt to find more optimal points based on these previous evaluations. An example of a popular evolutionary algorithm is the Non-dominated Sorting Genetic Algorithm II (NSGA-II)[47]. A basic overview of this algorithm is that it evaluates an initial population of points to determine which points are the most optimal (based on their ability to optimize the value metrics) and then uses those most optimal points to produce a new population of points – this process is repeated until a given convergence criteria is met. While NSGA-II is well-suited for certain problems, it often requires a large number of evaluations using an M&S environment, which can make it time consuming to execute. Furthermore, the results of NSGA-II are dependent on the specific conditions (e.g., size of population, convergence criteria) used in setting up the algorithm.

The specific type of problem being analyzed will influence which technique is preferred. One heuristic that can be used involves whether or not the input variables to the M&S environment are discrete or continuous – if discrete, then NSGA-II or MCS should be used, otherwise SQP would be preferred. Another heuristic involves the time required to execute the M&S environment – if the M&S environment is expensive to execute, then MCS should not be used. However, as previously stated, the CoDeS

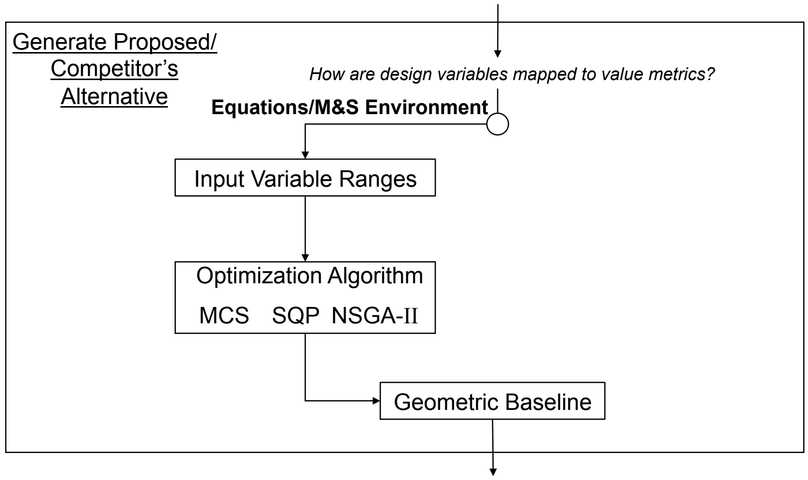

Figure 27: Flowchart of the *Determine Geometric Baseline* step when using an M&S environment.

Framework has the flexibility to use any of these approaches. The specific details of the problem should guide the selection of an appropriate optimization technique.

Impacts on CoDeS Framework:

The use of an M&S environment would be applicable to both the parallel and serial approaches (as shown in Figure 24) to the CoDeS step of *Determine Geometric Baseline*. This process could be done for either the competitor's geometric baseline or the proposed geometric baseline. Figure 27 illustrates this process and shows how either of three optimization techniques discussed above could be used. However, the use of an M&S environment is not the only approach that could be used to establish a geometric baseline – the next section discusses how SMEs could also be used in this step.

3.5.2 Considerations for Subject-Matter Experts

As previously stated, some aircraft designs cannot be analyzed using an M&S environment because the underlying physics or cost-basis may not be completely understood. When a situation like this occurs, aircraft manufacturers can use SMEs in order to help assess a proposed design alternative. While the notion of an expert may be hard to completely define, the US Department of Defense offers the following definition of a SME:

> "[A SME is] an individual who, by virtue of position, education, training, or experience, is expected to have greater-than-normal expertise or insight relative to a particular technical or operational discipline, system, or process." [166]

Identification of an appropriate SME was outside the scope of this dissertation, but has been discussed in the literature by several authors, including: Engler [58] and Pace & Sheehan [130]. But when using SMEs there are two major concerns that need to be addressed: 1) how to solicit data, and 2) how to use that data. Both of these concerns are related to establishing a geometric baseline; however, the same approach may also be applied to the next step of the CoDeS Framework, which evaluates strategy alternatives. Since SMEs were not solicited in this dissertation, this section provides a description of how to gather and use SME data so the CoDeS Framework could have more flexibility to analyze potential designs

How to Solicit Data:

A well-known approach to soliciting data from SMEs is the Delphi Method, which was first proposed by Dalkey and Helmer in 1963 from work they did at RAND Corporation. [46] A schematic of this method can be seen in Figure 28. The general philosophy of the Delphi technique is that, "two heads are better than one, or ... n heads are better than one." [45] One of the key purposes of the Delphi Method is, "to determine or develop a range of possible program alternatives." [48] This technique has been used by numerous authors throughout the years in order to develop consensus amongst groups (e.g., SMEs, stakeholders, decision-makers) in fields ranging from human resources to parks and recreation.[75, 163, 159, 165, 180] This method has been further developed by several authors throughout the years. [58, 43, 136] In general, these methods leverage planning workshops where individuals gather to reach some form of consensus about the proposed topic. In the context of this dissertation, this would involve getting SMEs together in order to reach a consensus about a Geometric Baseline. One of the key differences between using SMEs and an M&S environment is that an M&S environment could theoretically analyze millions of different alternatives by making small changes in variables, but SMEs would be limited in the number of alternatives they could affectively evaluate. Ideally, the number of alternatives should be as small as possible.

The Delphi Method (or similar) could be applied to an aircraft design problem by asking SMEs to rank alternative designs using a ratio scale based on a variety of metrics of interest. While these metrics of interest are based on the discretion of the decision-maker, SMEs would be most beneficial if the metrics were not able to be quantified using an M&S environment. To illustrate what this data may look like, consider the notional example below:

Notional Example: consider the metrics of *manufacturability* (i.e., how difficult a design would be to manufacturer) and *desirability* (i.e., whether airlines would think the design is worth purchasing). Suppose ten SMEs were asked to rate six designs, using these metrics, on a scale from one to ten, and the Delphi Method was used to help reach consensus. To clarify, a rating of 1 for manufacturability would mean that the design can be easily manufactured with current facilities, but a 10 would mean that significant advances/upgrades would be needed. As for desirability, a rating of 1 would mean that airlines would probably not be interested in the design, but a rating of 10 would mean that every airline would try to purchase that design. After several iterations, a final consensus is reached – the results are shown in Table 4.

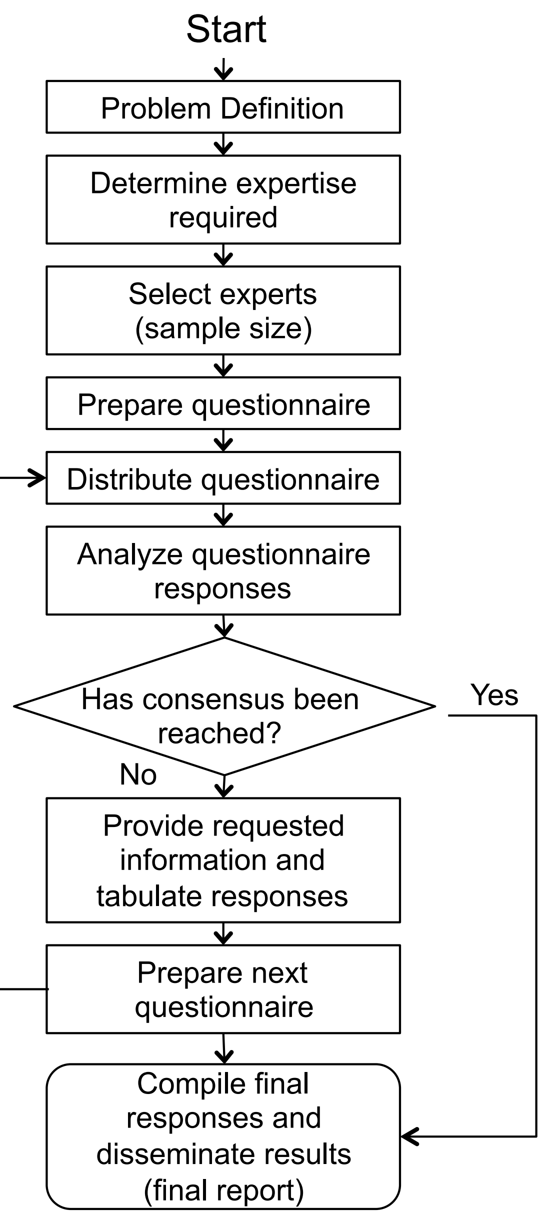

Figure 28: Delphi Method, which can be used to aid in soliciting information from subject-matter experts. [159]

Table 4: Example results of SMEs' evaluations of six design alternatives using the metrics of manufacturability and desirability.

Alternative	Manufacturability	Desirability
A	2	1
B	4	3
C	6	5
D	5	2
E	6	3
F	8	5

Now that the data has been acquired, a technique needs to be identified that can process the data.

Selecting a Geometric Baseline:

A desired technique should not be limited to a maximum number of metrics that can be evaluated. This technique should be able to handle data where no clear mapping exists between metrics. Furthermore, the technique should have a strong mathematical underpinning and have been thoroughly vetted in the literature. By examining the fields of operations research and economics, a technique called Data Envelopment Analysis (DEA) was identified and was cross-fertilized into the CoDeS Framework.

Classically, DEA has been used as a way of evaluating "productivity or efficiency when multiple outputs and multiple inputs need to be taken into account." [40] This analysis is commonly conducted by using linear programming techniques; however, modifications can be made for different problems, which increases the versatility of DEA. The use of DEA has increased throughout the years and has been applied to diverse topics of study, including education systems [17], natural resource extraction [160], technology development [16, 149], manufacturing [149, 181, 182], deregulation of the airline industry in the 1980s [15], and a wide range of other applications, even including baseball player efficiency [113]. These different applications use a variety of modifications and models, which are dependent on the specific application. In the context of the design problem examined in this dissertation, DEA could be used to identify preferred solutions from SME evaluations. In order to use DEA, the data would need to be in the form of a ratio scale with each metric having the same possible range of values – if this is not the case, then the data must be transformed or normalized.

One of the first DEA approaches developed was the Charnes, Cooper, and Rhodes (CCR) model, which was proposed in 1978.[35] Like most forms of DEA models, this model does not require prescribed weightings on the metrics being analyzed; instead it allows for the data available to determine the optimal weightings. The CCR model is shown in Equation 13 and is generalized for $o = 1, 2, \ldots, n$ design alternatives[‡], each with m inputs and s outputs. By solving for θ^*, one can determine whether a DMU is efficient based on the following criteria: $\theta^* = 1$ and there exists at least one optimal (ν^*, μ^*), with $\nu^* > 0$ and $\mu^* > 0$. Otherwise, the DMU is said to be CCR-inefficient.

$$
\begin{aligned}
\text{LP} \quad & \max_{\mu,\nu} \theta = \mu_1 y_{1o} + \cdots + \mu_s y_{so} \\
\text{subject to} \quad & \nu_1 x_{1o} + \cdots + \nu_m x_{mo} = 1 \\
& \mu_1 y_{1j} + \cdots + \mu_s y_{sj} \leq \nu_1 x_{1j} + \cdots + \nu_m x_{mj},\ j = 1, \ldots, n \\
& \nu_1, \nu_2, \ldots, \nu_m \geq 0 \\
& \mu_1, \mu_2, \ldots, \mu_s \geq 0 \\
\mu : \quad & \text{output ``weights''} \\
\nu : \quad & \text{input ``weights''}
\end{aligned} \tag{13}
$$

To demonstrate how DEA would be applied, the CCR model shown in Equation 13 was applied to the notional example of SMEs' assessments shown in Table 4. This was done by assuming that *manufacturability* was an input to the design alternatives and

[‡]Typical terminology for DEA analyzes Decision Making Units (DMUs), but in the context of this dissertation, this terminology is changed to design alternatives.

Table 5: Example DEA results of SMEs' assessments of data presented in Table 4.

Alternative	ν^*	μ^*	θ^*
A	0.5	0.6	0.6
B	0.25	0.3	0.9
C	0.167	0.2	1
D	0.2	0.24	0.48
E	0.167	0.2	0.6
F	0.125	0.15	0.75

desirability was an output. The analysis of Alternative A is shown in Equation 14. This same approach would be applied to all design alternatives; the final results of this analysis are shown in Table 5. From these results it can be seen that Alternative C is the preferred solution for the metrics given in the notional example.

$$\begin{aligned}
\text{A:} \quad & \max\theta = 1\mu \\
\text{subject to} \quad & 2\nu = 1 \\
\text{(A)} \quad & \mu \leq 2\nu \\
\text{(B)} \quad & 3\mu \leq 4\nu \\
\text{(C)} \quad & 5\mu \leq 6\nu \\
\text{(D)} \quad & 2\mu \leq 5\nu \\
\text{(E)} \quad & 3\mu \leq 6\nu \\
\text{(F)} \quad & 5\mu \leq 8\nu \\
\therefore \quad & \nu^* = 0.5,\ \mu^* = 0.6,\ \theta^* = 0.6
\end{aligned} \tag{14}$$

The CCR model can determine a production frontier, which is based on the inputs and outputs of the various DMUs and does not depend on a preassigned objective function. In principle, this is similar to the concept of a Pareto frontier. However, a major benefit of DEA analysis is the ability to identify inefficient DMUs that may appear to be on the Pareto/Efficiency[§]frontier. This is often accomplished by transforming the linear program model to a dual problem, which uses a real variable θ

[§]The terms *Pareto frontier* and *Efficiency frontier* are used interchangeably here to highlight their similarity, but should not be interpreted to suggest that these concepts are the same.

and non-negative vector $\boldsymbol{\lambda} = (\lambda_1, \ldots, \lambda_n)^T$ and is shown in Equation 15 – the bold symbols in this equation represent vectors. Equation 15 is just a slightly modified vector-form of Equation 13.

$$\begin{aligned} \text{DLP} \quad & \min_{\theta, \boldsymbol{\lambda}} \theta \\ \text{subject to} \quad & \theta x_o - X\boldsymbol{\lambda} \geq 0 \\ & Y\boldsymbol{\lambda} \geq \boldsymbol{y_o} \\ & \boldsymbol{\lambda} \geq 0 \end{aligned} \tag{15}$$

By solving for θ^* in Equation 15, an extension of the dual problem, which is shown in Equation 16, can then be solved in order to determine any input excesses, $\boldsymbol{s}^-$, and output shortfalls, $\boldsymbol{s}^+$, which are referred to as slacks. Using the notional example presented in Table 4 for context, an input excess would mean that the *manufacturability* of a design would need to decrease to be considered efficient; an output shortfall would mean that the *desirability* of a design would need to increase to be considered efficient. Models with these slacks can either be input-oriented, which means they show how much an input needs to decrease to become efficient, or output-oriented, which means they show how much an output needs to increase to become efficient. It is important to note that whether input-oriented or output-oriented, Equation 15 is first solved in order to determine θ^*. From that point, a second model is solved to determine the slacks – Equation 16 shows an input-oriented form of this equation. The only difference between the input-oriented and output-oriented forms of these equations is the constraints of $\boldsymbol{s}^-$ and $\boldsymbol{s}^+$. For the input-oriented form, they are defined as shown in Equation 16, but for the output-oriented form, $\boldsymbol{s}^+ = Y\boldsymbol{\lambda} - \theta^*\boldsymbol{y_o}$ and $\boldsymbol{s}^- = \boldsymbol{x_o} - X\boldsymbol{\lambda}$. To help provide more context, the notional problem described in Table 4 was solved using input-oriented and output-oriented models for slacks; the

Table 6: Example DEA results, including slacks to show input excesses or output shortfalls, of SMEs' assessments of data presented in Table 4.

Alternative	θ^*	**Input-oriented** (s^-)	**Output-oriented** (s^+)
A	0.6	0.8	0.667
B	0.9	0.4	0.333
C	1	0	0
D	0.48	2.6	2.167
E	0.6	2.4	2.0
F	0.75	2.0	1.667

results are shown in Table 6.

$$\begin{aligned} \max_{\boldsymbol{\lambda},\boldsymbol{s}^-,\boldsymbol{s}^+} \quad & w = \boldsymbol{es}^- + \boldsymbol{es}^+ \\ \text{subject to} \quad & \boldsymbol{es}^- = \theta^* \boldsymbol{x_o} - X\boldsymbol{\lambda} \\ & \boldsymbol{es}^+ = Y\boldsymbol{\lambda} - \boldsymbol{y_o} \\ & \boldsymbol{\lambda} \geq \mathbf{0}, \boldsymbol{s}^- \geq \mathbf{0}, \boldsymbol{s}^+ \geq \mathbf{0}, \\ & \text{where } \boldsymbol{e} = (1, \ldots, 1) \end{aligned} \tag{16}$$

It should be noted that θ^* remains the same between Table 5 and Table 6 because the CCR model is still used in the first phase of the analysis. The second phase of analysis used Equation 16 to calculate the slacks. An optimal solution was identified when all slacks were equal to zero. An alternative that satisfies both the CCR-efficiency stated above and has all slacks equal to zero is referred to as Pareto-Koopmans efficient, which is loosely defined as, "[being] fully efficient if and only if it is not possible to improve any input or output without worsening some other input or output." [40] Therefore, Alternative C is the only one considered Pareto-Koopman efficient.

While the notional example only dealt with one input and one output, this may not be the case for real aircraft design problems. Most likely, SMEs would be required to give assessments for several different metrics. As this number of metrics increases, it is more cumbersome to perform the necessary DEA calculations. Several commercially-available DEA programs exist that have been validated. Alternatively, there is a free, validated, open-source DEA solver available, OSDEA [171], that runs on JAVA and can be used to analyze large number of alternatives or metrics (i.e., inputs and outputs). This program was used to generate the results presented in Tables 5 and 6, and took less than three seconds to complete the calculations.

Other DEA models exists and are suited for a variety of problems. In order to determine the type of DEA model that should be used depends on the type of problem being analyzed. As an example, consider the notional example presented in this section. All of the DEA results assumed a constant returns-to-scale, but if a variable returns-to-scale model was used to analyze the data, then Alternatives A, B, and C would be considered efficient. A thorough discussion is provided by Banker et al. [14], which examines the values of λ for all alternatives that have $\theta^* = 1$. Since the λ values for Alternatives A, B, and C are all sum to unity for the variable returns-to-scale model, one can assume that constant returns-to-scale is appropriate for the given data. However, this represents only one different type of DEA model – as the number of metrics increases and the type of metrics change, there may be a need to investigate other DEA model types, but that cannot be known prior to selecting the metrics that will be used in evaluation.

Impacts on CoDeS Framework:

The use of SMEs would be applicable to both the parallel and serial approaches (as shown in Figure 24) to the CoDeS step of *Determine Geometric Baseline*. This process could be done for either the competitor's geometric baseline or the proposed geometric baseline. Figure 29 builds from Figure 27 to highlight how either an M&S environment or SME assessments could be used in identifying a geometric baseline. While these two approaches could occur exclusive of the each other, it is more likely that both SMEs and an M&S environment would be used in establishing the geometric baseline.

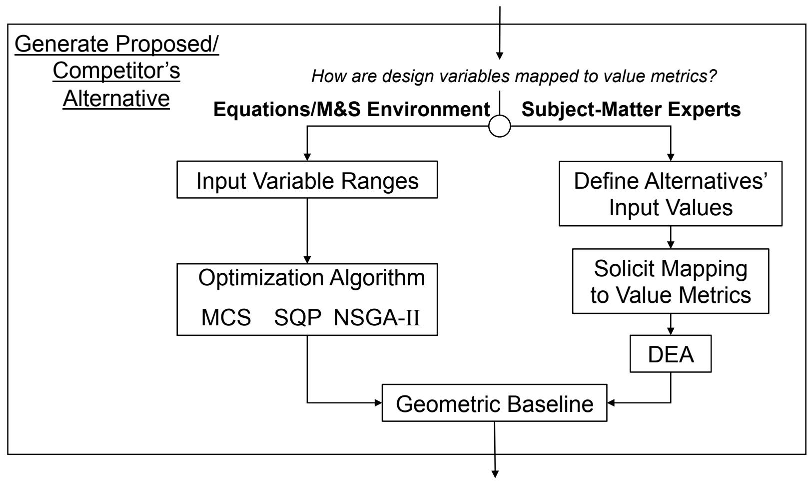

Figure 29: Flowchart of the *Determine Geometric Baseline* step when using an M&S environment or SME assessments.

3.5.3 Combination

There are obvious pros and cons to both SME assessments and analysis from an M&S environment. While an M&S environment might allow for more traceability and finer granularity in separation between design alternatives, SMEs can draw on their depth of knowledge to estimate values that cannot be captured using equations. This allows for SMEs to offer insight onto technologies still being developed or approximate values that may never be quantifiable a priori (e.g., desirability of proposed design). Obvious synergies exist if both SME and an M&S environment were used to evaluate alternatives. While there are a variety of ways that this could occur, this section describes one of the approaches that seems most intuitive.

As stated in § 3.3.2, multiple architectures exist that could describe an aircraft – Figure 20 shows possible architectures and highlights one with yellow boxes. It was also stated in this section that it would take too long to analyze every type of architecture. However, suppose that several possible architectures were selected as potential candidates. One method for determining an optimal candidate would be to build a model for each different architecture and analyze it based on value metrics, which may be difficult to quantify. This could be especially problematic if that architecture represents a revolutionary design or if the value metrics being used are hard to quantify. This could result in spending a large amount of time and resources constructing models of different architectures, when only one (or a few) is going to be further analyzed in the conceptual design phase.

Instead, it may be better to use SMEs to evaluate different architectures using the approach described in § 3.5.2. After an ideal architecture is selected, then more detailed models can be constructed in order to conduct further analysis. In this approach, the SMEs could also use metrics that are difficult to quantify, such as the manufacturability and desirability as previously described. But other metrics may also be used to make the analysis more robust, including: complexity, competitiveness, ease of certification, etc.

This style of combining SMEs and an M&S environment is captured in Figure 30 with the dotted line. Following the notional steps previously described, the analysis would begin with SMEs' assessments that lead to using DEA in order to determine a preferred architecture. From that point, the dotted-line would then be followed to the M&S portion of the flow chart, where a model of that architecture would be constructed and different combinations of geometric variables then analyzed. This process would culminate in a geometric baseline that can be further analyzed.

For the purposes of this dissertation, SMEs were not used. However, it was deemed necessary to highlight the ability to use SMEs within the CoDeS Framework because of the likelihood that they would be used by an aircraft OEM. The remainder of this dissertation work assumed that an M&S environment was used for analyzing alternatives.

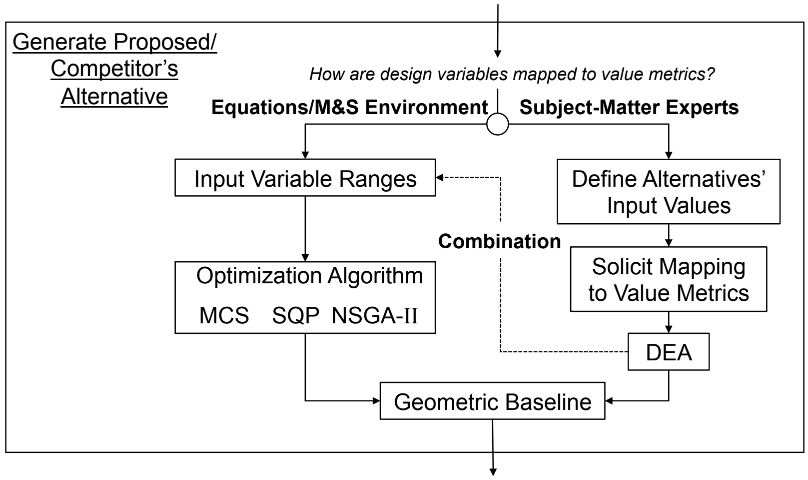

Figure 30: Flowchart of the *Determine Geometric Baseline* step when using an M&S environment, SME assessments, or the combination of both.

3.6 Step 5: Evaluate Strategy Alternatives

The fifth step of the CoDeS Framework is to *Evaluate Strategy Alternatives*. While this evaluation could be done using SMEs, using the same process of soliciting and analyzing their assessments as discussed in § 3.5.2, it was assumed that an M&S environment was used for this analysis. The specific strategies that need to be investigated would be identified in step two, which was *Define the Problem*. These strategies fall into two broad categories: technologies and enterprise solutions, which are not necessarily mutually exclusive (i.e., an aircraft could both infuse technology strategies and implement enterprise strategies). The main concern with both of these strategies is utilizing an approach that can be easily implemented for a wide-range of options.

Ideally, an approach should be adopted that allows for both exploratory and normative forecasting to be applied. Exploratory forecasting occurs by evaluating the impacts of identified strategies on the aircraft's value metrics. Normative forecasting examines what *should* be done in order to achieve given change in the aircraft's value metrics – for this approach specific strategies are not examined. Instead, the amount of an improvement in a parameter is quantified and then a strategy(ies) is sought that leads to that improvement. The benefits of these two types of analysis provide flexibility for the CoDeS Framework. § 3.6.1 examines the approach adopted for analyzing technologies and § 3.6.2 describes how a similar approach was adopted for analyzing enterprise strategies.

3.6.1 Technologies

The M&S environment must be capable of analyzing the various forms of technology-based strategies described in § 2.2. While the tool does not necessarily need to have exact processes that mimic the technology, there must be a way to capture the impacts of various technology strategies by manipulating certain model inputs. Mavris et al. proposed an approach that uses technology k-factors in order to manipulate model inputs to mimic the impacts of a technology. [108] This approach is advantageous because it took advantage of preexisting correction factors that were used in the M&S environment being used to analyze technologies. These correction factors are often used in M&S environments to aid in model calibration, but Mavris et al. adapted these correction factors to model technologies. These k-factors can be applied to design variable or system/subsystem-level metrics in order to demonstrate the impacts of technologies. This approach is beneficial because it does not necessarily require and exact description of the technology, which may still be in development, but can utilize forecasts of that technology's impacts. To demonstrate how these k-factors can be used for technologies, consider the following notional example:

Notional Example: Suppose a technology, T1, reduces the profile drag (D_{Prof}) of an aircraft by X%. This effect can be simulated using the k-factor approach shown in Equation 17 by setting $k_{T1} = X\%$. This equation shows that the system-level benefit of this technology is applied to the baseline (BL) value for the metric that the technology impacts. Alternatively, a normative forecasting approach could be applied if a target value for profile drag was known, and Equation 17 was manipulated to solve

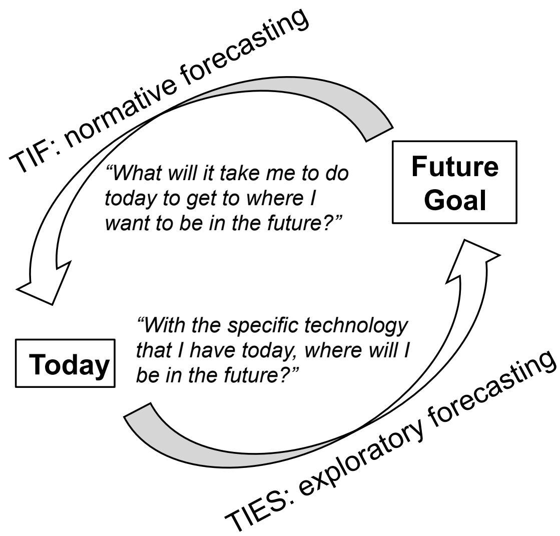

Figure 31: Relationship between TIF (normative forecasting) and TIES (exploratory forecasting), adapted from Kirby [91].

for the k-factor.

$$D_{Prof,T1} = k_{T1} D_{Prof,BL} \tag{17}$$

The use of k-factors, originally proposed by Mavris et al.[108] for assessing economic viability of commercial aircraft was further refined by Kirby and Mavris [90], applied to performance assessments of military vehicles by Mavris et al. [109], applied to civil tiltrotor by Mavris et al. [106]. All of these techniques mainly focused on the use of these technology k-factors for normative forecasting. This process was referred to as Technology Impact Forecasting (TIF). In 2000, Kirby and Mavris formalized this k-factor approach for exploratory forecasting in the TIES methodology. [93]; furthermore, in her PhD thesis, Kirby demonstrated how, "TIF is a fallout of applying TIES." [91] The relationship between TIF and TIES is shown in Figure 31, which was adapted from Kirby [91].

The TIES methodology can be used to evaluate many different technologies in order to select an optimal technology or set of technologies to infuse into an aircraft. For this analysis to occur, the compatibilities between technologies must be taken into account. If technologies are compatible, then it may be necessary to also account

Table 7: Adding impacts of compatible notional technologies, adapted from Kirby [91].

k-factors	T1	T2	T3	T1&T2	T1&T3
$k_{O\&SCost}$	+4%	-	-10%	+4%	-6%
$k_{RDT\&ECost}$	-1%	-	-2%	-1%	-3%
k_D	-	-3%	-	-3%	-
$k_{FuelBurn}$	-2%	-2%	+3%	-4%	+1%

for any interactions that may exist. Kirby utilizes an additive approach [91], which was assumed to provide appropriate fidelity during early phases of conceptual design. To illustrate this, consider the data shown in Table 7, which shows three notional technologies and their impacts on four different system-level metrics. To illustrate the additive nature of these k-factors, it was assumed that T2 and T3 were not compatible, but T1 & T2 and T1 & T3 were compatible.

One of the major elements that needs to be addressed with using technology k-factors is determining their values. Kirby suggest literature reviews and interviews with SMEs, which could be conducted using the approach described in § 3.5.2. The values for these technology k-factors could be either deterministic (i.e., described by a single value) or probabilistic (i.e., described by a probability density function (PDF)). Uses of both probabilistic and deterministic k-factors occur in Chapter 5, which examines three *use cases* of the CoDeS Framework.

3.6.2 Enterprise

Besides technology-based strategies, § 2.2 highlighted enterprise strategies as a way in which aircraft OEMs compete. Two specific enterprise strategies, manufacturing initiatives and maintenance programs, were described in § 1.3.3, which examined how Boeing was using enterprise strategies. Besides these enterprise strategies, the CoDeS Framework should utilize an approach that is capable of modeling a wide variety of enterprise strategies. To this end, an approach similar to the technology k-factors was adopted. However, since enterprise strategies and technologies strategies can be

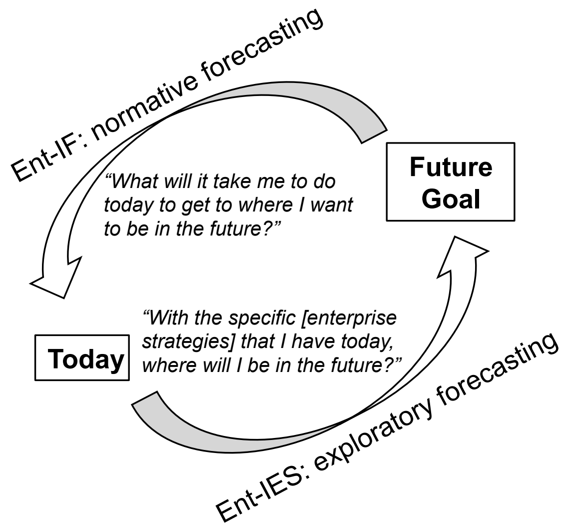

Figure 32: Comparison of enterprise-based normative and exploratory forecasting approaches – Ent-IF and Ent-IES, respectively.

implemented simultaneously, impacts from enterprise strategies were modeled using λ-factors. For example, consider the following notional example:

Notional Example: Suppose a notional enterprise strategy, E1, was investigated that was expected to impact the manufacturer's learning curve by X%. This could be captured using Equation 18, which uses a λ-factor to modify the learning curve parameter presented in Equation 2 of § 3.3.4, if the value of λ_{E1} = X%.

$$Y_{E1} = ax^{-\lambda_{E1}b} \tag{18}$$

By applying λ-factors in the same manner as k-factors, then both normative and exploratory forecasting techniques can be utilized. Instead of TIF and TIES, these techniques were referred to as enterprise impact forecasting (Ent-IF) and enterprise identification, evaluation, and selection (ENT-IES The relationship between these two approaches is illustrated in Figure 32, which was adapted from Figure 31.

It was also assumed that enterprise strategies effects would be additive. Furthermore, it was assumed that impacts from implementing both enterprise and technology strategies were additive, if they were compatible. While both strategies could be assessed simultaneously using the CoDeS Framework, it may allow for more insight if these strategies were assessed in series. This would allow for clear insight into the specific benefits of each strategy without confounding of the results. By implementing this approach, exploratory and normative forecasting approaches can be used simultaneously for technologies or enterprise strategies. For example, if a decision-maker was trying to analyze specific technologies using TIES, but realized that the desired benefits were not achieved, then they could perform an Ent-IF analysis to see the requirements of an enterprise-based strategy to supplement the benefits of technologies.

The similarity between using λ-factors and k-factors is not only in their application, but also their quantification. While some enterprise strategies may have been previously used by an OEM for a different aircraft, there is a chance that OEMs may not be able to rely on historical data for quantifying the impacts of enterprise strategies. If this is the case, then SMEs can be consulted to provide insight using an approach similar to the one described in § 3.5.2. However, one of the difficulties in using λ-factors is determining which variables they should be applied to.

Consider, the notional example and Equation 18 discussed previously. Since the enterprise strategy being examined was related to manufacturing, it would make sense to apply the λ-factor to the learning curve parameter b. However, if an enterprise strategy was examined that utilized virtual experimentation to reduce the first unit costs of a new design, then it would be more appropriate to apply the λ-factor to a in Equation 18. The exact terms that will be effected by λ-factors not only depends on the specific enterprise strategy, but also the specific M&S environment being utilized for analysis. By ensuring that appropriate λ-factors are used in the M&S environment, then the decision-maker can have more confidence in the results.

Whether evaluating technology strategies, enterprise strategies, or both, the basic

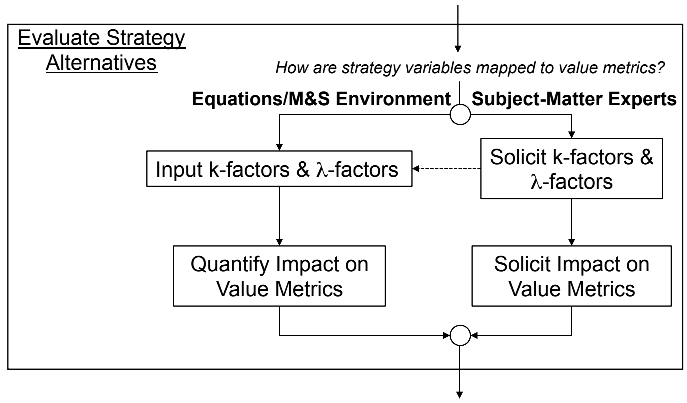

Figure 33: Specific actions to be taken in the *Evaluate Strategy Alternatives* step of the CoDeS Framework.

process of this step in the CoDeS Framework is shown in Figure 33. In this figure, a dotted line from the *Solicit k-factors & λ-factors* to the *Input k-factors & λ-factors* box is shown to highlight that SMEs may be needed to quantify these values even if an M&S environment is used for the analysis.

3.7 Step 6: Compare to Competitor's Design

One of the major benefits of the CoDeS Framework is the direct comparison between proposed design alternatives and a competitor's design. This comparison, using the same value metrics, allows for the decision-maker to make a more informed decision because they are taking into account the competitive environment in which their aircraft will exist. However, because of the nature of this design problem, it can be difficult to gain clear insight into the problem. This is due to the inherent uncertainty associated with this problem. The following section describes these difficulties in further detail. Then § 3.7.2 through § 3.7.5 explore different techniques that can be used to mitigate the difficulties described in § 3.7.1.

3.7.1 Difficulties

There are multiple sources of uncertainty that cause difficulties to occur in comparing a proposed design to a competitor's design:

Strategy Uncertainty Since there are multiple strategies that can be implemented, which may have a range of impacts, it can be difficult to determine a preferred solution.

Economic Uncertainty As discussed in § 3.3.4, some variables are not under the control nor influence of an aircraft OEM, but they still can have a large impact on the success of a proposed design.

Competitor Uncertainty The actions of a competitor can significantly impact a design because if airlines prefer their design, then this competition will gain a larger portion of the market.

These sources of uncertainty make it difficult to have confidence in any decisions that are made. Part of the reason for this difficulty is that the OEM may not be able to control or influence the sources of uncertainty. To illustrate this point, consider the step of *Determine a Geometric Baseline* through the lens of uncertainty. Since the various design variables could take a variety of values, one could consider that to be *geometric uncertainty*; however, all of these values are under control of the aircraft OEM. Even though multiple metrics may be considered multi-objective optimization techniques, as stated in § 3.5, could be used to determine an optimal design whether using an M&S environment or SMEs. The result of this multi-objective optimization would be a determination of what values to set the geometry variables in order to achieve a preferred outcome. While this approach works for optimizing geometry, it cannot be applied to situations where the decision-maker has no control/influence over the variables that affect the design – while an aircraft OEM may have a preferred value for the inflation rate, they cannot set inflation rate to any value. When analyzing variables that cannot be controlled optimization cannot occur, at least in the approach that it was used in § 3.5. Notional figures illustrating this difficulty can be seen in Figure 34.

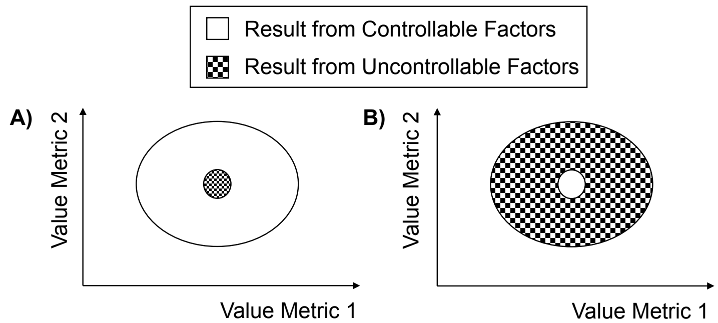

Figure 34: Notional figure showing different impacts of uncertainty: A) The effects from controllable factors is much larger than the effects from uncontrollable factors, B) The effects from uncontrollable factors is much larger than the effects from controllable factors.

In Figure 34, plot A shows the case where the effects from controllable factors is much greater than the effects from uncontrollable factors for both value metrics. This is similar to the previously described case of *geometry uncertainty*. In that context, plot A's controllable factors could represent the design variable settings and the uncontrollable factors could represent the uncertainty in manufacturing tolerances. In a situation like plot A, it is easy to determine optimal values for the geometry variables. In Figure 34, plot B represents the opposite case where the impacts of uncontrollable factors is much larger for both metrics. In this situation, it is difficult to pick optimal values because the effects of uncontrollable factors dominate to the point that any decision's impact is lost in the noise of the uncontrollable factors. Since the effects of uncertainty cannot be known a priori, there is a need to examine how to make decisions in either situation.

Research Question 1: How to ensure a decision-maker has confidence in their decisions in the presence of uncertainty from economic factors and the competitive market?

With regards to Research Question 1, it is not difficult to answer if the effects of uncertainty resemble plot A of Figure 34 – § 3.5 introduced several techniques that could be used to choose preferred settings for controllable factors. But if a situation similar to that of plot B in Figure 34 occurs when analyzing a proposed design compared to a competitor's design, then a mitigating technique needs to be implemented. However, in order to answer this question, the impacts of the various sources of uncertainty need to be analyzed and if necessary mitigated.

Research Question 2: How can the impacts of uncertainty be determined with regards to controllable and uncontrollable factors?

In order to answer Research Question 2, there is a need to explore the impacts of uncertainty on the design space. To this end, a sensitivity analysis would provide the most insight into the influences of each factor, whether controllable or uncontrollable. This is the main thrust of Experiment 1, which is described in detail in § 4.2. This experiment is used to characterize the design space in terms of single-factor sensitivities and multiple-factor sensitivities. Experiment 1 also examines the sensitivity of the approach used for describing the uncertainty of various factors (i.e., shapes of probability density functions to represent uncertainty). However, the motivating examples presented in Chapter 2 demonstrated that uncertainty from economic factors and the competitive market did have large impacts on the success of a design – this lead to the assumption that mitigating steps would need to be taken in order to answer Research Question 1.

Research Question 3: What technique is most appropriate to mitigate the impacts of uncertainty?

Scenario-based analysis creates a finite number of logically reasoned possible future events. The history of scenario-based analysis can be traced back to ancient philosophers and their use of treatise to examine various scenarios. [28] The modern use of scenario analysis has military origins; Herman Kahn used scenario-based analysis at the RAND Corporation involving thermonuclear war during the 1950s. [85, 86, 141] A widely quoted definition of a scenario was described by Kahn and Weiner in 1967 as a "hypothetical sequences of events constructed for the purpose of focusing attention on casual processes and decision-points." [86] Using this definition, scenarios can serve as a way to examine the performance of a system under specified conditions, which can effectively quantify the effects of an uncertain future. In a 1968 publication from the RAND Corporation, Quade provides the following advice for system analysis:

> "The essence of the questions with which systems analysis is concerned is uncertainty, not only about economic, technical, and operational parameters – which can be serious but are to a large extent under our control and somehow appear limited – but also about future environments or contingencies ... an analytic scenario might be useful." [134]

By adopting scenario-based analysis to mitigate the effects of uncertainty, the concerns of Research Question 3 was addressed. This claim was further investigated in Experiment 1, which is described in § 4.2.4. The use of scenarios should create a situation similar to plot A of Figure 34 – this is predicated on the assumption that scenarios would be intelligently defined and based on established forecasting techniques. While it was outside the scope of this dissertation to explore specific scenario forecasting techniques, the parametric capabilities of the CoDeS Framework means that any scenario can be rapidly analyzed. The use of scenarios mitigates the effects of uncertainty by reducing the effective design space. Figure 35 shows a notional representation of three scenarios that are much smaller than the total design space with uncertainty. The amount of reduction in the design space is not only predicated on the values/ranges of variables used to define the scenario, but also on the sensitivities of the impacts from those variables and their interactions, which is addressed with Research Question 2. These scenarios can be defined in Step 2 of the CoDeS Framework when defining the ranges on the economic noise variables. This modification is shown in Figure 36, which highlights the general steps of the CoDeS

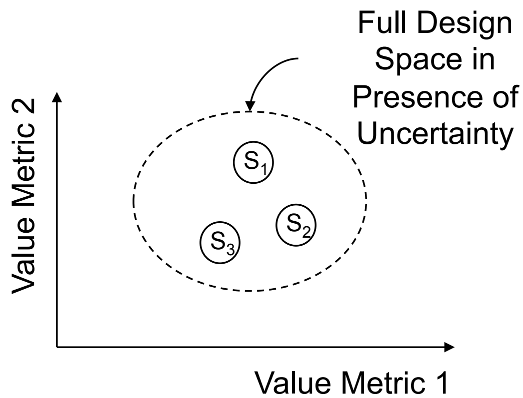

Figure 35: Notional figure showing three scenarios (S_1, S_2, and S_3) reducing the effects of uncertainty.

Framework. By addressing Research Questions 2 and 3, techniques can be explored to fully address Research Question 1.

While scenarios can help mitigate the impacts of uncertainty, they may not completely reduce all of the elements of uncertainty. For this reason, it was assumed that the results would still be probabilistically defined, which limits the ability to clearly evaluate strategy alternatives and/or compare design alternatives to a competitor's design. This becomes even more difficult when multiple value metrics are considered. The field of multi-criteria decision making (MCDM) has many well-established techniques that can be used for analyzing alternatives, but most of these techniques work best when they are applied to point-solutions, not a probability space. To illustrate this difficulty, Figure 37 highlights three notional situations that may occur with these multi-criteria, probabilistic solution space for two alternatives. The direction of improvement (DoI) is indicated in Figure 37 by the arrow in the bottom right corner of each graph, which means that Value Metric 1 should be maximized while Value Metric 2 is minimized.

The graph in row A shows that the red ellipse dominates the blue ellipse for each of the value metrics; however, there is no guarantee that only situations resembling graph A would be analyzed in the CoDeS Framework. The graphs in row B show

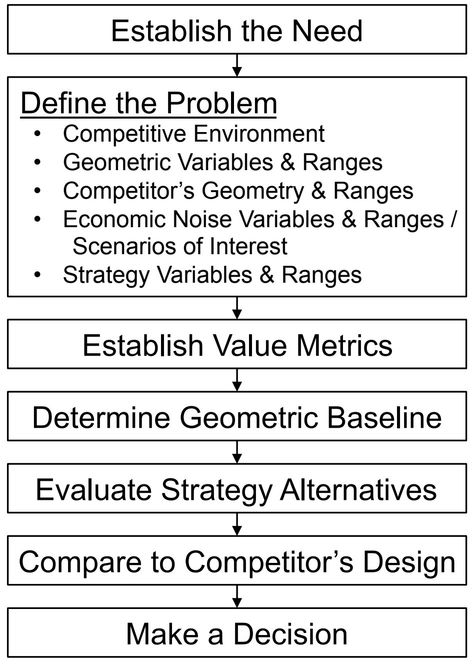

Figure 36: General steps of the CoDeS Framework with a modification to *Define the Problem* that incorporates defining scenarios of interest.

the case where either the red or blue ellipse appears dominate for one value metric, but not the other value metric. The graph shown in row C highlights a case where there is significant overlap between the red and blue ellipses, but the blue ellipse has larger variability in Value Metric 2. Furthermore, this increased variability extends in the direction of worsening for Value Metric 2. There is significant difficulty in having confidence in a decision made involving the situations depicted in rows B or C. Each of these notional situations was further analyzed in order to help hone in on a technique that can be applied, regardless of which situation that occurs.

In row B, there are two major concerns in each of the figures: 1) there exist regions of overlap and regions where one alternative is clearly dominate in one value metric while being simultaneously worse in the other value metrics, and 2) the preferences or elasticities¶ of Value Metric 1 and Value Metric 2 are unknown and not taken

¶In this context, elasticities refers to the acceptable differences that can occur in one value metric relative to the other (e.g., a difference of 5% in Value Metric 1 is the same as a difference of 10% in Value Metric 2)

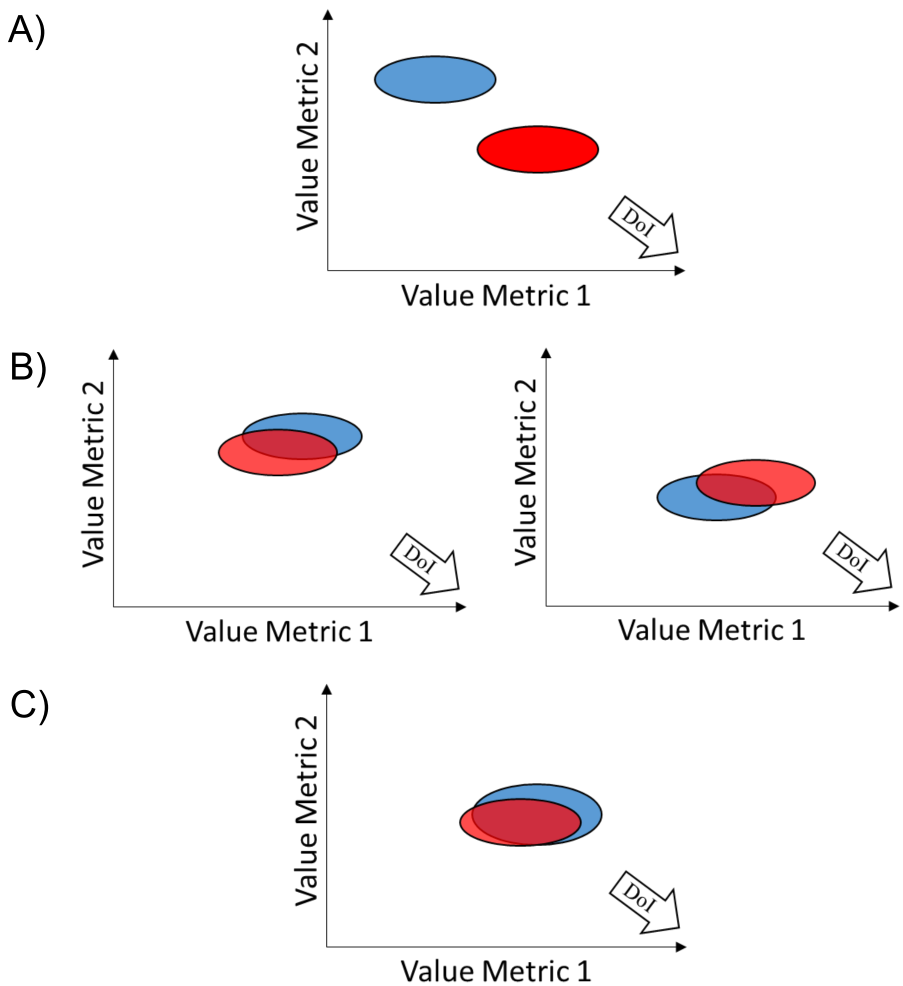

Figure 37: Notional figures of probabilistically comparing two alternatives denoted by the red and blue ellipses – the direction of improvement is indicated to identify the preferred alternative.

into account. The second concern can be addressed by soliciting relative weightings for each value metric. The first concern could be taken into account by identifying a meaningful statistic to describe each ellipse. An example of a candidate statistic is the centroid of the ellipse. The centroid can be thought of as a single value that represents the average of each value metric simultaneously – the use of the average can be beneficial because it provides a decision-maker with insight into an expected outcome.

In row C, the concern of relative weightings of value metrics is present, but the concerns involving regions of overlap is not the same as discussed regarding the graphs in row B. In row C, it is obvious that the variance in the blue ellipse is larger for Value Metric 2 and not in the preferred direction. If a single statistic, like the centroid, was used to evaluate these ellipses then the results may be misleading because they do not take into account the greater variance of the blue ellipse. But if only the magnitude of the variance is taken into account for the blue ellipse, then the information regarding the skew of the distribution not being in the preferred direction may be lost.

Based on these insights, an appropriate technique to fully address Research Question 1 should have several key characteristics:

- Account for elasticities/preferences between different value metrics
- Account for the direction of improvement for each value metric
- Account for the average of a distribution and the variance simultaneously

3.7.2 Overall Evaluation Criteria

Many MCDM techniques allow for a decision-maker to input their preferences by using weightings for the various metrics. For example, consider a well-known MCDM technique called the overall evaluation criterion (OEC), which is shown in Equation 19. This technique seeks to collapse multiple criteria or objectives (O_i), which are normalized by baseline values (O_i^{BL}), into a single metric that can easily be used to compare options. Each of the criteria/objectives has an individual weighting (w_i), which can be specified by a decision-maker in order to show relate their relative preference of that objective compared to other objectives. However, several authors have suggested that decision-makers may not know their exact preferences a priori. [177, 175, 82, 152] To mitigate this, the weightings can be varied in order to provide more insight into the elasticities of various objectives. Figure 38 depicts a notional representation of the OEC values for two alternatives (Alt_1 and Alt_2) as the relative weightings (w_1 and w_2) vary – in this figure, a value of (1,0) means that all of the importance is placed on Objective 1 and no importance is placed on Objective 2, a value of (0.5, 0.5) means that both objectives are equally-weighted, and a value of (0,1) means that all importance is placed on Objective 2 and no importance is placed on Objective 1. From this figure, it can be seen that the OEC score of Alt_1 is not as sensitive to changes in the weighting values and dominates the OEC value for Alt_2 for majority of the weighting cases.

$$
\begin{aligned}
OEC &= \sum_{i=1}^{n} w_i \left(\frac{O_i}{O_i^{BL}}\right)^k \\
k &= \begin{cases} -1, & \text{if } \min O_i \\ 1\ , & \text{if } \max O_i \end{cases}
\end{aligned}
\tag{19}
$$

Besides these variables weightings, the OEC formulation also allows for a decision-maker to specify the direction of improvement for each objective, which is shown by the possible values of k in Equation 19. While the OEC formulation does address two of the three characteristics of a preferred selection method, it is not well-suited for handling a range of values for alternatives. Several authors have suggested that OEC formulations may not fully capture the intricacies associated with decision making involving complex systems like an aircraft. [13, 93, 91, 179, 79] Instead, the Technique for Ordered Preferences by Similarity to Ideal Solution (TOPSIS) may be more

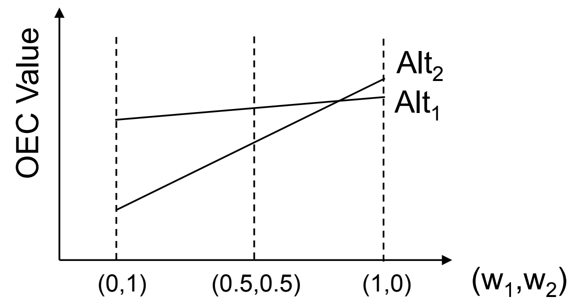

Figure 38: Notional figure showing impacts of variable weightings for two alternatives (Alt_1 and Alt_2) on their relative OEC values.

useful.

3.7.3 Technique for Ordered Preferences by Similarity to Ideal Solution

TOPSIS was first described on page 120 of Kwangsun Yoon's 1980 doctoral dissertation from Kansas State University. [179] This work was further elaborated on by Hwang and Yoon in 1981 [79]. A benefit of TOPSIS is that it first identifies both positive- and negative-ideal solutions from the given objectives. The technique then identifies which alternative is closest to the positive-ideal solution and furthest from the negative-ideal solution calculating their Euclidean distances. This general process is demonstrated with the notional representation in Figure 39. In this figure, four alternatives (Alt_1, Alt_2, Alt_3, and Alt_4) are compared to each other using TOPSIS with the goal of maximizing both Metric 1 and Metric 2. The positive-ideal point is constructed using Alt_4's value for Metric 2 and Alt_2's value for Metric 1; the negative-ideal is determined from Alt_4's value for Metric 1 and Alt_1's value for Metric 2. The Euclidean distances from each alternative to the positive- and negative-ideal are then shown by the black arrows. For specific details on implementing TOPSIS, the reader should examine [79, 179], but the process of TOPSIS is summarized in the following five steps:

1. Construct the normalized decision matrix
2. Construct the weighted normalized decision matrix
3. Determine ideal and negative-ideal solutions
4. Calculate the separation measure
5. Rank the preference order

As shown in step 2 of TOPSIS, the weightings for each metric/objective is included in the decision making process, which is similar to the OEC formulation. The TOPSIS approach can be adapted to show relative sensitivities of the weightings using a similar

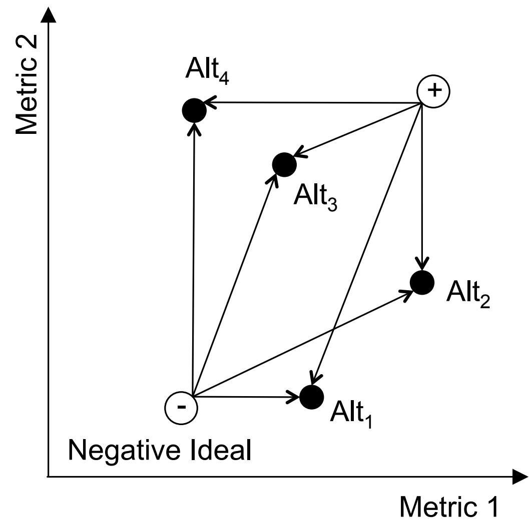

Figure 39: Notional TOPSIS figure comparing four alternatives (Alt$_1$, Alt$_2$, Alt$_3$, and Alt$_4$) using TOPSIS.

approach for the OEC formulation. Another similarity between TOPSIS and OEC is that both techniques are best suited for situations where an alternative is defined using one value for each metric and not a distribution of values. This means that neither TOPSIS nor OEC can fully address the key characteristics of a preferred selection technique, which were detailed at the end of § 3.7.1.

3.7.4 Taguchi's Signal to Noise Ratio

To account for the distribution of ranges, other techniques outside of MCDM were examined. The field of quality engineering offers relevant insight. This field was arguably started by Taguchi [157, 158] and is often applied to manufacturing processes. In general, Taguchi divides a process into factors that are under control of the designer and factors that are uncontrollable. By separating these factors into formally defined experiments and recording the results, Taguchi was able to determine the optimal settings for factors that are controllable while taking into account the effects of uncontrollable factors. This was accomplished by repeating experiments to produce a range of values for the results and then intelligently collapsing that range of values into a single metric; this metric would not only account for the average values, but also the variability in the values. The metric that was used is the *signal to noise ratio* (S/N). Furthermore, Taguchi's method allows for the specification of the direction of improvement. For the situation where a smaller value is preferred, Equation 20 should be used – in this equation y_i represents the values of each metric for the N different results. If a nominal target (T) is preferred, then Equation 21 should be used to calculate S/N. If larger values for a metric is preferred, then Equation 22 should be used. Regardless of which equation is used, S/N is always sought to be maximized – whichever alternative has the highest S/N value is the preferred solution.

$$S/N = -10log_{10}\left(\frac{\sum_{i=1}^{N} y_i^2}{N}\right) \tag{20}$$

$$S/N = -10log_{10}\left(\frac{\sum_{i=1}^{N} (y_i - T)^2}{N}\right) \tag{21}$$

$$S/N = -10log_{10}\left(\frac{\sum_{i=1}^{N} \frac{1}{y_i^2}}{N}\right) \tag{22}$$

Since Taguchi's entire optimization process was not considered relevant for this dissertation work, a formal overview was not included; however, interested readers can consult [157, 158] for detailed descriptions of the entire process. As previously described, Taguchi's S/N approach seems well suited for comparing alternatives in the CoDeS Framework. The only key characteristic not addressed is the ability to handle multiple metrics and apply variable weightings to each of those metrics. The inability to apply Taguchi to multi-criteria problems has been recognized in the literature and several authors have made suggestions to adapt Taguchi's S/N formulation for these problems. More detail into these techniques is provided in the following section.

3.7.5 Hybrid Approach

The application of Taguchi's S/N to problems with multiple responses have been receiving more attention in recent years [161, 99], but an ideal solution has yet to be finalized. As discussed in the previous sections, neither Taguchi's S/N, OEC, or TOPSIS are capable of addressing all of the elements required to make a decision. However, there may exist a way of combining these MCDM techniques with Taguchi's S/N formulation may result in an approach that can be applied in the CoDeS Framework. To this end, a literature review was conducted to determine whether any similar approaches exist.

Multiple authors have combined Taguchi's S/N formulation using a weighted-sum [77, 145, 9, 100, 161]. The weighted-sum approach is similar to an OEC formulation. However, the application of this approach is not the same amongst these authors. The main point of contention seems to occur about whether the OEC formulation should be applied to the data prior to the logarithm or after the logarithm. Shiau [145] advocates applying the weightings after the logarithm, but Tong et al. states that this would provide confusion to the meanings of the weightings in the context of Taguchi's quality loss [161]. However, since this dissertation does not focus on manufacturing, the meaning of Taguchi's quality loss is not as applicable. For this reason, an approach that should be considered is an OEC using Taguchi's S/N formulation, which is shown in Equation 23. Since larger values are always preferred in Taguchi's S/N formulation (as described by Equations 20 to 22), no k values need to be specified like in Equation 19.

$$OEC = \sum_{i=1}^{N} w_i \frac{S/N_i}{S/N_{BL,i}} \tag{23}$$

While the OEC could be applied to the S/N formulations, several authors advocate a different approach in which the OEC formulation occurs before the logarithm. [9, 161, 100] Tong refers to this approach as the multi-response signal to noise (MRSN) ratio. [161] To demonstrate this approach, the S/N formulations given by

Equations 20 to 22 should be rewritten in the form of Equation 24. The three-step description for calculating MRSN, given by Equations 25, 26, and 27, was adopted from [161], but similar approaches are presented in [9, 100].

$$S/N = -10log_{10}(L)$$
$$L = \begin{cases} \sum_{i=1}^{N} \frac{y_i^2}{N}, & \text{Smaller is Better} \\ \sum_{i=1}^{N} \frac{(y_i - T)^2}{N}, & \text{Target is Better} \\ \sum_{i=1}^{N} \frac{\frac{1}{y_i^2}}{N}, & \text{Larger is Better} \end{cases} \tag{24}$$

Step 1: Normalize the quality loss for each alternative for each response, given by Equation 25. In this equation, QL represents the normalized quality loss, i represents the number of responses, and j represents the number of alternatives.

$$QL_{ij} = \frac{L_{ij}}{\max(L_{i1},\ L_{12},\ \ldots,\ L_{ij})} \tag{25}$$

Step 2: Compute the total normalized quality loss (TNQL) for each alternative, given by Equation 26.

$$TNQL_j = \sum_{i=1}^{m} w_i QL_{ij} \tag{26}$$

Step 3: Determine the MRSN for each alternative using Equation 27.

$$MRSN_j = -10log_{10}(TNQL_j) \tag{27}$$

Finally, a combination between TOPIS and Taguchi's S/N ratio can be performed. This approach has been advocated in the literature as being superior to other results because of its implementation of the TOPSIS methodology as opposed to the OEC. [96]. This approach first calculates the S/N values for each metric and then uses those values as the inputs to the TOPSIS methodology, as described in § 3.7.3.

From this section, three different approaches have been identified as possible solutions for combining the benefits of MCDM and Taguchi's S/N formulation in order to adequately assess the differences between alternatives. For each of these three approaches, the weighting values (w) can be varied in order to see the sensitivities/elasticities of each alternative as described in § 3.7.2 and shown in Figure 38.

3.7.6 Considerations for CoDeS Framework

As described in the previous section, three different approaches were identified to be used to make comparisons between alternatives in the CoDeS Framework. These three alternatives are:

1. OEC with S/N Formulation
2. MRSN
3. TOPSIS with S/N Formulation

However, before examining these three approaches, their applicability to the CoDeS Framework should be more thoroughly examined. Regardless of the approach, the basic process for this step of the CoDeS Framework is the same – strategy alternatives evaluated in Step 5 are compared directly to the competitor's design and their possible strategies. The basis for this comparison is using the value metrics that were defined in Step 3. Since two value metrics (profit and \$/RPM – discussed in § 3.4) were selected for this dissertation work, their use in these proposed approaches should be further described in detail. Figure 40 shows a notional representation of how these value metrics were translated to S/N values. These two value metrics do not have the same direction of improvement – \$/RPM should be minimized and profit should be maximized, which means that different formulations for S/N were used. These formulations are shown in Equation 28.

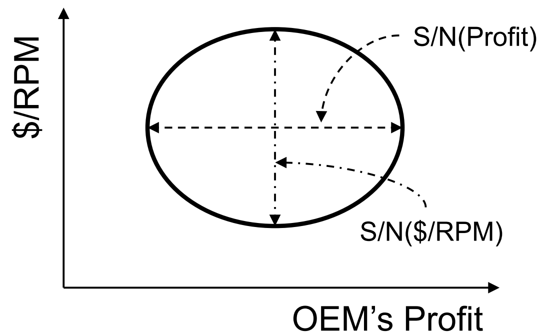

Figure 40: Notional depiction of converting ellipses to S/N values.

$$\begin{aligned}
&\text{Profit (larger is better):} \quad S/N(Profit) = -10log_{10}\left(\frac{\sum_{i=1}^{N}\frac{1}{Profit_i^2}}{N}\right) \\
&\text{\$/RPM (smaller is better):} \quad S/N(\$/RPM) = -10log_{10}\left(\frac{\sum_{i=1}^{N}\$/RPM_i^2}{N}\right)
\end{aligned} \tag{28}$$

When examining the formulation for S/N(Profit), an important aspect must be taken into consideration: values for OEM's profit could be negative. This is important because Taguchi explicitly states, "The [larger is better] characteristic should be nonnegative, and its most desirable value is infinity." [158] In order to maintain the usefulness of S/N, this contradiction was addressed. The most obvious way to address this concern is by performing a transformation, which can take two forms: 1) Shift all of the profit values by a constant, or 2) Introduce a target value for profit and use the *target is better* formulation of S/N. Both of these approaches are based on information found in the literature. The first case of shifting the data uses a well-known and often used mathematical principle – for instance, in Linear Programming when numbers cannot be negative, a large positive constant is introduced to shift all of the data to non-negative values [169]. The latter option has been used with Taguchi approaches when there is a finite target due to practical limitations because infinity is not a possible option, as is the case if the maximum is 100%. [144]. Partially for this reason, Sharma and Cudney introduced a finite target and changed the quality characteristic to *target is better* instead of *larger is better*. [144].

Since profit is not theoretically limited, there is not an obvious reason to choose one of the proposed transformations. For this reason, both transformations were examined in Experiment 2, which is described in § 4.3.1. Since both transformation techniques have strong mathematical underpinnings, it was not expected that the results from either would be different; however, since each technique affects different aspects of the S/N formulation, the guidelines for using them may not be the same. By addressing this concern associated with possible nonpositive values for profit, the three approaches to compare alternatives were further explored.

These three approaches were examined in Experiment 3, which is described in § 4.3.2. However, since there is no way to run a confirmation experiment or compare to previously established data, the experiment can only be used to determine if the three different approaches give the same or different results when comparing alternatives and competition. Regardless of the specific approach adopted, the outcome is expected to be the same – a preferred alternative. Therefore, the CoDeS Framework could handle any of these three approaches, and it is expected that selection would depend on the preferences of the decision-maker.

3.8 Step 7: Make a Decision

The final step of the CoDeS Framwork is to *Make a Decision*. Regardless, of the preferred evaluation technique, this step has two possible outcomes, which depend on the results of comparing a proposed design to a competitor's design.

Terminate: If a proposed design and strategy combination *beats* the competitor's design, then that design and strategy should be implemented and analysis with the CoDeS Framework terminated.

Iterate: If the competitor's design *beats* the proposed design and strategy alternative, then more strategies should be considered by iterating steps 5-7.

As previously stated in § 3.6, separating the evaluation between technology strategies and enterprise strategies may provide the most insight into the competition problem. Based on this recommendation, the CoDeS Framework should first analyze possible technology strategies to see if they result in a "winning design option". If the competitor's design is still preferred against the analyzed technologies, then enterprise strategies can be explored in during the iteration. However, the CoDeS framework was constructed with the principle of flexibility, which means that it can be used to evaluate only enterprise strategy alternatives, technology strategy alternatives, or both (simultaneously or separately). The entire CoDeS Framework, with the specific actions taken during each step is shown in Figure 41.

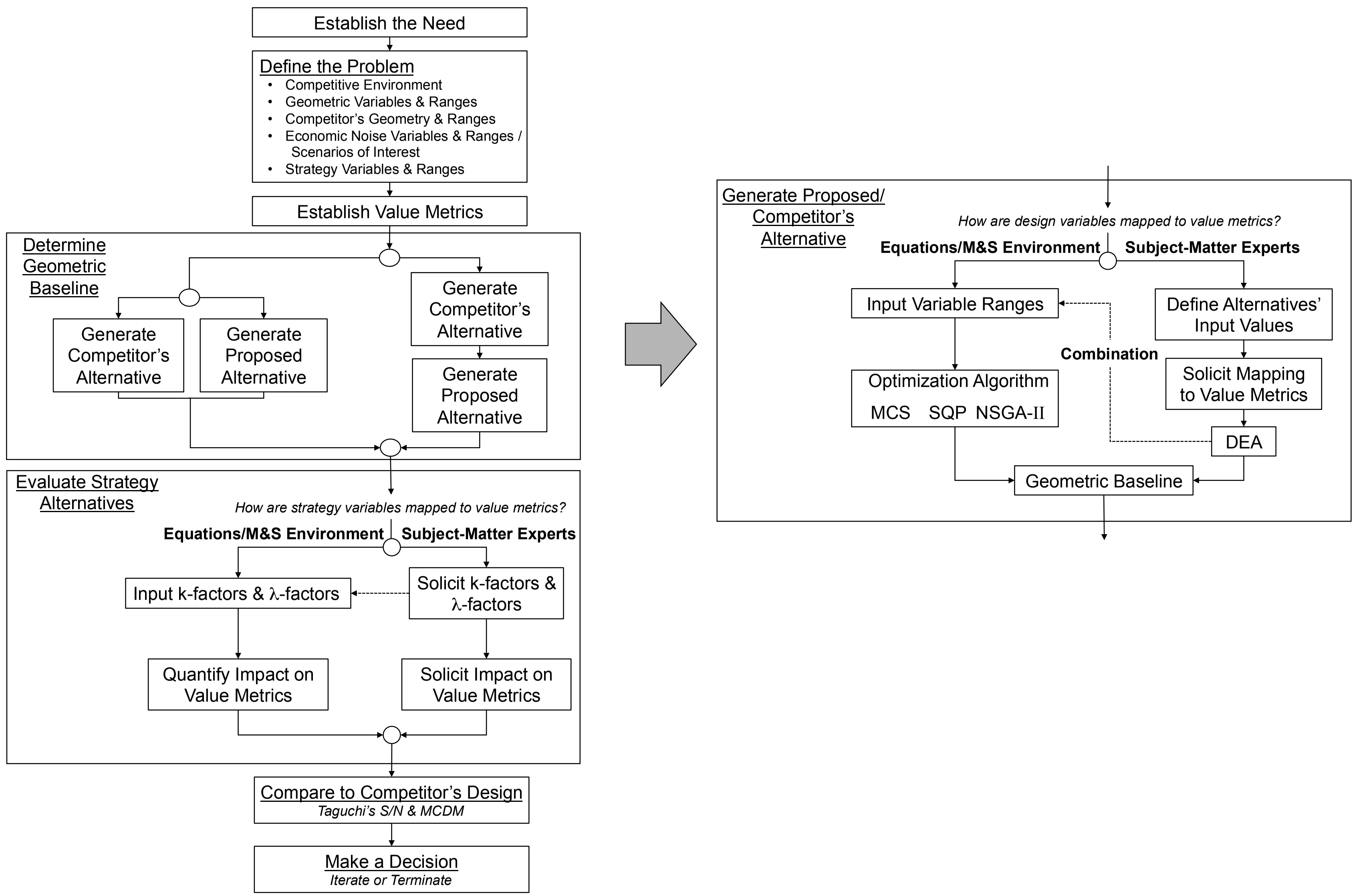

Figure 41: All of the steps of the CoDeS Framework with specific actions taken in each step explicitly shown.

3.9 *Summary of Chapter*

This chapter has not only highlighted the specific actions required during each step of the CoDeS Framework, but also posed several research questions that will be addressed by experiments covered in the following chapter. Before examining these experiments, it was deemed necessary to highlight some of the key insights presented in this chapter; Figure 41 should be referenced to help provide context.

In order to utilize the CoDeS Framework, the need must be established – for this dissertation work it was assumed that the need, and therefore the requirements of an aircraft, were the same. The next step is define the parameters of the problem under analysis. This consist of five steps: 1) Define the Competitive Environment, 2) Define Geometric Variables and their Ranges, 3) Define the Competitor's Geometric Baseline and their Ranges, 4) Define the Economic Noise Variables and their Ranges & Define Scenarios of Interest, and 5) Define Strategy Variables and their Ranges. The third step in the CoDeS Framework was to establish value metrics, which were assumed to be \$/RPM and OEM's profit for this dissertation work – both of these metrics were normalized in order to provide greater insight into the differences between strategy options and the competitor, which was discussed in § 3.4. By using the value metrics and the ranges of geometric variables, a geometric baseline is established in the fourth step of the CoDeS Framework using one of the techniques discussed in § 3.5. During that step, the competitor's geometric baseline is also established, either in series or in parallel; if the competitor already has an aircraft deployed in the market, then reverse engineering techniques can be implemented. § 3.6 discussed methods for evaluating strategies. Technologies are evaluated using the established k-factor method, and enterprise strategies are evaluated using a similar λ-factor approach. The sixth step constitutes the significant difference between the CoDeS Framework and other design techniques because the competitor's design and/or strategies and proposed design and/or strategies are evaluated head-to-head. In § 3.7, multiple hybrid approaches were discussed to combine the benefits of Taguchi's S/N formulation with established MCDM techniques. Using the information from Step 6, the final Step of the CoDeS Framework can be completed, which is to make a decision. The outcome of this final step is either to iterate the CoDeS Framework to evaluate different strategies or to terminate and pick the preferred strategy(ies).

Besides introducing and elaborating on the various steps of the CoDeS Framework, this chapter also introduced the research questions. These research questions also lead to necessary experiments that were conducted in order to gain further insight and refine the CoDeS Framework. In order to conduct these three experiments, an appropriate M&S environment was selected. The selection of this M&S environment and the results from the experiments are discussed in the following chapter.

CHAPTER IV

EXPERIMENTATION

> "At the time...[aeronautics] was neither an industry nor even a science; both were yet to come. It was an art and I might say a passion. Indeed, at that time it was a miracle."
> Igor Sikorsky [50]

Chapter 1 introduced motivating examples that provided the rationale for this dissertation work. Chapter 2 provided background information regarding competition in order to help determine the context of the proposed CoDeS Framework. The previous chapter provided insight into the technical formulation of the CoDeS Framework. This chapter elaborates on experiments necessary to address research question posed in Chapter 3. Besides these research questions, an implementation consideration was addressed.

In order to perform the experiments in this section, an appropriate M&S environment was selected. This M&S environment was used in Experiment 1, which sought to characterize the impacts of uncertainty from the economic noise variables. Experiment 2 leveraged a canonical example in order to provide deeper insight into the impacts of nonpositive values being used with Taguchi's S/N formulation. Experiment 3 uses the results from Experiment 1 in order to evaluate the three different approaches for combine Taguchi's S/N with MCDM techniques that were discussed in § 3.7.5.

4.1 M&S Environment

§ 3.5.1 covered extensively the requirements of suitable M&S environment for the CoDeS Framework. This section highlighted the need for physics-based performance analysis that was directly linked to activity-based costing. Figure 26 captured this idea of the M&S environment using a flow chart. Further considerations for an M&S environment were discussed in § 3.6, where the concept of k-factors and λ-factors was introduced to model the impacts of technology strategies and enterprise strategies, respectively.

While an M&S environment could be constructed that would address the concerns raised in the previous sections, the results may be suspect. This is due to the immense difficulty of validating an M&S environment, especially one that links together physics-based analysis and activity-based costing. Instead, a previously validated M&S environment would not only reduce the burden, but also provide more confidence in the results. The following sections identify an M&S environment and then examine an implementation consideration that was addressed in order to fully incorporate the M&S environment into the CoDeS Framework.

4.1.1 Selection

While an M&S environment that has been developed and thoroughly vetted by an aircraft OEM would allow for the most insight to be gained, especially into the specific economic details related to that OEM, these tools are proprietary and were not available for this dissertation work. Fortunately, NASA has helped create two non-proprietary tools that can be linked together and meet the requirements of an acceptable M&S environment. These tools are FLight OPtimization System (FLOPS) [115] and Aircraft Life Cycle Cost Analysis (ALCCA) [1]. The FLOPS and ALCCA M&S environment comprises a stand-alone tool that addresses the requirements discussed in § 3.5.1. This section first describes the individual elements of FLOPS and

ALCCA and then discusses some limitations that need to be addressed.

FLOPS is a physics-based sizing and synthesis (S&S) tool that allows for many different inputs to be altered. Firstly, the design mission is inputted – this includes the basic phases of commercial flight as described in Figure 25, and other phases can also be inputted if desired. While some of these phases are based on historical data (e.g., pre-takeoff and post-landing), other phases are based on first-principles analysis. This is accomplished by allowing for flexibility with several key factors. Firstly, a large variety of geometric design variables can be manipulated to specify a variety of configurations and architectures, including the geometric parameters specified in § 3.3.2. Secondly, specific information regarding the drag polar for the aircraft being analyzed can be inputted, which means that analysis is not limited to preexisting airfoils or body configurations. Thirdly, FLOPS can analyze any engine because it allows for the specification of an engine deck. An engine deck contains information about how thrust and fuel flow vary as functions of Mach number and altitude; several commercial programs, like Numerical Propulsion Simulation System [38] can be used to generate engine decks for different engines. Finally, FLOPS allows for specific information regarding component weights by accounting for geometry and materials used. Based on this information, FLOPS is able to perform S&S analysis in order to determine whether the characteristics of the aircraft inputted are able to meet the inputted mission requirements. Besides outputting information related to performance characteristics, FLOPS results are directly fed into ALCCA to provide detailed costing information.

ALCCA provides costing information related to both the aircraft OEM and the airlines. Data related to the airlines are specifically tied to the performance metrics calculated in FLOPS, which includes the calculation of $/RPM. In order to accurately calculate this metric, information related to the specific airline (e.g., average load factor and indirect operating costs (IOCs)) must also be inputted. With regards to the aircraft OEM, the cost associated with RDT&E, Manufacturing, and Sustainment are calculated yearly for the production life cycle of the aircraft – these costs are dependent on inputted factors including RDT&E complexities, number of aircraft produced, manufacturing rate, plant upgrades, and manufacturing learning curve. While ALCCA is not a true activity-based costing tool, it does allow for modifications to be implemented to the cost estimating relationships in order to simulate effects of different activities. To elaborate, ALCCA does not simulate the various elements of an aircraft being manufactured on different assembly lines in a factory, but allows for the user to input complexity factors that are used to model the effects of manufacturing difficulty associated with different aircraft. Furthermore, these complexity factors can be treated as technology k-factors or enterprise λ-factors.

Not only do FLOPS and ALCCA address all of the requirements of an acceptable M&S environment discussed in § 3.5.1, but it also allows for technology k-factors and enterprise λ-factors to be implemented for a variety of metrics – this is due to the existence of correction factors in the codes. This flexibility to not only model existing aircraft, but also impacts of future technologies on aircraft caused Mavris, Kirby, and others to utilize this M&S environment for analyzing the impacts of aircraft technologies. [108, 109, 106, 90, 93, 91]

While FLOPS and ALCCA provide many advantages to analyzing a proposed aircraft design, there are some drawbacks to using this M&S environment. Due to the large number of variables that can be varied within FLOPS and ALCCA, it can be difficult to develop accurate models of aircraft. To overcome this, FLOPS and ALCCA will default some variables if no specified user input is provided. In this dissertation, a previously developed model similar to a Boeing B737 [92] was used as a baseline model for both proposed designs and competitor's designs – various parameters of this model could be altered to represent different OEMs. The use of a baseline model allows for more confidence in the results since many of the correction parameters have already been adjusted to validate the physical performance of the aircraft.

This model had some key characteristics that should be discussed further. While the aircraft model was constructed to represent a Boeing B737, it had a range of acceptable inputs for geometric design variables of interest – these variables and ranges are shown in Table 8. The basic drag polar that was used as an input for the M&S environment is shown in Figure 42. This drag polar is for an inputted cruise altitude of 41,000 ft and cruise Mach number of 0.785. It is important to note that the exact drag experienced during flight may change depending on a variety of factors, and this drag polar in Figure 42 should be taken as somewhat of an average value. Besides the geometric data, an engine deck is inputted into the model that was generated using NPSS. Each of the two engines is modeled as having an installed thrust of 27,293.2 pounds of force (lb_f) at sea-level conditions. While the engine deck has information regarding how thrust and fuel consumption vary with Mach number and altitude, Figure 43 shows how thrust and thrust specific fuel consumption vary at the cruise altitude and cruise Mach number; each point in this figure represents a different throttle setting for the engine. While information regarding the geometry, drag polar, and engine deck do not comprise all of the details of the model, they provide basic description of the model that is sufficient for conceptual design.

A concern with FLOPS and ALCCA is that these codes were initially designed for point design evaluation, which means that an input file that describes one aircraft geometry is analyzed with each execution of the M&S environment. This is further complicated because any slight change in design variables requires a new input file to be generated. While the current version of FLOPS does have parametric and optimization models, they are limited in the number of parameters that are varied. While these updates may be appropriate for some applications, they do not provide enough flexibility for the CoDeS Framework. To this end, the following sections

Table 8: Ranges for key design variables that are used in the early phases of conceptual aircraft design for the FLOPS model of the aircraft used in this dissertation.

Geometric Variable	Min. Value	Max. Value
Wing Area (ft^2)	1200	1500
Thrust to Weight Ratio	0.25	0.3
Aspect Ratio – Wing	7	10
Taper Ratio – Wing	0.18	0.34
Thickness to Chord – Wing Root	0.14	0.2
Thickness to Chord – Wing Tip	0.085	0.15
Wing Sweep Angle (^{o})	20	35
Aspect Ratio – Horizontal Tail	3	7
Taper Ratio – Horizontal Tail	0.155	0.345
Thickness to Chord – Horizontal Tail	0.07	0.15
Aspect Ratio – Vertical Tail	1.2	3.6
Taper Ratio – Vertical Tail	0.2	0.4
Thickness to Chord – Vertical Tail	0.09	0.15

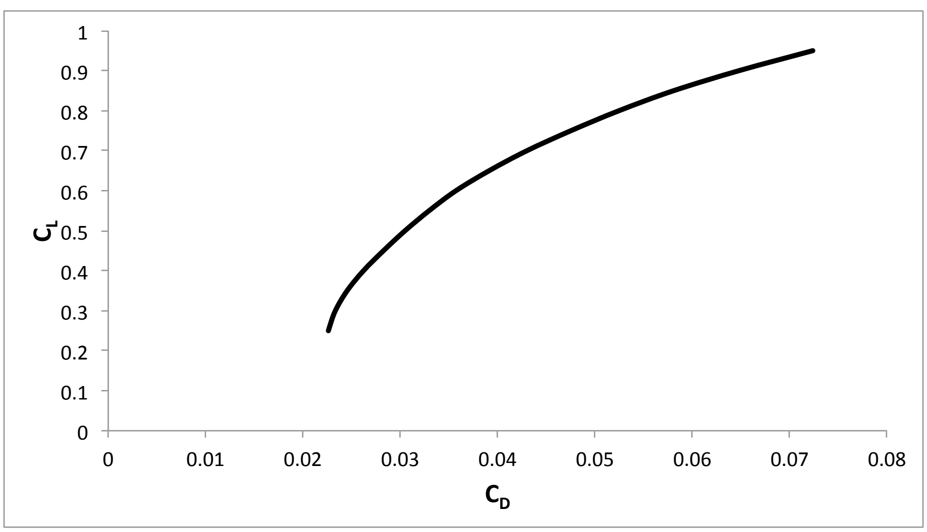

Figure 42: General drag polar for cruise altitude and cruise Mach number.

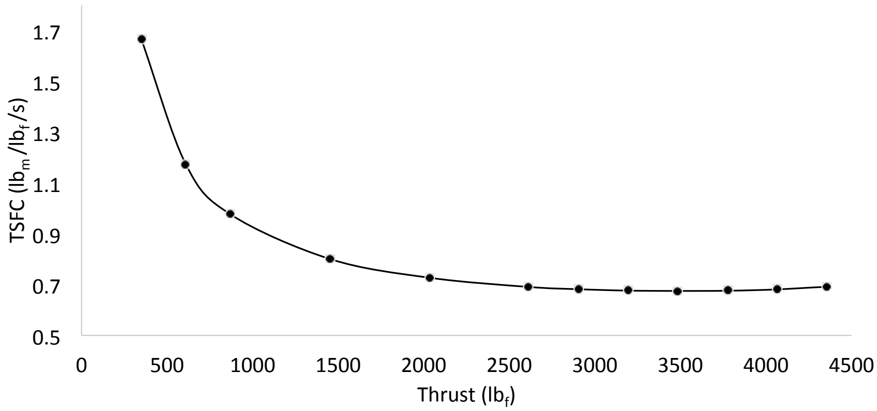

Figure 43: Thrust vs Thrust-Specific Fuel Consumption (TSFC) at cruise altitude and cruise Mach number – each point represents a different throttle setting.

describes some modifications that can be made to the M&S environment in order to address this concern.

4.1.2 Modifications

In order to increase the parametric nature of FLOPS and ALCCA, the codes were incorporated into a software integration environment, ModelCenter [132]. This integration environment was used to automate the execution of FLOPS and ALCCA with regards to different input values. By doing this, two distinct advantages were gained: 1) FLOPS and ALCCA can be parametrically varied with more flexibility by being able to select any inputs and outputs, and 2) uncertainties can be easily analyzed by inputing a range of values for given variables.

By incorporating a software integration environment, input values can be quickly altered and their effects rapidly quantified. This is because ModelCenter allows for inputs to be a varied directly in its graphical user interface. ModelCenter will then pass these new input values into the FLOPS and ALCCA M&S environment in order to obtain the new output values, which are also visualized in through ModelCenter. Besides this ability to quickly see changes in inputs, ModelCenter also allows for a Design of Experiments (DoE) analysis to be performed. A DoE is predefined set of

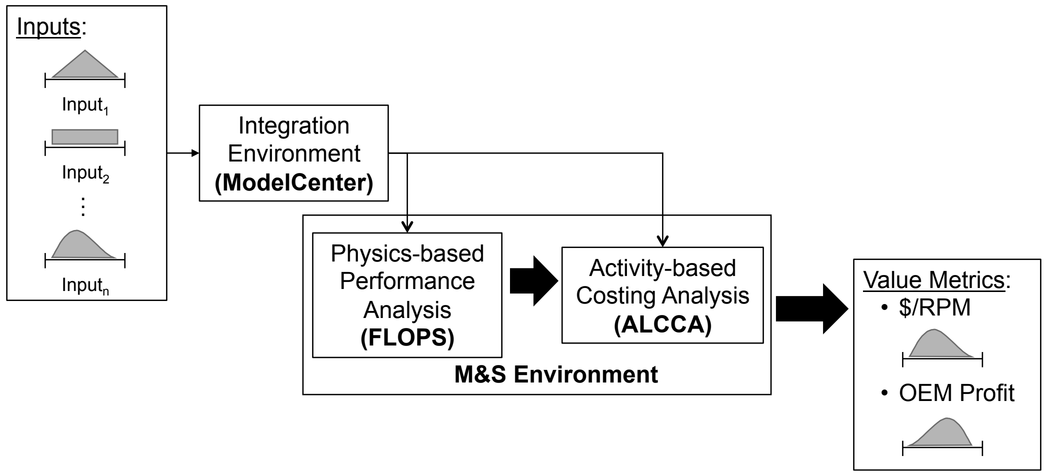

Figure 44: Incorporation of a software integration environment in order to allow for ranges on input variables to be evaluated using the M&S environment.

experiments that varies input values in an intelligent manner in order to gain some insight about the design space. This is accomplished by inputting a range of input values in order to generate a range of output files using the M&S environment. A visual representation of this is shown in Figure 44, which is a modification of Figure 26.

While the integration environment rapidly analyzed changes in the aircraft model, the time required for analysis could be further decreased. This can be accomplish by the creation of surrogate models, which greatly increase the speed of analyzing alternative designs. This was necessary because analysis of 400 alternatives using FLOPS and ALCCA took approximately 4 minutes on a single machine with a 3.4 GHz processor and 8.0 GB of RAM. By creating surrogate models, thousands of alternatives can be analyzed in a matter of seconds, while still retaining the physics-based and activity-based capabilities of FLOPS and ALCCA. That is because these surrogate models are generated from data that was created using these analysis codes. Multiple authors have demonstrated how various surrogate modeling techniques can be used to more rapidly explore the design space of these design problems. [107, 112, 93, 91, 114, 142, 29, 44, 97, 78]

While a variety of surrogate modeling techniques exist, some may be better suited

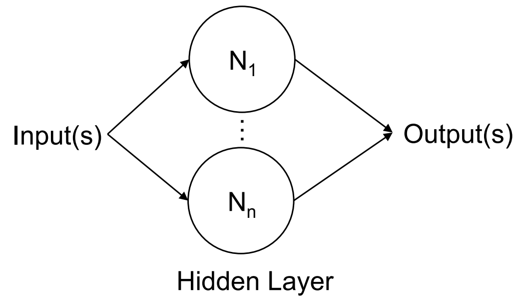

Figure 45: Notional diagram of a single-layer artificial neural net.

for an aircraft design problem. To help better capture the non-linearities and higher-order interactions that exist in aircraft design problems, some authors have leveraged the Response Surface Methodology (RSM). [122, 107, 112, 93, 91, 114, 142, 29, 44] The general equation for a second-order response surface is shown in Equation 29. In this equation, β represents the linear coefficients of regression, x represents the design variables, ϵ represents the residuals term, R represents the response, and n is the total number of design variables. Other authors have focused on another surrogate modeling technique referred to as Artificial Neural Nets (ANN), which was inspired by neural networks that exist in the brain. The algorithmic and mathematical framework for ANN was described in 1943 by McCulloch and Pitts [116], but took several decades for computational resources to increase for this technique to become usable. In general, ANN makes use of hidden layers and activation functions in order to more accurately capture non-linear behavior. [44, 97, 122, 32, 78] A generalized schematic of a single-layer ANN is shown in Figure 45.

$$R = \beta_0 + \sum_{i=1}^{n} \beta_i x_i + \sum_{i=1}^{n} \beta_{ii} x_{ii}^2 + \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} \beta_{ij} x_i x_j + \epsilon \tag{29}$$

Regardless of the surrogate modeling technique chosen, data are needed to create, verify, and validate the surrogate model. Multiple, mathematically based techniques exist in order to verify and validate surrogate models. While a common technique is to estimate the coefficient of determination (R^2) or adjusted-R^2, the results may be misleading. A more accurate approach is to examine the *actual by predicted* and *residual by predicted* plots; multiple guidelines exist for evaluating these plots. [91, 122] Another approach involves examining the Model Fit Error (MFE), which constitutes a distribution of the error between the model's predicted points and the data points. These techniques can verify a model because they check the predictions of the model versus the data points used to create the model. Model Representation Error (MRE) uses data points that were not the same used to create the model. MRE is a technique for validating the model and is insightful because it captures a models accuracy of capturing the effects of data not used in model generation.

In the context of the CoDeS Framework, surrogate models were used to capture the impacts of the value metrics with regards to changes in various inputs. During Step 4 of establishing a geometric baseline, second-order RSEs were sufficient at capturing the changes in value metrics with regards to different geometric inputs. The ranges for these geometric inputs used are shown in Table 8 of the previous section. While RSEs were appropriate to capture the effects of changes in geometry, they were not sufficient at capturing the effects of economic noise and strategy variables.

An ANN approach was adopted in order to account for highly nonlinear behavior that occurs with changes in economic noise and strategy variables. To fit these ANN surrogate models, a software package called Basic Regression Analysis for Integrated Neural Networks (BRAINN) [84] was used. The use of BRAINN was preferred because the variable structure associated with ANN can have significant impacts on their accuracy and usability of the surrogate model. As opposed to RSEs, where the equation increases in size with new terms being added or increasing the order of magnitude (e.g., second-order to third-order), an ANN equation increases in size with each additional node and can drastically increase in size by adding additional hidden layers. Since it is hard, if not impossible, to know the preferred ANN structure a priori, BRAINN allows for different, single-layered ANN structures to be generated and compared in order to determine the optimal number of nodes in the hidden layer. [84] After an optimal ANN structure is determined by BRAINN, the surrogate model should still be analyzed using the goodness of fit criteria previously described in order to ensure that it accurately represents the FLOPS and ALCCA M&S environment.

As described in this section, the FLOPS and ALCCA M&S environment can be incorporated into a software integration environment to enable parametric analysis, which increases the speed of analyzing alternatives. However, this modification was still not sufficient at rapidly exploring the design space. For this reason, surrogate models were introduced in order to greatly increase the speed of analyzing design and strategy options. While this increased capability was beneficial to the CoDeS Framework, there are potential drawbacks to using surrogate models that are discussed in the following section.

4.1.3 Surrogate Models

As described in § 3.4, the metric for OEM's profit was quantified by analyzing the various sources of incomes and expenses throughout the years of development and production – this allows for the creation of the manufacturer's cumulative cash flow (CCF) curve, which provides more insight to the decision-maker. When this is combined with the previous discussion on surrogate models, a potential problem arose. The problem occurs due to the residual term that exists for every surrogate model. When surrogate models for the income and costs are summed throughout the aircraft's production life cycle, the residuals would also be added and that may cause large errors in the estimation of total profit.

> **Implementation Consideration:** Is the accuracy of yearly cash flow surrogate models acceptable to use as a value metric? Does this result depend on the type of surrogate model (RSE or ANN) used?

As stated by Equation 3, profit is a function of the incomes and costs throughout the years. The incomes are a function of the price of an aircraft and the quantity sold. The costs is composed of three elements: RDT&E Costs (C_R), Manufacturing Costs (C_M), and Sustainment Costs (C_S), which vary throughout the years of production and are determined based on the specific inputs to the M&S environment. Consider a surrogate model for year i of RDT&E costs, denoted by $\hat{C}_{R,i}$ in Equation 30 – $C_{R,i}$ is the actual value, and $\epsilon_{R,i}$ is the residual term. This could also be applied to the manufacturing and sustainment costs, which are shown in Equations 31 and 32, respectively.

$$\hat{C}_{R,i} = C_{R,i} + \epsilon_{R,i} \tag{30}$$

$$\hat{C}_{M,i} = C_{M,i} + \epsilon_{M,i} \tag{31}$$

$$\hat{C}_{S,i} = C_{S,i} + \epsilon_{S,i} \tag{32}$$

If the price and quantity are assumed to be inputs of the M&S environment, then the cash flow for a given year i can be written as shown in Equation 33, depending on whether or not surrogate models are used. Therefore, when the total profit is calculated, by summing all of the yearly cash flow values, the residuals could create a significant discrepancy.

$$\begin{gathered} CF_i = f(C_{R,i}, C_{M,i}, C_{S,i}, P_i, Q_i) \\ \Rightarrow \hat{CF}_i = f(\hat{C}_{R,i}, \hat{C}_{M,i}, \hat{C}_{S,i}, \epsilon_{R,i}, \epsilon_{M,i}, \epsilon_{S,i}, P_i, Q_i) \end{gathered} \tag{33}$$

Consider two different ways of creating a surrogate model for OEM profit (Π). The first approach creates a surrogate model directly from the total profit, which is seen in Equation 34 and as a residual term, $\epsilon_{Tot,A1}$. The second approach sums the individual surrogate models for $C_{R,i}$, $C_{M,i}$, and $C_{S,i}$ and can be seen in Equation 35 – this approach has a different definition for the residual term, which is based on the

Table 9: Percent ranges for ϵ_{Tot} for OEM's Profit surrogate models using both an RSE and an ANN approach.

Approach	RSEs	ANN
Approach 1 $\epsilon_{Tot,A1} = \hat{\Pi}_{Tot} - \Pi_{Tot}$	0.678%	4.51%
Approach 2 $\epsilon_{Tot,A2} = \sum_{i=1}^{N} (\epsilon_{R,i} + \epsilon_{M,1} + \epsilon_{S,i})$	0.927%	6.16%

summation of all the other surrogate models' residual terms. While it is intuitive to think that $\epsilon_{Tot,A1} \leq \epsilon_{Tot,A2}$, these results were analyzed in order to determine whether yearly cash flow values can still be used as value metrics with surrogate models.

$$\hat{\Pi}_{Tot} = \sum_{i=1}^{N} CF_i = PQ_{Tot} - (C_{R,Tot} + C_{M,Tot} + C_{S,Tot}) + \epsilon_{Tot,A1} = \Pi_{Tot} + \epsilon_{Tot,A1} \quad (34)$$

$$\begin{aligned} \hat{\Pi}_{Tot} &= PQ_{Tot} - \sum_{i=1}^{N} \left(\hat{C}_{R,i} + \hat{C}_{M,i} + \hat{C}_{S,i}\right) \\ \hat{\Pi}_{Tot} &= PQ_{Tot} - \sum_{i=1}^{N} (C_{R,i} + C_{M,i} + C_{S,i}) + \sum_{i=1}^{N} (\epsilon_{R,i} + \epsilon_{M,1} + \epsilon_{S,i}) \\ \therefore \epsilon_{Tot,A2} &= \sum_{i=1}^{N} (\epsilon_{R,i} + \epsilon_{M,1} + \epsilon_{S,i}) \end{aligned} \quad (35)$$

To address the Implementation Consideration, surrogate models were created using both Equation 34 and 35. These surrogate models were created using an RSE approach and an ANN approach. The residuals of the validation points were examined in order to quantify the difference between the two approaches for ϵ_{Tot}. The distributions from the two approaches of quantifying the residuals are shown in Figures 46 and 47. Both of these figures demonstrate a similarity between the distributions of the residuals, regardless of the surrogate modeling approach used. Furthermore, the ranges of the distribution are rather small, being withing ± 5% of 0. The quantification of these ranges are stated in Table 9.

While Approach 1 does provide a smaller residual term, the residual terms associated with Approach 2 were still within the acceptable ranges for surrogate models.

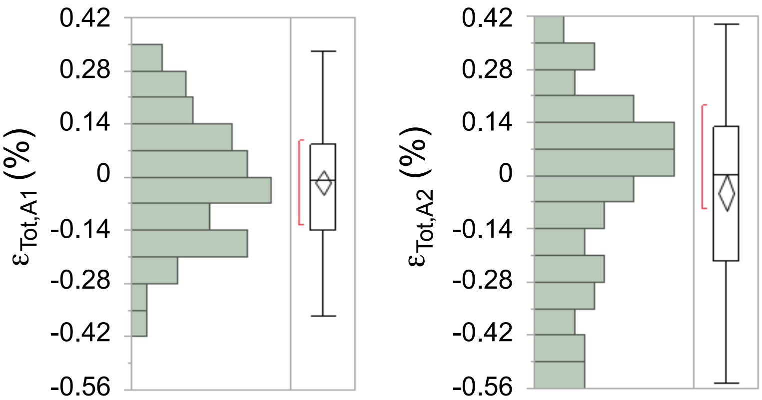

Figure 46: Distribution of ϵ_{Tot} for the two approaches of create surrogate models using an RSE approach for OEM's profit.

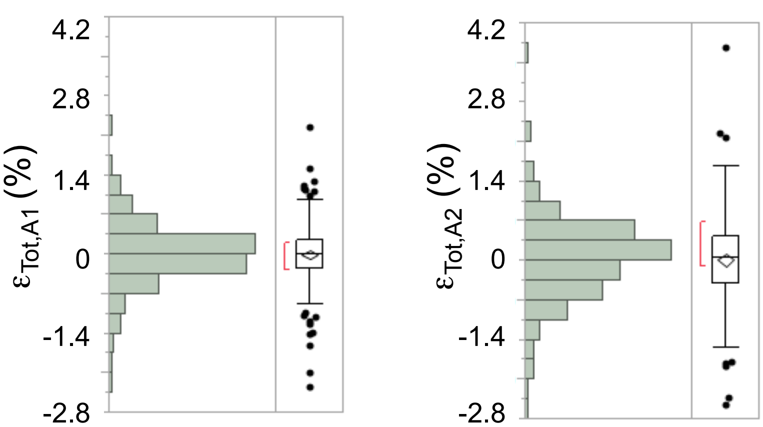

Figure 47: Distribution of ϵ_{Tot} for the two approaches of create surrogate models using an ANN approach for OEM's profit.

Therefore, the increased flexibility of using yearly cash flow values causes Approach 2 to be the preferred approach, regardless of whether RSE or ANN surrogate models are used.

Since surrogate models can be implemented to rapidly increase the speed of analysis for the CoDeS Framework, the process of the CoDeS Framework should be updated to include their use. This is shown in Figure 48; the dotted lines around the surrogate model boxes indicate that their use is not required to complete the *Generate Geometric Baseline* or *Evaluate Strategy Alternatives* steps, but can be used to increase the speed of analysis.

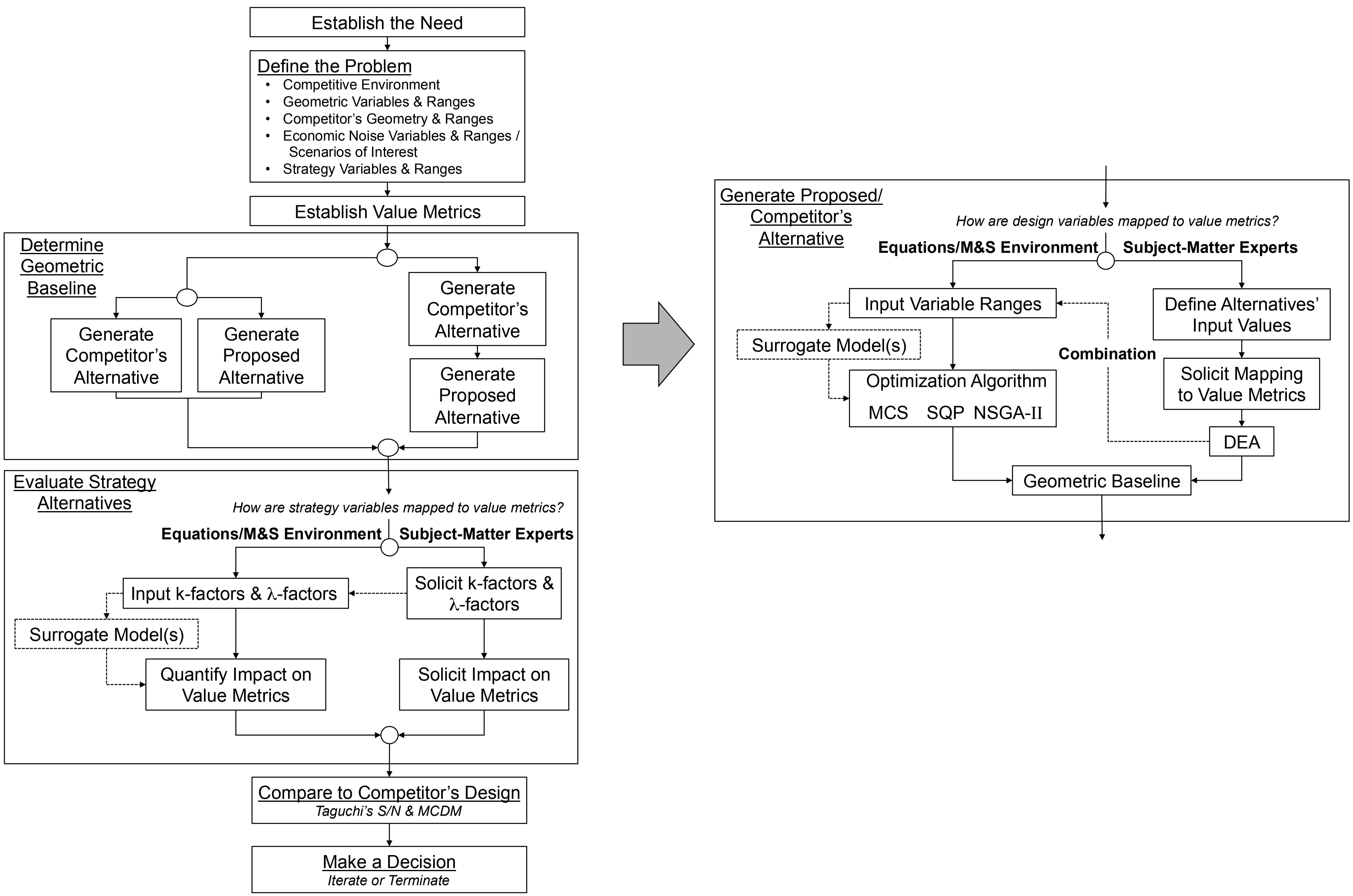

Figure 48: Modified version of the CoDeS Framework to incorporate the use of surrogate models to increase the speed of analysis.

4.2 Characterizing Uncertainty (Experiment 1)

Since surrogate models have been shown to be accurate enough to use with the value metrics of interest, Experiment 1 utilized these surrogates as the M&S environment. It should be noted that since these surrogates were derived from the FLOPS and ALCCA M&S environment, they still captured the effects from the geometric variables, economic noise variables, and strategy variables on the value metrics.

Experiment 1 has three major aims:

1. Determine sensitivities of the value metrics to specific variables and their interactions
2. Determine sensitivities of the value metrics to different probability density functions that represent the uncertainty of these variables
3. Quantify the impacts of scenario-based analysis at mitigating the effects of uncertainty

The following sections will not only describe in detail how this experiment was conducted, but also highlight key results. For this experiment, a baseline geometry was selected from the range of design variables. This baseline geometry was selected using the approach that was described in § 3.5.1. Both NSGA-II and SQP techniques were used and both produced similar results for the optimized baseline. The values for the geometry variables of interest are described in Table 10.

Table 10: Description of the geometric baseline that was used in Experiment 1.

Geometric Variable	Baseline Value
Wing Area (ft^2)	1200
Thrust to Weight Ratio	0.25
Aspect Ratio – Wing	10
Taper Ratio – Wing	0.34
Thickness to Chord – Wing Root	0.2
Thickness to Chord – Wing Tip	0.15
Wing Sweep Angle (^{o})	35
Aspect Ratio – Horizontal Tail	3
Taper Ratio – Horizontal Tail	0.155
Thickness to Chord – Horizontal Tail	0.07
Aspect Ratio – Vertical Tail	1.2
Taper Ratio – Vertical Tail	0.4
Thickness to Chord – Vertical Tail	0.09

4.2.1 Sensitivity Analysis: Single Variables

This sensitivity analysis is focused on determining the impacts that different single economic noise variables have on the value metrics; § 4.2.2 discusses a sensitivity analysis concerning the interactions of these variables. This was motivated by Research Question 2, which is restated below:

> **Research Question 2:** How can the impacts of uncertainty be determined with regards to controllable and uncontrollable factors?

While several techniques exist in the literature, including Taguchi's inner and outer arrays [157, 158], some of them may not be applicable to this design problem. Taguchi's approach cannot be implemented because there are too many different values (i.e., levels) that different factors can take – all of the variables being analyzed in this experiment are assumed to be continuous. Instead, a one-at-a-time sensitivity analysis was performed in order to examine the impacts of various variables and the impacts from their interactions. As a reminder, the economic noise variables being considered were: manufacturing learning curve, production facility costs, inflation rate, number of aircraft produced, price of the aircraft, average load factor, and fuel price; these variables were discussed in detail in § 3.3.4.

Before determining the sensitivities of individual variables, there was a need to first examine the general effects that the economic noise variables have on the value metrics. This was done by first assuming that no information was known about these variables so each range of uncertainty was modeled as a uniform probability distribution. These probability distributions were then parametrically varied in the M&S environment by increments of ± 1%, ± 5%, ± 10%, and ± 15%, around the assumed baseline values. This was done in order to quantify the impacts of increasing uncertainty of the economic noise variables on the value metrics. Each of these increments was analyzed using 5,000 cases, which took less than three seconds to complete using the surrogate models – this is a significant improvement from the four minutes required to analyze 400 cases using FLOPS and ALCCA directly.

The manufacturer's CCF curves for each of these cases was generated using box plots in order to capture the variability in the cash flow values from each year. These CCF plots for ± 1%, ± 5%, and ± 10% are described in detail; the CCF results for ± 15% were not shown because of the large variability seen in the results for ± 10%. Figure 49 shows the CCF results for ± 1% with three specific aspects highlighted by letters A, B, and C. Point A show that with this level of uncertainty, the breakeven year may occur during year eleven, has a high likelihood of occurring during year twelve and has definitely occurred by year 13. Point B illustrates the range of total expected OEM profit at the end of the twenty year production – this box plot highlights the low expectation that the proposed design would achieve the base level of profit that occurs with the Geometric Baseline in the presence of no uncertainty. Point C highlights the maximum possible sunk costs, which is equal to approximately -150% of the Geometric Baseline profit.

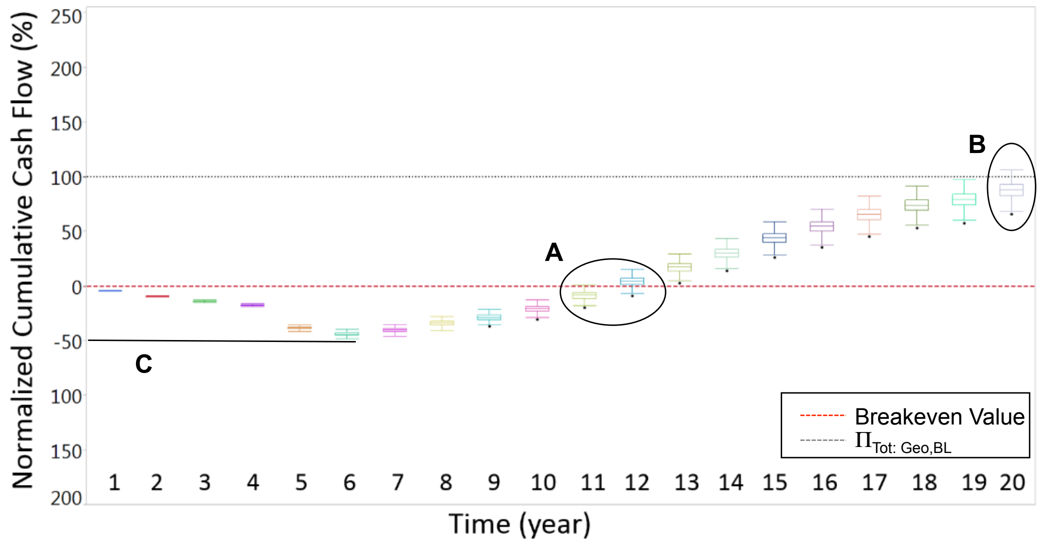

Figure 49: Manufacturer's CCF curve, with ± 1% uncertainty for all of the economic noise variables.

Figure 50 shows the manufacturer's CCF curve for ± 5% economic uncertainty. In this figure point A shows that the expected breakeven year could occur any where between year 10 and year 16, with the mean occurring in between years 11 and 12. It is important to note that the increase in uncertainty means that there are some cases where the aircraft may perform better than the Geometric Baseline due to favorable market conditions. To further illustrate those effects, point B highlights the range of expected total profit, with approximately 25% of the cases earning higher profit than the Geometric Baseline. Point C shows that the maximum total sunk cost is approximately -160% of the Geometric Baseline, which is not drastically different from the case of ± 1% uncertainty shown in Figure 49. It is also noteworthy that the maximum sunk cost occurs during year 6 for both ± 1% and ± 5% uncertainty.

The final result shown is of ± 10% uncertainty, which can be seen in Figure 51. This figure highlights how uncertainty quickly grows to the point that is almost impossible to have confidence in a decision – when considering a projection of twenty

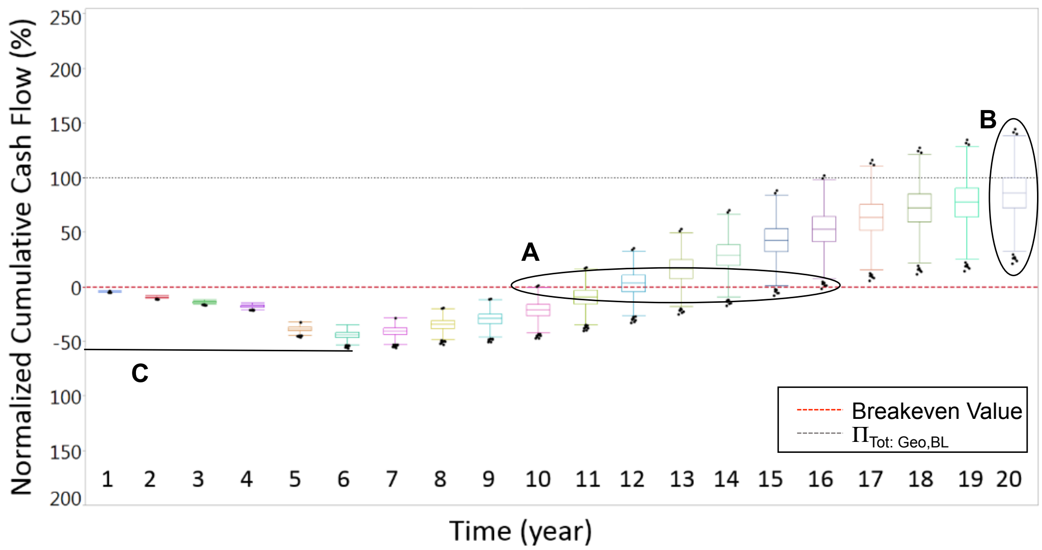

Figure 50: Manufacturer's CCF curve, with ± 5% uncertainty for all of the economic noise variables.

years in the future, having confidence within ± 10% of a estimate may be optimistic*. In Figure 51, point A highlights how the breakeven year may occur in year 9, but also may not occur by the end of the twenty year production. Point B shows that the range of values for possible profit, which has about 30% of the data above the Geometric Baseline, but also has approximately 10% of the data earning a negative profit. Point C also shows that maximum possible sunk cos has increased to approximately -175% of the Geometric Baseline. Point C also shows that the this maximum sunk cost may occur in year 10, which would be four years after the first delivery of a completed aircraft.

While valuable information can be gained from examination of the OEM's CCF curves, there is no information related to the other value metric of \$/RPM contained in those curves. The elliptical distributions of both value metrics are shown in Figure 52 – these ellipses cover 95% of the data points for each uncertainty range. One of the first things to notice in this figures is that the normalized profit metric has a much

*Between 2006 and 2016, the yearly inflation rate in the US has fluctuated between 0.1% and 4.1%, with an average around 1.95% [31]

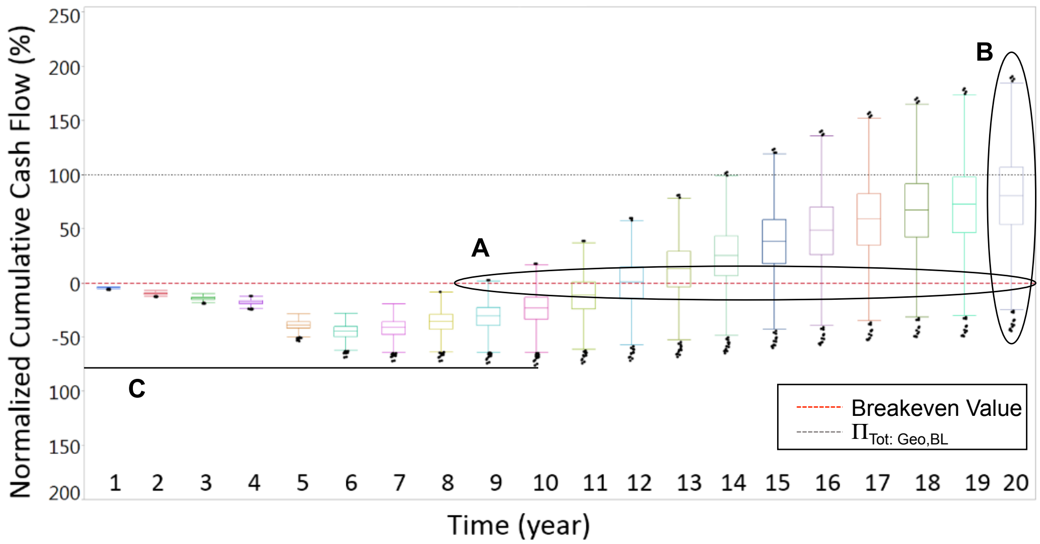

Figure 51: Manufacturer's CCF curve, with ± 10% uncertainty for all of the economic noise variables.

larger range of possible values than normalized $/RPM for all the cases examined. This makes sense because the normalized profit accounts for the production (and sale) of all aircraft, but $/RPM is evaluated on a per aircraft basis. Another important characteristic exhibited by these ellipses is that they are more skewed towards lower profit values than higher profit values, which is especially obvious in the case of ± 1%. This occurs for several reasons:

- The manufacturing learning curve exhibits nonlinear behavior, which means that symmetrical shifts may result in different increase/decrease in average cost. This effect is shown in notional representation of changes in the learning curve paramter b (specified by Equation 2 of § 3.3.4) Figure 53 where it can be seen that A is obviously larger than C.

- There may also be nonlinear behavior exhibited by other economic noise variables or their interactions. This needs to be further examined by performing a sensitivity analysis on these variables. This section examines the sensitivities of single variables, while the following section explores sensitivities between economic noise variable interactions.

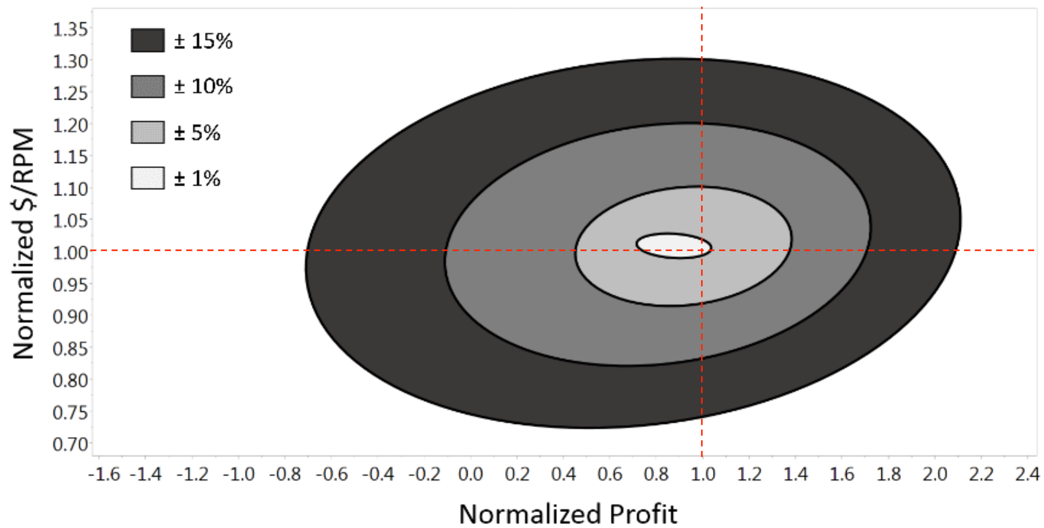

Figure 52: Distributions for both value metrics when analyzing ± 1%, ± 5%, ± 10%, and ± 15% uniform uncertainty of the economic noise variables.

Instead of performing the sensitivity analysis of the economic noise variables by varying them by ± 1%, ± 5%, ± 10%, and ± 15% around a baseline value, the uncertainty range of ± 10% was selected as an appropriate value. This sensitivity analysis was performed using only uniform distributions since further insight into other probability distributions occurs in the following section (§ 4.2.3). The first cases analyzed varied only one factor at a time and defaulted the other factors to their baseline values.

The first variable analyzed was the average inflation rate – the results of this sensitivity analysis can be seen in Figure 54. In this figure, the ellipse represents coverage of 99% of the data points that occur when varying all of the noise factors simultaneously by ± 10%. Examining the line of points, which represents the sensitivity of varying only average inflation rate, it can be seen that there was a larger impact on the profit metric. The reason this impact was larger on the profit metric compared to the $/RPM metric is that the price of aircraft was not adjusted to account for varying changes in inflation rate. Besides the difference in impacts on value metrics, it was observed that the sensitivity analysis was slightly skewed towards lower values

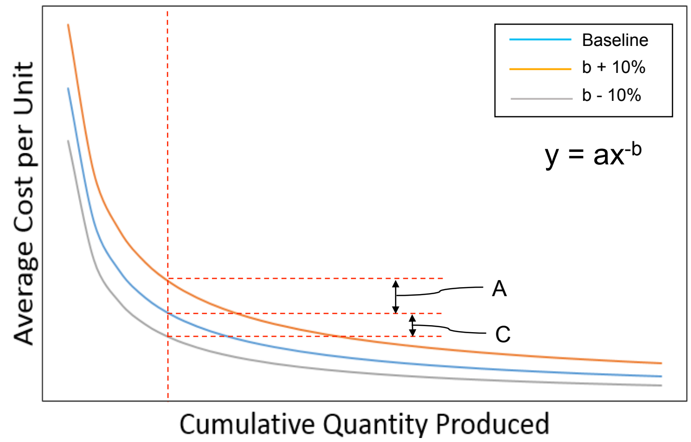

Figure 53: Notional figure of manufacturing learning curve that highlights nonlinear effects, which is shown by A > C.

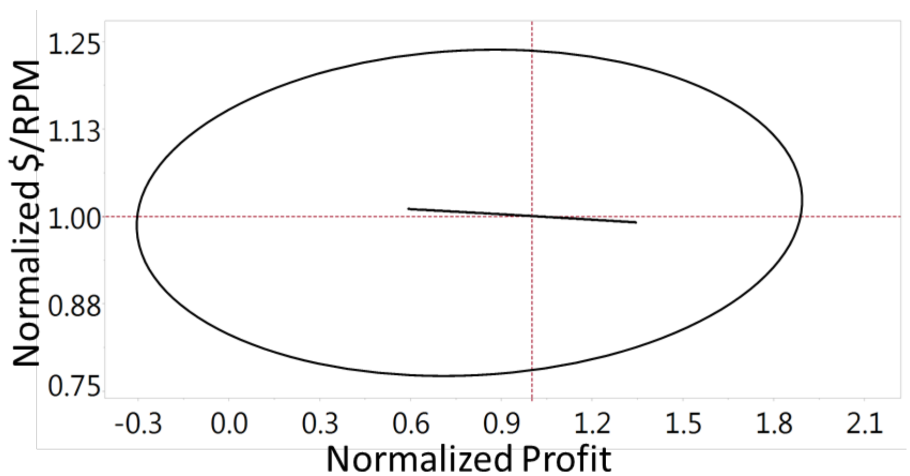

Figure 54: Sensitivity analysis of varying only average inflation rate.

of profit; the data points have a range of approximately 0.58 to 1.35.

Next, the manufacturer's learning curve was analyzed in order to determine the sensitivity of value metrics. It was expected that the variability should only occur for the normalized profit metric – this was because price was held constant so increases/decreases in manufacturing costs were not passed on to the airlines. However, when examining Figure 55, there was a slight variating in the $/RPM value for different value of the OEM's learning curve. Upon further investigation, it was discovered that the result in the figure overstates the variability – the actual range of variability

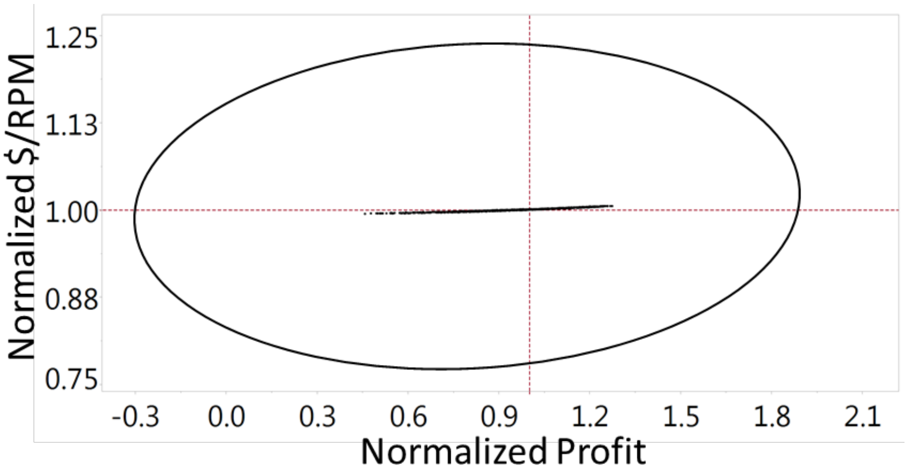

Figure 55: Sensitivity analysis of varying only OEM's learning curve.

in the normalized \$/RPM metric was within ± 1%. This almost negligible variation in normalized \$/RPM was attributed to the residuals associated with the surrogate models. In terms of the normalized profit metric the trend was as expected because it was skewed towards lower values with a range of approximately 0.45 to 1.30. The reason for this skewness was attributed to the nonlinearity shown in Figure 53.

The sensitivity of the value metrics to average load factor was examined and the results are shown in Figure 56. This variable was not expected to have any impact on the normalized profit metric because the average load factor is only used in computing \$/RPM, as shown in Equation 6 of § 3.4. Since the average load factor is directly stated in the denominator of this equation, it makes sense that it would have a large impact. This result is more interesting when compared to the sensitivity that \$/RPM exhibits from fuel costs, which is shown in Figure 57.

The results from the sensitivity analysis of fuel costs were not as expected because the variability was rather small. This was due to the expectation that fuel costs play a major role in determining the profitability of airlines; however, this initial expectation was flawed for a major reason. The normalized \$/RPM metric shows the total operating costs of one aircraft, not a fleet of aircraft. When an airline is

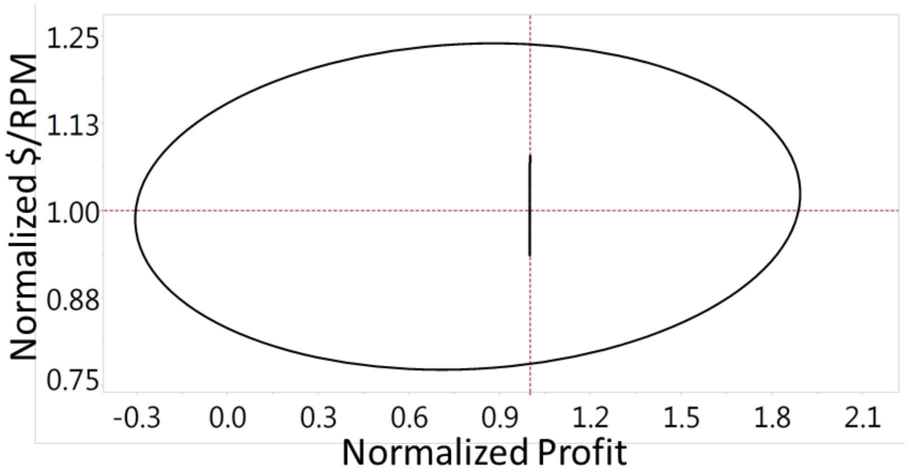

Figure 56: Sensitivity analysis of varying only average load factor.

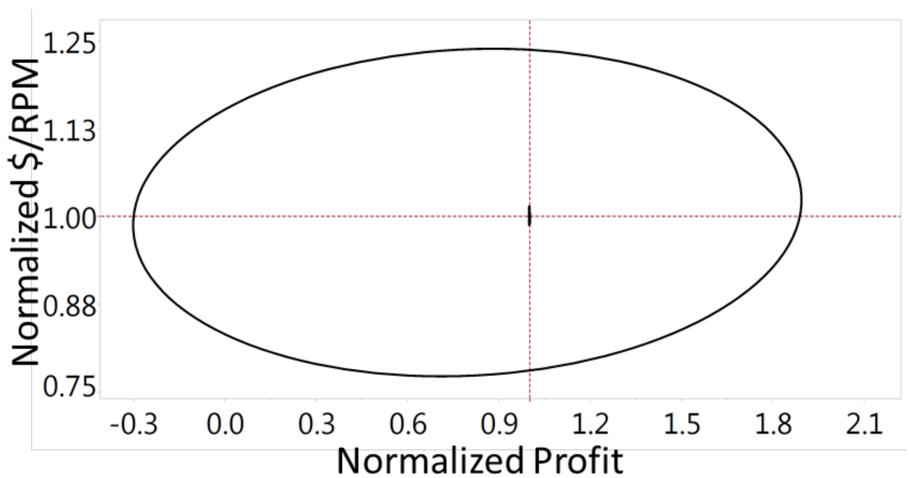

Figure 57: Sensitivity analysis of varying only average fuel costs.

concerned with the fuel costs for hundreds of aircraft, then their profitability is greatly affected by small fluctuations in this economic noise variable.

The sensitivity analysis for the price of the aircraft yielded results that were more aligned with expectations. Figure 58 shows the results of this sensitivity analysis. Changes in the price has not only a large impact on the $/RPM metric, but also the profit metric. The curve also has a positive slope, which means that as price increases, the value metrics increase and visa-versa.

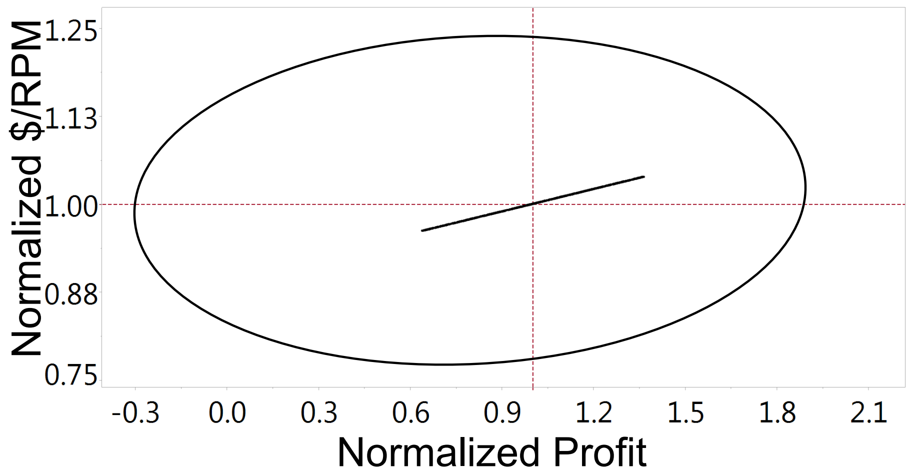

Figure 58: Sensitivity analysis of varying only the price of the aircraft.

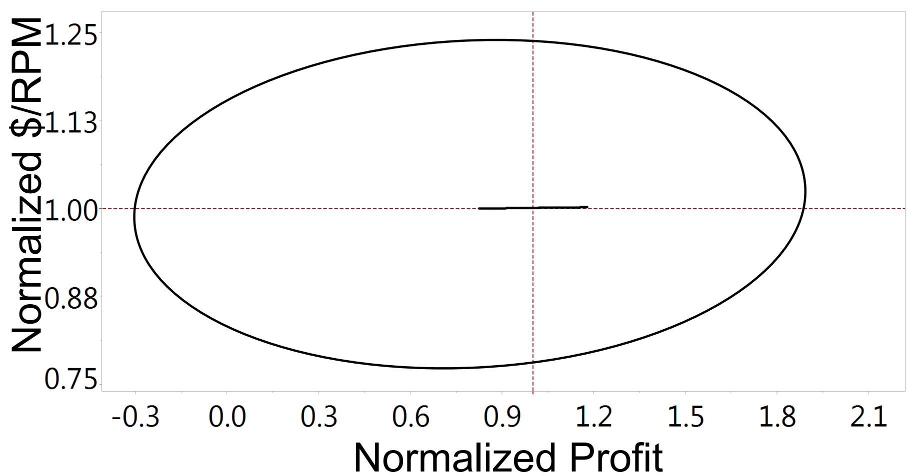

Figure 59: Sensitivity analysis of varying only the Number of the aircraft produced.

Figure 59 shows the results of a sensitivity analysis on the number of aircraft purchased. Intuition would suggest that only the OEM's profit should be affected. However, the figure does show a slight variation in the $/RPM metric. Upon further inspection, it was determined that this result was most likely due to residuals associated with the surrogate models used since the variability for this value metric was less than $\pm$ 0.5%.

The final sensitivity analysis conducted examined how the production facility costs impacted the variability of the value metric. As opposed to other economic

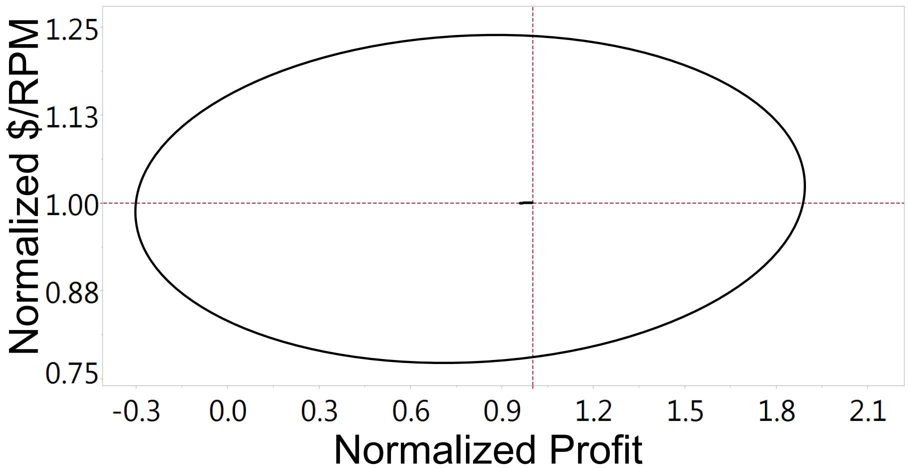

Figure 60: Sensitivity analysis of varying only the facility costs to manufacturer the aircraft.

noise variables, the production facility costs were varied from zero to $1 billion USD. The results from this variation are shown in Figure 60. While this figure shows that the variability was limited to the OEM profit metric, which was expected, the total variation was much lower than expected considering the maximum value of the input was large. This was further examined by conducting a detailed cost breakdown, which is shown in Figure 61. This cost breakdown was conducted using the Geometric Baseline and the only factor not set to its baseline value was the production facility costs, which were set to $1 billion USD. As can be seen from Figure 61, the production facility costs only account for approximately 1% of the manufacturing costs, which account for approximately 71% of the total costs. Further mitigating the impacts of the production facility costs is that the M&S environment used (ALCCA) spreads this cost over the twenty-year production life cycle of the aircraft.

One of the key takeaways that becomes apparent by examining Figures 54, 55, 56, 57, 58, 59, and 60 is that no single economic noise variable can fully account for the variability in either of the value metrics. This is a key observation because it suggests that the interactions between metrics is the main contributor to reduced ability to make decisions. This has implications towards scenario-based analysis because it

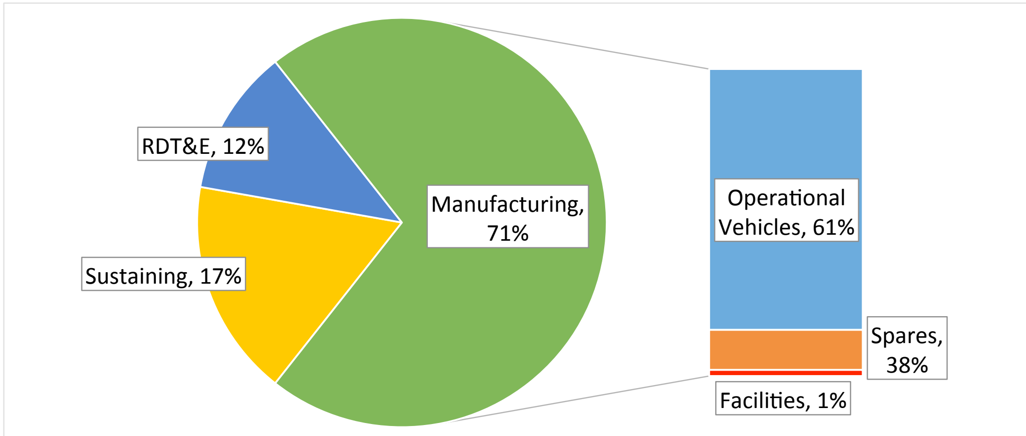

Figure 61: Detailed cost breakdown to help explain minimal impacts of facility costs.

means that scenarios should be defined using multiple metrics – for example, consider the following two, notional scenarios:

Notional Scenario 1: Fuel price increases by 5%

Notional Scenario 2: Fuel price increases by 5%, airlines reconfigure flights to increase load factor by 2%, and inflation rate is expected to remain stagnant

Based on the insight from these one-variable-at-a-time sensitivity analysis, Notional Scenario 2 would provide more insight because the interactions between those noise variables may drive the variability of the result more than any single variable. However, this insight might not be accurate – to examine its validity, more sensitivity analyses were conducted based on interactions between variables, which are discussed in the following section.

4.2.2 Sensitivity Analysis: Interactions

While the previous section explored the impacts of economic noise variables by examining their individual influences on the variability of the results for the value metrics, this section focuses on the impacts of their interactions. Furthermore, these sensitivity analyses varied the defaulted values of other economic noise variables in order to better characterize the design space. In order to quantify these sensitivities, a similar approach was adopted as in the previous section. However, since there exists a large number of interaction terms – there are 21 second-order interactions and 35 third order interactions from the seven economic noise variables – not all of the possible combinations were examined. Instead, a smaller number of cases were analyzed because it was expected that their sensitivities could provide insight into other interactions without the need of analyzing all possible combinations.

The first case that was analyzed involved only average inflation rate being varied, but including the defaulting of the manufacturer's learning curve to different values of either -5% or +5%. This was done in order to see if the value that other economic noise variables are defaulted to impacts the sensitivity analysis. These results are shown in Figure 62, where the "new baseline" values around which inflation was varied are highlighted by an x symbol. In this figure the impacts of the different values for manufacturing learning curve are easily seen – they shift the range of values to the left or right of the baseline profit. While less obvious to notice in the figure, the range of variability when the manufacturing learning curve is defaulted to +5% is slightly larger than the range when that variable is defaulted to -5%. This trend further highlights the nonlinear effects that are present when examining variation in OEM's learning curve.

Before examining the effects of varying two noise variables simultaneously, there was a need to further examine the shift caused by defaulting other economic noise variables. This was done by defaulting OEM's learning curve to either -5% or +5% while simultaneously defaulting the average load factor to -10% or +10%. The results are shown in Figure 63. In this figure, the "new baseline" are marked with an o symbol. When comparing the results in this figure to the results shown in Figure 62, the only difference that exists is the vertical shift due to the different values of average load factor. This comparison further highlights the orthogonality that is present

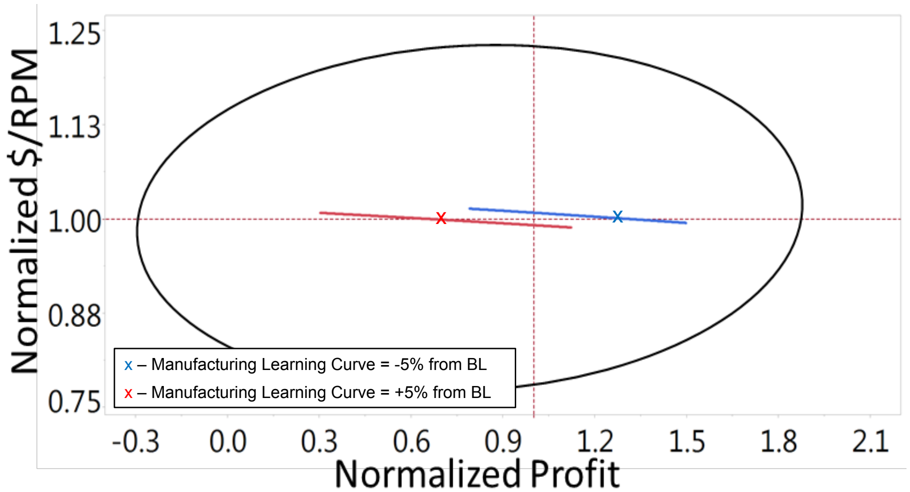

Figure 62: Sensitivities analysis based on average inflation rate with OEM's learning curve defaulted to different values.

between the impacts of load factor and manufacturing learning curve.

While the results shown in Figure 62 are technically showing second-order effects, there was a need to examine the impacts of varying two economic noise variables simultaneously. This was done in a similar manner as with Figures 62 and 63 by defaulting other economic noise variables to different values in order to further examine their impacts. Figure 64 shows the results of varying inflation rate and the number of aircraft manufactured while defaulting manufacturing learning curve to -5% and +5%. This figure shows two key results: 1) the interaction between inflation rate, number of vehicles, and defaulted settings of the OEM's learning curve almost entirely cover the full range of variability seen in the normalized profit metric, and 2) regions of overlap exist between these two ellipses, which means that different combinations of economic noise variables can recreate the same results. The latter point highlights the non-uniqueness of the design space and highlights the need for clearly defined scenarios to reduce the impacts of uncertainty – by examining the design space, a decision-maker may be unable to determine the factors that drive the result. Based on these results, the sensitivity of these two economic noise variables was further

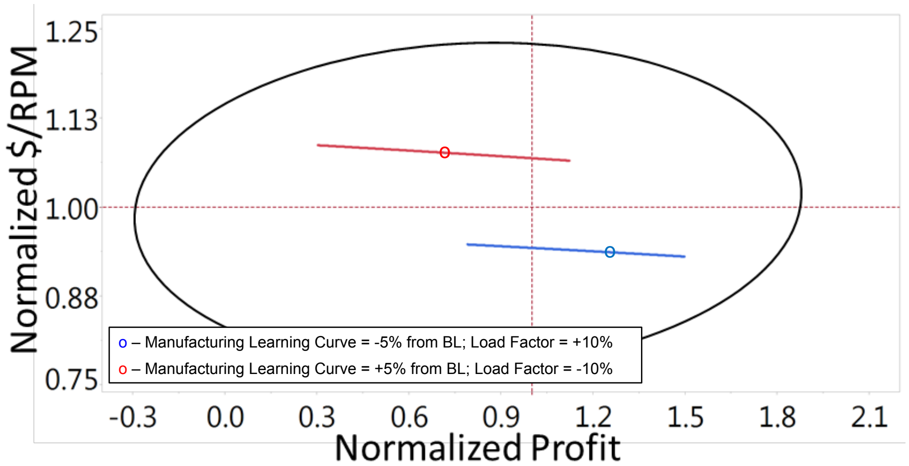

Figure 63: Sensitivities analysis based on average inflation rate with OEM's learning curve and average load factor defaulted to different values.

examined by also defaulting the load factors to either -10% or +10%. These results are shown in Figure 65. This figure shows similar results to those presented in Figure 63, except that there is more variability in the value metrics, which is due to the interactions between inflation rate and the OEM's learning curve.

To conclude the interaction sensitivity analysis, a third economic noise variable was included. Figure 66 shows the results of varying average inflation rate, number of aircraft manufactured, and fuel costs while defaulting the OEM's learning curve to values of -5% and +5%. This figure shows even more of an overlap region than Figure 64, which is due to the results having more variability in the $/RPM value metric. These results further highlight the need to have clearly defined scenarios. When the same three economic noise variables are varied, but average load factor is defaulted to different values a vertical shift occurs in the ellipses, which was expected – these results are shown in Figure 67. While this process of varying additional economic noise variables could continue, the information gained from the results has a diminishing returns. For this reason, the sensitivity analysis involving interactions between economic noise variables was not continued.

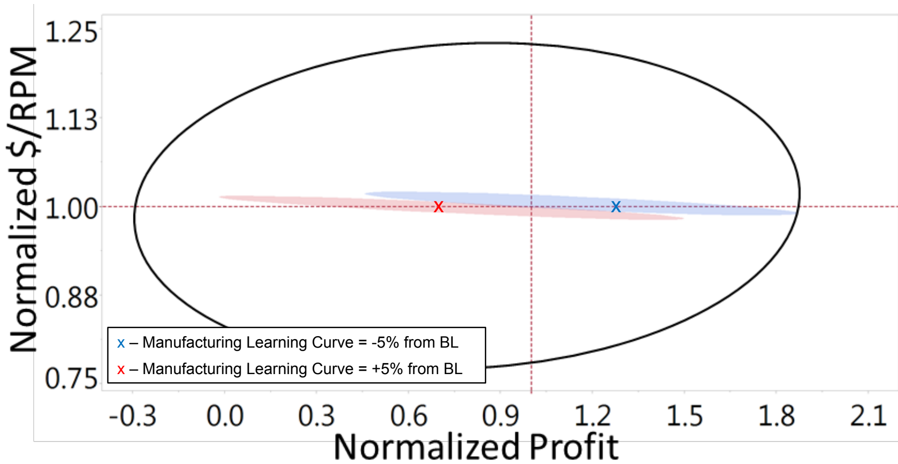

Figure 64: Sensitivities analysis based on the interaction of average inflation rate and number of aircraft manufactured with OEM's learning curve defaulted to different values.

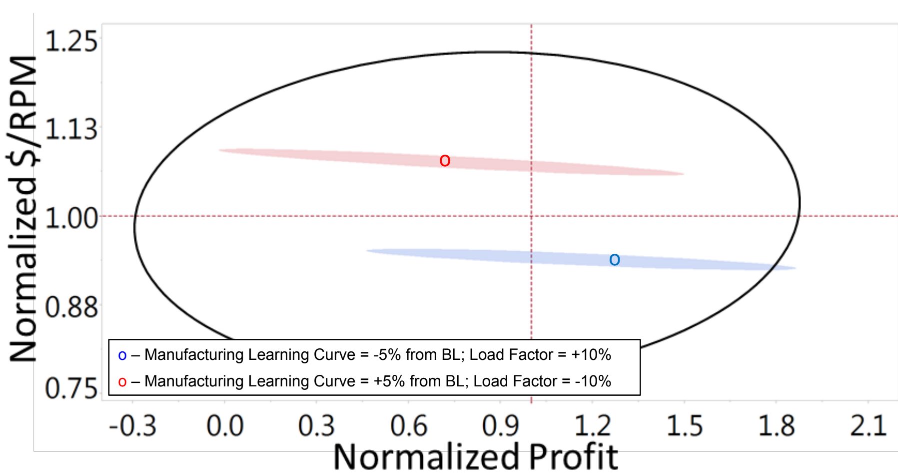

Figure 65: Sensitivities analysis based on the interaction of average inflation rate and number of aircraft manufactured with OEM's learning curve and average load factor defaulted to different values.

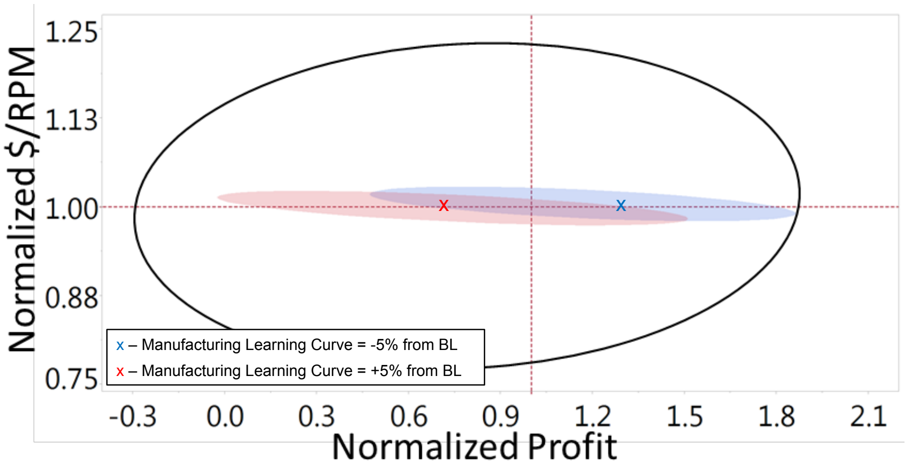

Figure 66: Sensitivities analysis based on the third-order interaction of average inflation rate, number of aircraft manufactured, and fuel cost with OEM's learning curve defaulted to different values.

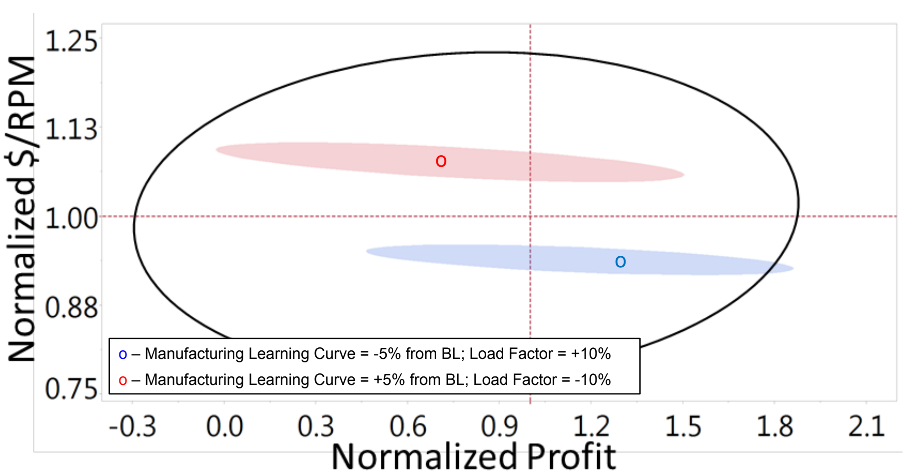

Figure 67: Sensitivities analysis based on the third-order interaction of average inflation rate, number of aircraft manufactured, and fuel cost with OEM's learning curve and load factor defaulted to different values.

Several key observations were made regarding the results of these sensitivity analyses of interactions between economic noise variables. It was shown that interactions between several variables were able to recreate almost the entire variability of the value metrics, especially OEM profit. Another observation was that results of the value metrics do not necessarily represent a unique combination of variables. This was highlighted by the overlap regions in Figures 64 and 66. This result suggest that the design space cannot be linearly decomposed into unique regions that represent a range of values for different metrics. Before applying the lessons gained from the single variable and interactions sensitivity analysis, it was necessary to first examine the sensitivity of the value metrics to probability distributions other than uniform.

4.2.3 Sensitivity Analysis: Probability Density Functions

All of the previous sensitivity analyses have been conducted assuming uniform PDFs to describe the range of uncertainty in the economic noise variables. While this helps gain insight into the sensitivities of variables and their interactions, it is not sufficient to fully characterize this design problem. The reason for this is that a uniform PDF implies no knowledge about an expected value because all values within the range are equally probable to occur. This does not adequately characterize the uncertainty associated with the economic noise variables since past (or other sources) information may help specify a value that is likely to occur. While the specific distributions associated with each economic noise variable are discussed in the following section (§ 4.2.4), this section seeks to characterize the effects of different PDF shapes on the variability of the value metrics.

While PDFs be specified in a manner to generate an infinite number of uniquely shaped distributions, three alternative distributions were considered besides uniform distributions. The three different distributions considered were Beta (β), which allow the users to specify two shape parameters in order to determine the skew and kurtosis

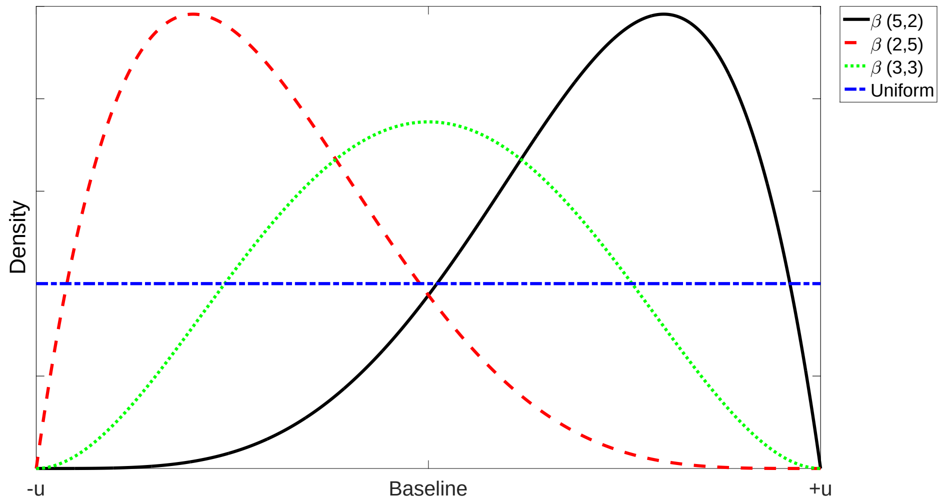

Figure 68: Notional graphs to highlight differences between different PDFs used in this sensitivity analysis.

of the shape. The skew represents a bias towards some values over other values and the kurtosis is defined as the peakedness of a distribution which relates to the frequency that a number is selected. A β(3,3) is a symmetric distribution that has no skew. A β(2,5) has a skew towards lower values in the range of the distribution and a β(5,2) is skewed towards higher values in the range of the distribution. A comparison between all four distributions can be seen in Figure 68.

This sensitivity analysis was conducted by varying all of the economic noise variables to $\pm$ 1%, $\pm$ 5%, $\pm$ 10%, and $\pm$ 15% for each of the distributions shown in Figure 68. By comparing the resulting ellipses that show the variability of the value metrics, further insight can be gained into the impacts of different PDF shapes. To compare the results of the β distributions, the results from the uniform distribution are shown in Figure 69. This figure also highlights the range of variability for the normalized OEM profit metric at $\pm$ 5% uncertainty; the range is approximately 95% of the Geometric Baseline value and is slightly skewed towards lower values.

The results from the symmetric β(3,3) distribution are shown in Figure 70. When this figure is compared to the uniform distribution shown in Figure 69, the effects of

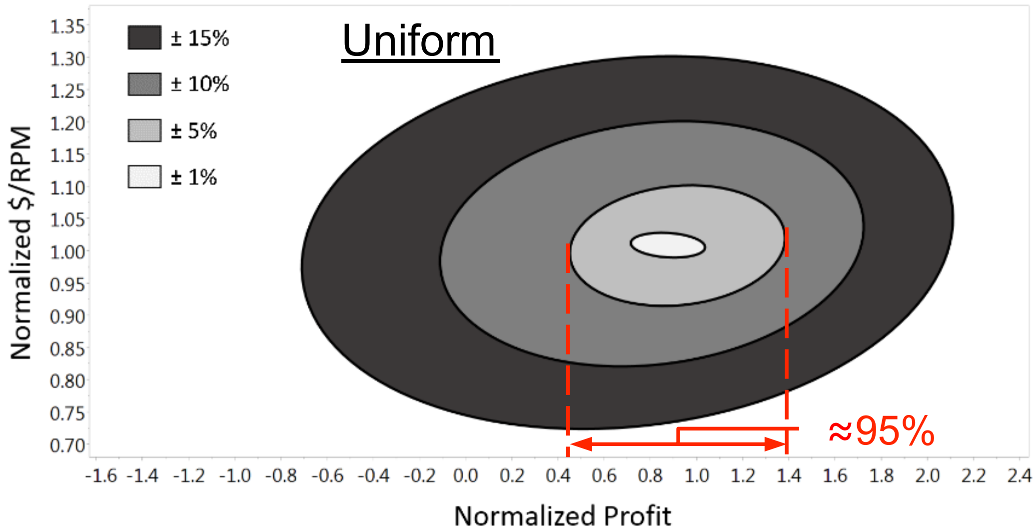

Figure 69: Sensitivity of results to uniform distributions with different levels of uncertainty, the range of variability for normalize profit at ± 5% is explicitly shown.

the different probability distributions is rather apparent. The ± 5% uncertainty has a range of approximately 65%, which is not only smaller than the uniform distribution, but also more closely centered around the Geometric Baseline value. However, in general the results for the different levels of uncertainty are still skewed towards negative profit values. In general, the ranges for both value metrics are not as large as the ranges for the uniform distribution. This suggest that the interactions between the values near the minimums and maximums of the economic noise variables cause large variation in the value metrics.

Figure 71 shows the results from using $\beta(2,5)$ distributions for all of the economic noise variables. These distributions on input parameters cause the smallest range of distributions on the value metrics. When the uncertainty was set to ± 5%, the variability for normalized profit was 50% of the Geometric Baseline. Furthermore, these results are almost perfectly symmetrical about the Geometric Baseline; however, as the uncertainty increases the values are more skewed towards high profit values. When examining the variation for the normalized $/RPM values, the results show that there is a skew towards lower values. This is different from the results for $\beta(3,3)$ and

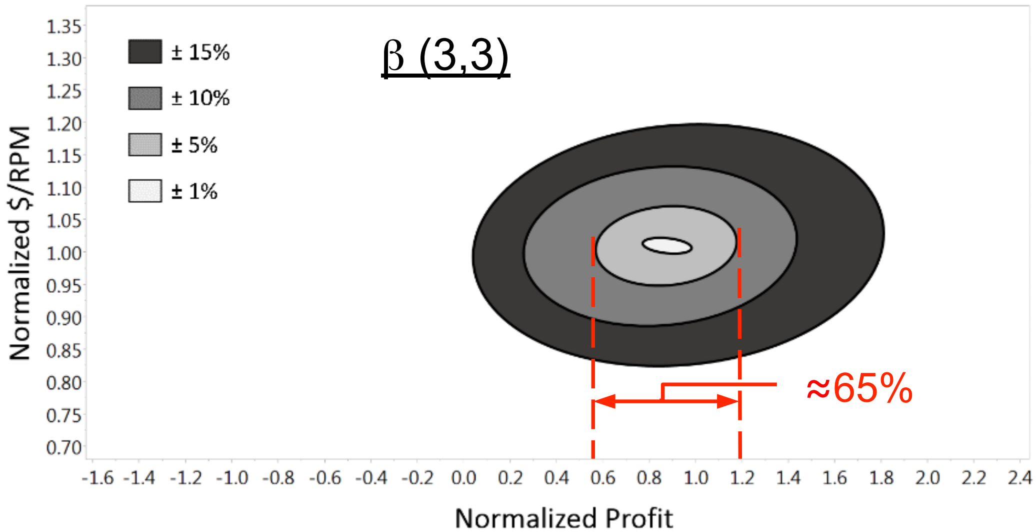

Figure 70: Sensitivity of results to symmetric beta distributions (β(3,3)) with different levels of uncertainty, the range of variability for normalize profit at $\pm$ 5% is explicitly shown.

uniform distributions where the variability around \$/RPM was more symmetrically distributed around the Geometric Baseline. This result is somewhat counter-intuitive because this distribution was biased towards lower values for load factor. Upon further inspection, the lower values for price, fuel costs, and inflation compensate for this *decrease* in load factor.

The final distribution analyzed was the β(5,2) distribution which is biased towards higher values for the economic noise variables. The results for this sensitivity analysis are shown in Figure 72 where it can also be seen that the range of profit for $\pm$ 5% uncertainty is approximately 55% of the Geometric Baseline. The similarity between the ranges for the β(2,5) and β(5,2) distributions was not expected. However, the range of profit values for the β(5,2) distribution are much lower, with none of the points achieving the same value as the Geometric Baseline. When the results of this distribution are compared to the results form the uniform distribution (Figure 69), it can be seen that the minimum values of profit for the $\pm$ 5%, $\pm$ 10%, and $\pm$ 15% are lower for the β(5,2). When the results in Figure 72 are compared to the results from the β(2,5) distribution (Figure 71), it can be seen that the \$/RPM values are

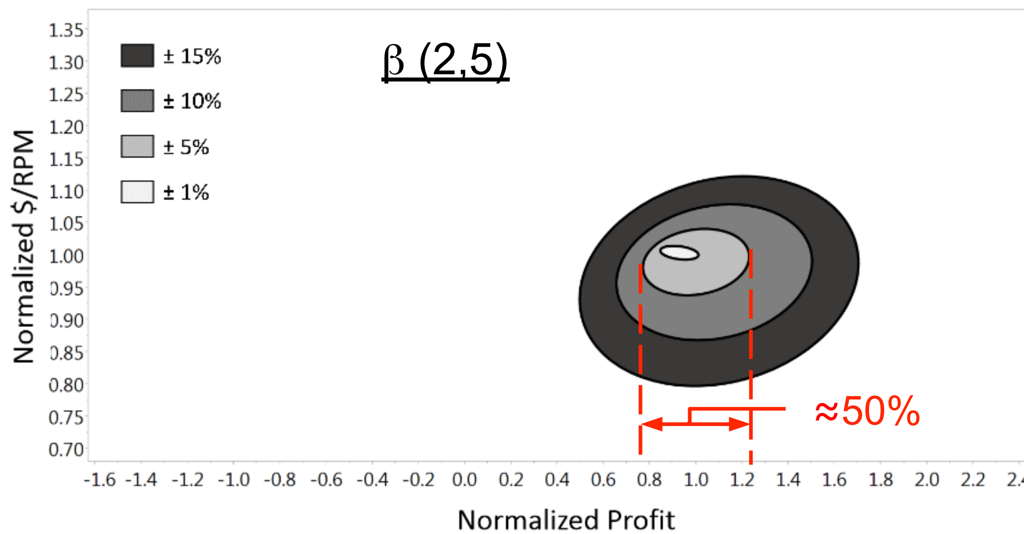

Figure 71: Sensitivity of results to beta distributions skewed towards lower values (β(2,5)) with different levels of uncertainty, the range of variability for normalize profit at $\pm$ 5% is explicitly shown.

skewed in opposite directions. Again, this result occurs because the increase in price, fuel costs, and inflation cancel the benefits from an *increase* in average load factor.

While analyzing the distributions separately has provided significant insight into characterizing the effects of uncertainty from the economic noise variables, more insight might be gained by comparing these effects to the effects of geometric variability. These results are shown in Figure 73 where the $\pm$ 5% values for each of the four distributions discussed previously is compared to the results of full geometric variability, which were defined for each variable in Table 8 of § 4.1.1. This figure clearly shows how uncertainty of economic noise variables dominates the results. Even at $\pm$ 5% uncertainty, the variability in the value metrics from factors that are under the control of the OEM is dominated by the factors that are uncontrollable.

While it was assumed that the effects from economic noise variables dominated the problem, these results from Experiment 1 have shown this to be the case. Figure 73 was sufficient to answer Research Question 2 because it shows that uncontrollable factors exhibit more influence on the value metrics than controllable factors. This means that mitigating steps need to be implemented in order for a decision-maker to

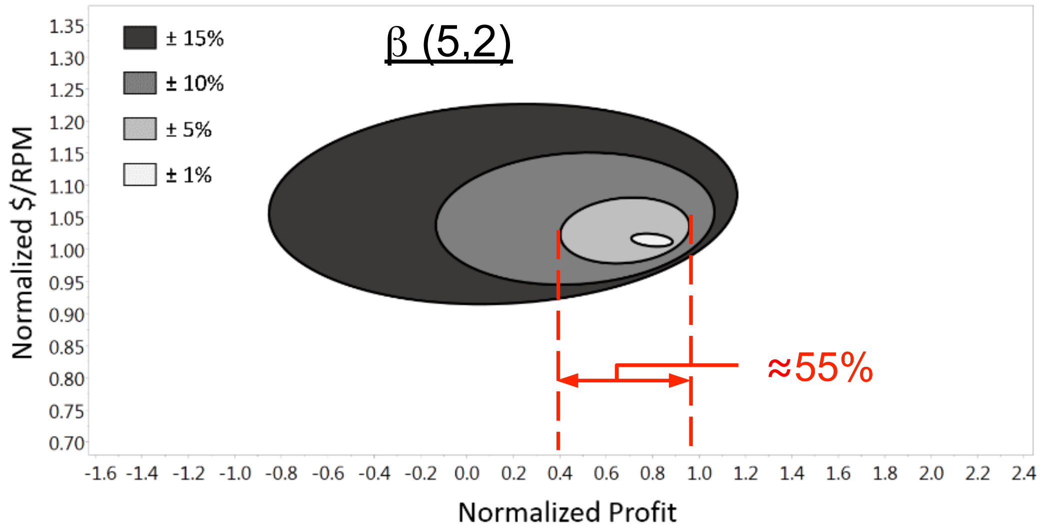

Figure 72: Sensitivity of results to beta distributions skewed towards higher values (β(5,2)) with different levels of uncertainty, the range of variability for normalize profit at $\pm$ 5% is explicitly shown.

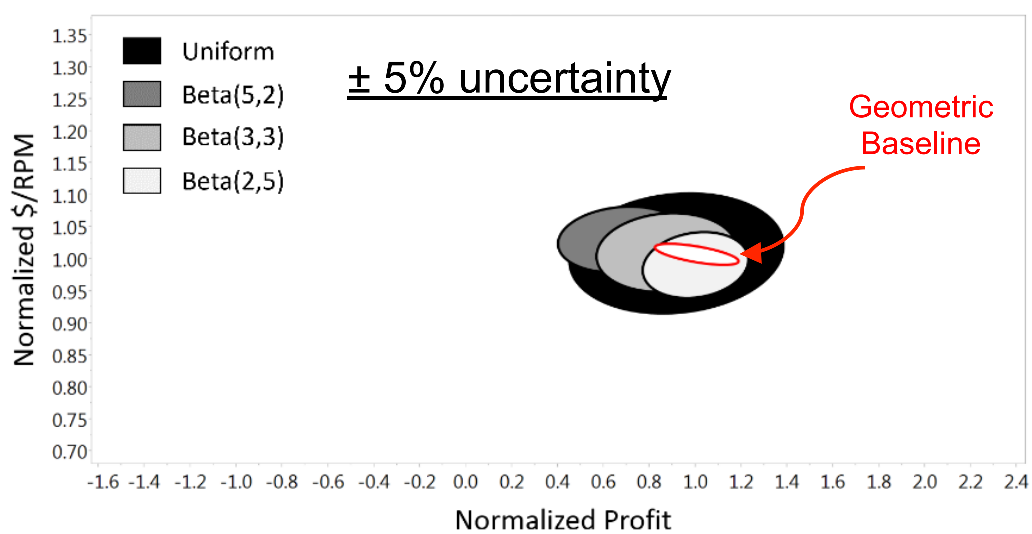

Figure 73: Comparing $\pm$ 5% uncertainty for different PDFs of economic noise variables to the effects from the full range of geometric variables.

have confidence in their decisions, which was the subject of Research Question 3. As discussed in § 3.7.1, a scenario-based approach was implemented to mitigate these effects. The following section examines the impacts of scenario-based analysis.

4.2.4 Scenario-based Analysis

Instead of conducting the scenario-based analysis with one of the four probability distributions previously discussed, there was a need to create a more realistic representation of the uncertainty associated with this problem. This was done by examining historical information related to each of the economic noise variables in order to select an appropriate distribution. A summary of the PDFs selected for each economic noise variable is provided in Table 11, but a rationale for selecting those distributions is provided in below:

Manufacturer's Learning Curve: Manufacturing aircraft has become more expensive over time due to increased complexity, increased wage rates, etc. $\rightarrow$ a β(5,2) distribution would capture this behavior.

Production Facility Costs: As with the manufacturing learning curve, modern aircraft often require a more expensive factory upgrades or the creation of new facilities $\rightarrow$ a β(5,2) distribution would capture this trend towards higher costs.

Inflation Rate: Since inflation rate is heavily influenced by governmental policy and the behavior of other markets, it can be difficult to determine an exact trend $\rightarrow$ a uniform distribution was used.

Number of Aircraft Manufactured: Some aircraft designs are very successful causing a larger number than expected to be purchased, which increases the number manufactured; however, some designs perform poorly on the market causing a much lower number than expected to be manufactured $\rightarrow$ a uniform distribution was used to model since no obvious trend could be discerned.

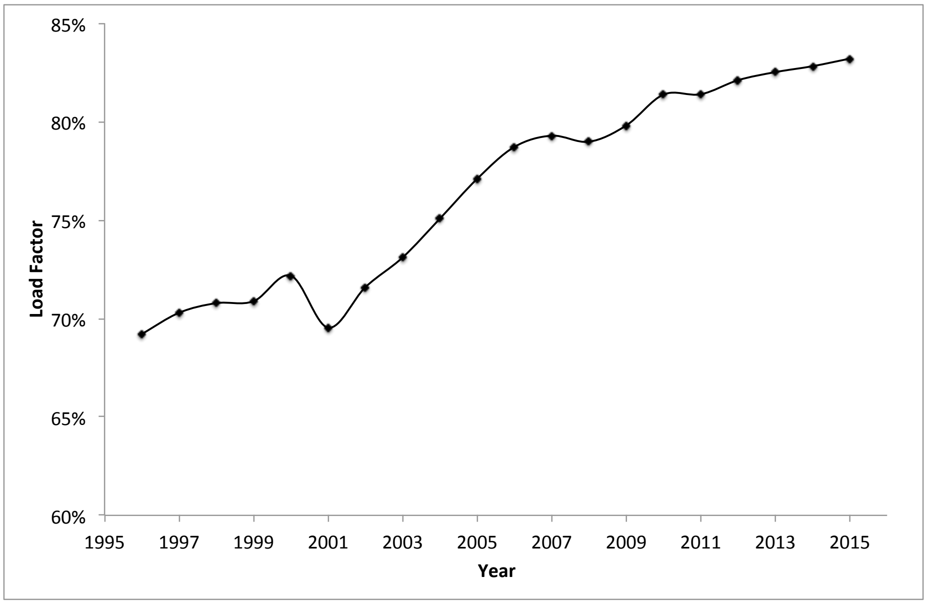

Figure 74: Changes in average load factor between 1995 and 2015. [49]

Price of Aircraft: This has previously been discussed in § 2.2 – while aircraft OEMs often have a target price for selling there aircraft, there can be fluctuation above and below that price → a β(3,3) distribution was used to capture this variability.

Load Factor: Airlines have spent considerable effort to increase their average load factors over the years, as seen in Figure 74 from the U.S. Department of Transportation [49]. However, this trend is not always increasing, as seen by slight down turns between 2000-2001, 2007-2008, and 2010-2011. → a β(5,2) distribution was used to capture skew towards higher values of load factor.

Fuel Price: Historically, fuel price has generally increased, but recent fluctuations have caused a drastic decrease in the price of jet fuel, as seen by Figure 75 [80]. However, it is doubtful that fuel price will continue to stay at very low values → a β(5,2) distribution was used to model the tendency for fuel price to increase.

Using the probability distributions preciously described and summarized in Table 11, a general analysis was conducted with all the ranges of uncertainty for each economic noise variable set to ± 10%. The results from this analysis are shown in

Figure 75: Changes in average price of jet fuel between 1991 and early 2016. [80]

Table 11: Distributions used for the various economic noise values for the scenario-based analysis portion of Experiment 1.

Economic Noise Variable	PDF Selected
Manufacturing Learning Curve	β(5,2)
Production Facility Costs	β(5,2)
Inflation Rate	Uniform
Number of Aircraft Produced	Uniform
Price of Aircraft	β(3,3)
Load Factor	β(5,2)
Fuel Price	β(5,2)

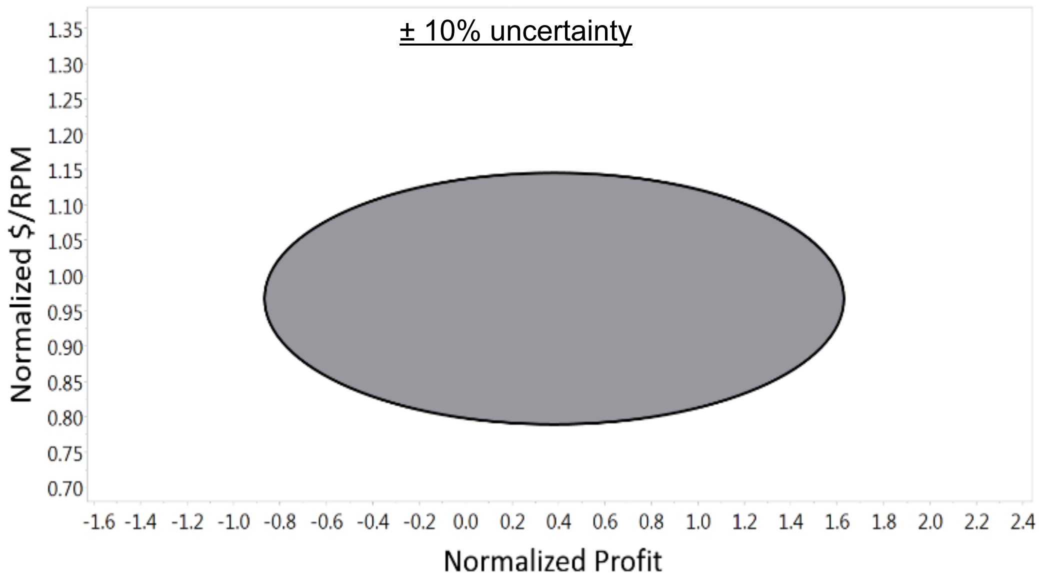

Figure 76: Ellipse showing design space with ± 10% uncertainty on all economic noise variables using distributions described in Table 11.

Figure 76. In this figure, the ellipse represents 95% of the data points that and shows the variability of the normalized profit and normalized $/RPM value metrics. When this ellipse is compared to the ellipses in Figures 69, 70, 71, and 72 from the previous section, it is interesting to note that the range of values for normalized profit are more similar to the ± 15% uncertainty ranges, but the ranges for normalized $/RPM are more similar to ± 10% uncertainty for the uniform distribution (Figure 69). While this suggests that the interactions between the different shaped PDFs are causing this behavior, the focus of this section was on the effects of using a scenario-based analysis. To this end, two randomly-generated scenarios were created in order to quantify their impacts on the design space – these scenarios are described in Table 12. These scenarios were described by inputting a range of values for each economic noise variable where 0% represents the baseline value. As an example, consider the range of prices for Scenario 1 – the price would vary between the baseline value and +10% of the baseline value with a median price occurring at +5% of the baseline value.

Table 12: Ranges for two randomly defined scenarios in order to quantify impacts of scenario-based analysis.

Economic Noise Variable	Scenario 1	Scenario 2
Manufacturing Learning Curve	[0, +10%]	[-10%, 0]
Production Facility Costs	[0, +10%]	[-10%, 0]
Inflation Rate	[0, +10%]	[-10%, 0]
Number of Aircraft Produced	[0, +10%]	[-10%, 0]
Price of Aircraft	[0, +10%]	[-10%, 0]
Load Factor	[0, +10%]	[-10%, 0]
Fuel Price	[0, +10%]	[-10%, 0]

While the scenarios used for the conclusion of Experiment 1 are not representative of any real-world scenarios, they are sufficient to validate whether or not scenario-based analysis could be used to mitigate the large amounts of variability in the value metrics shown in Figure 76. Before examining these scenarios overall impact on both value metrics, the manufacturer's cumulative cash flow (CCF) curves were examined using box plots to show the variability for each year. Figure 77 shows the CCF curve for Scenario 1 and highlights three important traits. Point A shows that the variability in the breakeven year is rater large, spanning between years 11 & 12 to year 19, with an outlying point in year 20 being just above the breakeven value. Point B shows that the final profit has a large range of possible values, with very few points being above the Geometric Baseline value for profit. Lastly, point C highlights that the maximum possible sunk cost occurs in year 7 and has a value that is approximately -163% of the Geometric Baseline profit.

The CCF curve for Scenario 2 is shown in Figure 78. This figure highlights the difference in results that occur between the two scenarios. Point A shows that the breakeven year is expected to occur between years 10 and 12, which is much lower variability than in Scenario 1. Furthermore, point B highlights that the median range of profit is above the Geometric Baseline value for Scenario 2. Finally, point C shows that the maximum possible sunk cost is only about -140% of the Geometric Baseline

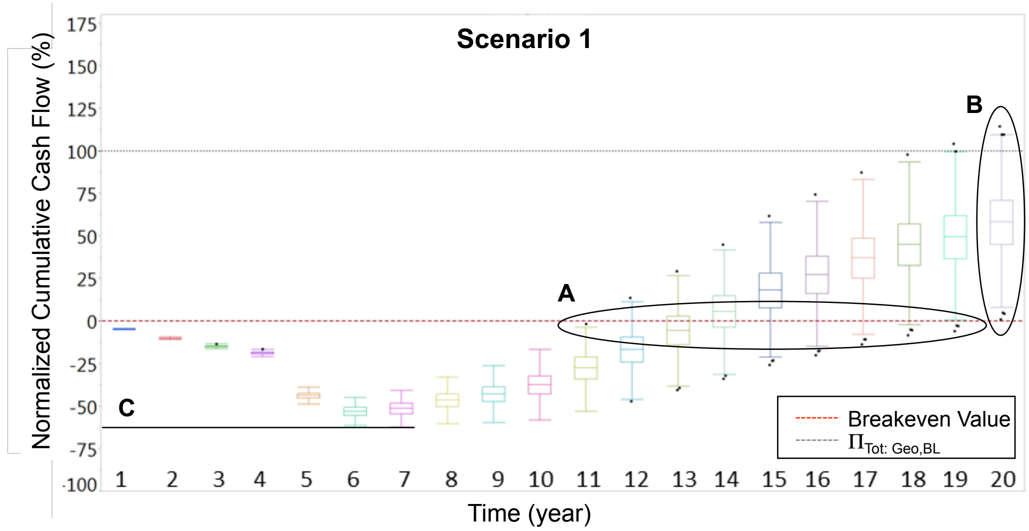

Figure 77: Plot of the normalized OEM's CCF curves for Scenario 1 with three specific points highlighted: A) breakeven year, B) range of estimated profit, and C) maximum possible sunk cost.

and occurs in year 6, which is when initial deliveries of aircraft occurs. While this information concerning normalized profit for both scenarios is useful, it does not account for the scenarios' impacts on normalized \$/RPM.

Before examining the ellipses that illustrate the variability of both metrics simultaneously, each value metric was examine independently. This was done by examining their cumulative distribution functions (CDFs), which show the probability of a value metric being above or below a certain value. For normalized profit, the CDFs were used to quantify the probability that profit would be greater than the Geometric Baeline profit with no uncertainty. For normalized \$/RPM, the CDFs were used to quantify whether \$/RPM would be below the Geometric Baseline \$/RPM. The resulting CDF plots for Scenario 1 are shown in Figure 79. In these plots, it can be seen that Scenario 1 not only hurts the expected profitability of a design, but also its desirability by airlines. If this were a real-world scenario, then the aircraft OEM would probably seek to infuse strategy options that cause their design to perform better for both of these value metrics. To contrast these results, the CDF plots for Scenario 2 are shown in Figure 80. These plots show that in this scenario there are

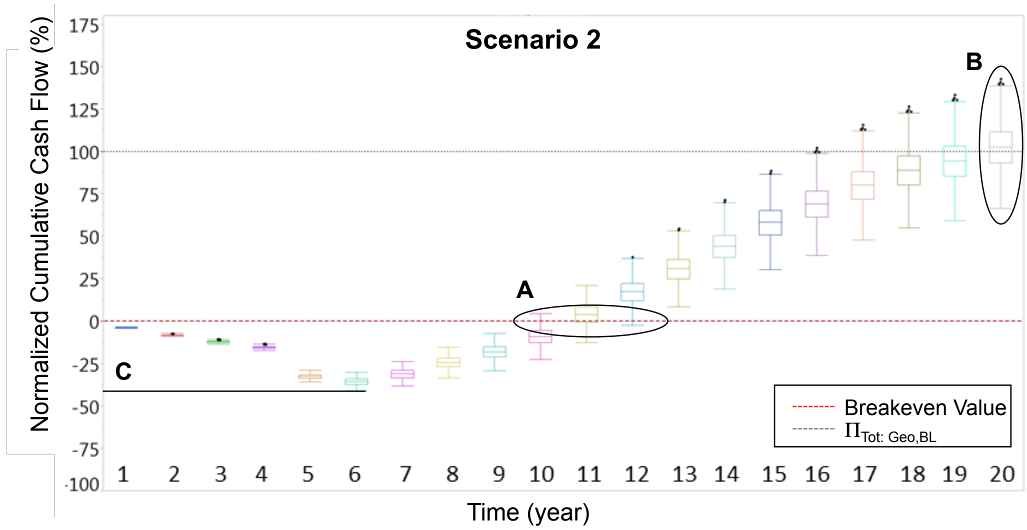

Figure 78: Plot of the normalized OEM's CCF curves for Scenario 2 with three specific points highlighted: A) breakeven year, B) range of estimated profit, and C) maximum possible sunk cost

reasonably high probabilities for the aircraft to perform well with regards to the two value metrics.

While the results from the CDF plots in Figures 79 and 80 allow for some insight to be gained, they do not directly aid in decision making. This is because none of the factors examined in Scenarios 1 or 2 were under control of the decision-maker. However, the use of these scenarios does provide a much clearer picture for the decision-maker to further analyze. This can be seen by examining the relative

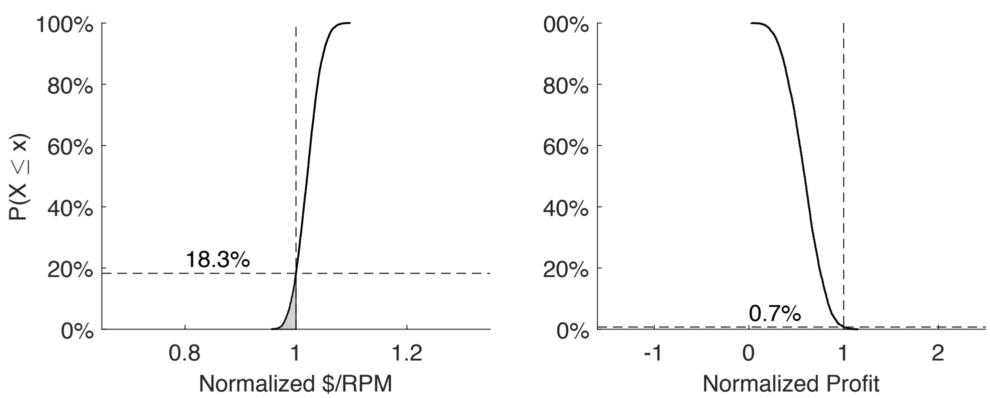

Figure 79: Plot of the CDFs for Scenario 1, which depicts the probability of profit and $/RPM having better values than the Geometric Baseline with no uncertainty.

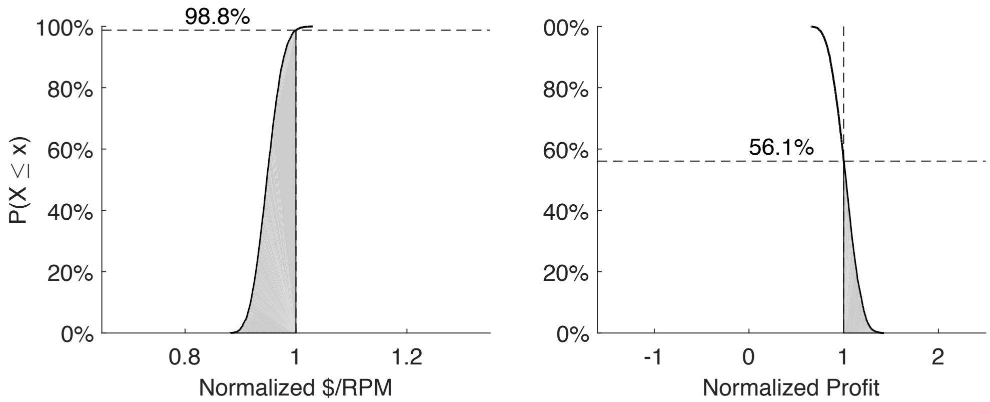

Figure 80: Plot of the CDFs for Scenario 2, which depicts the probability of profit and $/RPM having better values than the Geometric Baseline with no uncertainty.

Table 13: Summary of the percentage reduction of the total design space by using each scenario for each value metric.

	Normalized Profit	**Normalized $/RPM**
Scenario 1	$\downarrow$ 64%	$\downarrow$ 69%
Scenario 2	$\downarrow$ 74%	$\downarrow$ 67%

variability of both value metrics for Scenarios 1 and 2 compared to the variability for the full range (i.e., ± 10%) of uncertainty. This comparison can be seen in Figure 81. While the figure is sufficient to highlight a significant reduction in variability for each value metrics, the percentage reductions are quantified in Table 13.

The results from this scenario-based analysis showed that significant reductions in the design space could occur. This shows that scenario-based analysis can be used reduce the variability in the design space, which may allow for more insight into the design problem. These results further suggest that more tightly-defined scenarios (i.e., with smaller ranges around each economic noise variable) may lead to even better insight being gained. Regardless, scenario-based analysis is not sufficient to allow a decision-maker to pick a relevant strategy as it was conducted in Experiment 1. Instead, it was necessary to evaluate the effects of different strategies in these scenarios in order to quantify their impacts on the value metrics.

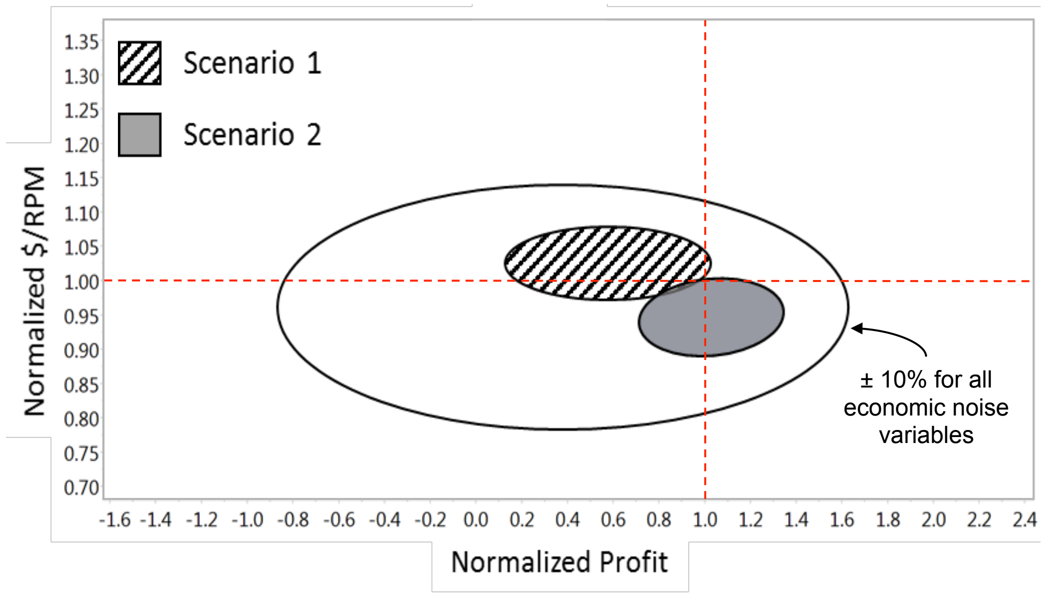

Figure 81: Ellipses showing two scenarios compared to the ellipse of ± 10% uncertainty on all economic noise variables.

After the impacts of strategies are assessed, a technique must then be applied in order to provide insight about which strategy is preferred. The rationale for a technique to do this was discussed in § 3.7.1 and shown in Figure 37. One of three possible techniques that combine Taguchi's S/N and MCDM techniques should be used to evaluate strategies. This is the focus of Experiment 3, which is discussed in § 4.3.2. But before conducting that experiment it was necessary to first examine a canonical experiment (Experiment 2) to determine how S/N ratio could be applied if there are negative value metrics – while the scenario-based analysis presented in Experiment 1 did not result in any scenarios with negative values for normalized profit, it is not unreasonable to assume that this may occur given different scenario descriptions. The following section describes Experiment 2 and Experiment 3 and relevant conclusions.

4.3 Selecting Strategies

This section is comprised of § 4.3.1 and § 4.3.2, which address Experiment 2 and Experiment 3, respectively. The major aim of both experiments was to examine the process of comparing proposed designs and strategies to a competitor's design. The difficulties associated with this task are detailed in § 3.7.1, but stem from the probabilistic nature of the resulting value metrics. To mitigate these concerns, a comparison was suggested that utilizes selection techniques that combine Taguchi's S/N and MCDM techniques of OEC and TOPSIS, which were described in § 3.7.5. However, since OEM's profit was selected as a value metric, there is a possibility of having negative values for that value metric, given a specific scenario. Since these negative values cannot be used in Taguchi's S/N formulation, a mitigating technique must be implemented.

The concern with negative value metrics was explored § 4.3.1 by Experiment 2. This experiment examines a canonical problem in order to determine a preferred mitigating strategy. Two transformation strategies were examined in order to determine if the different approaches lead to different results. Based on the results of this experiment, several heuristics are suggested that are applicable to any problem using Taguchi's S/N formulation with negative inputs. By accounting for the possibility of negative value metrics, Experiment 3 can further examine the hybrid S/N-MCDM techniques in order to determine a preferred approach.

Instead of using a canonical experiment, as was the case with Experiment 2, Experiment 3 uses the data from the scenario-based analysis conducted in § 4.2.4, which occurred as the final step in Experiment 1. The use of this data allows for more insight to be gained into the nature of this design problem; however, Experiment 3 does not directly compare the possible alternatives to a competitor. This was done in order to gain clear insight into the three possible techniques for selecting a preferred strategy. The end of Experiment 3 concludes by describing how these techniques would be applied when comparing to competition. Chapter 5 examines three *use cases* of the CoDeS Framework where the results of Experiment 3 are directly used to compare competition. The results of Experiment 2 were needed to successfully analyze the second use case.

4.3.1 Negative Value Metrics (Experiment 2)

As previously stated, Experiment 2 in this section analyzed a canonical example problem that focused on mitigating strategies for using negative numbers with Taguchi's S/N formulation. This was a concern because values of OEM's profit can be negative, positive, or zero. Since profit is a value metric that should be maximized, obvious problems can occur for negative or zero values based on Taguchi's *larger is better* formulation, which was shown in Equation 22 and restated below. If a value of zero was analyzed in the equation, then the fraction would become infinity. If a negative value was used, then it could wrongly bias the results since the term is squared – for example, consider two values of -5 and 3, obviously 3 should be preferred for the larger is better metric, but the -5 would have a more favorable value because $-5^2 = 25$ but $3^2 = 9$. A technique should be implemented that addresses both of these concerns, but does not alter or ignore the relevant data.

$$S/N = -10log_{10}\left(\frac{\sum_{i=1}^{N}\frac{1}{y_i^2}}{N}\right)$$

One mitigating technique may be to use value metrics that cannot take negative values – in the case of this aircraft design problem, cost would be an example of a metric. However, if cost was used, then information regarding price and quantity sold would not be captured, which would be ignoring two important factors. Another mitigating technique may be to ignore data points that have non-positive, but this technique would also wrongly bias the results – in fact data that showed negative values for profit may be more important to a decision-maker because they could represent high risk. Instead of these techniques, transformations were examined.

The transformations analyzed are well-established techniques either within the general field of mathematics or by practitioners of Taguchi's S/N formulation, as described in § 3.7.6. Two transformation techniques were analyzed: 1) Transform the data to positive values only (shift-transformation), and 2) Transform the S/N formulation to *target is better* (target-transformation). The *target is better* formulation was described by Equation 21, but is also restated below:

$$S/N = -10log_{10}\left(\frac{\sum_{i=1}^{N}(y_i - T)^2}{N}\right)$$

The formulation for the first approach is shown in Equation 36 where γ represents an arbitrary constant that is added to make all the values positive. The formulation for the second approach is described by Equation 37 where Γ is an arbitrary constant that is introduced.

$$S/N = -10log_{10}\left(\frac{\sum_{i=1}^{N}\frac{1}{(y_i+\gamma)^2}}{N}\right) \tag{36}$$

$$S/N = -10log_{10}\left(\frac{\sum_{i=1}^{N}(y_i - \Gamma)^2}{N}\right) \tag{37}$$

In order for either of these transformations to be applicable, guidance needs to be provided for values of γ and/or Γ. To evaluate whether a preferred value for these constants was obvious, regardless of the data, partial derivatives were taken in order to determine whether any minima or maxima occur. The partial derivative of Equation 36 with respect to γ is given by Equation 38, where the summations go from $i = 1$ to N. From examination, this equation has no obvious values of a minimum or maximum and as $\gamma >> y_i$ then $\frac{\partial S/N}{\partial \gamma} \rightarrow 0$ because the numerator approaches zero faster than the denominator. The partial derivate of Equation 37 with respect to Γ is given by Equation 39, where the summations go from $i = 1$ to N. Similar to the other transformation, this equation shows no obvious minimum or maximum and as $\Gamma >> y_i$ then $\frac{\partial S/N}{\partial \Gamma} \to 0$. Since these partial derivatives show that there are no obvious values for γ or Γ and further analysis showed that the constants cannot just be set to arbitrarily large values, there was a need to further experimentally determine preferred values for γ and Γ.

$$\frac{\partial S/N}{\partial \gamma} = \frac{20}{ln(10)} \frac{\sum \frac{1}{(y_i+\gamma)^3}}{\sum \frac{1}{(y_i+\gamma)^2}} \tag{38}$$

$$\frac{\partial S/N}{\partial \gamma} = \frac{20}{ln(10)} \frac{\sum (y_i - \Gamma)}{\sum (y_i - \Gamma)^2} \tag{39}$$

Since the values for γ or Γ need to be experimentally determined, Experiment 2 was slightly modified – besides determining whether one transformation was preferred, the experiment also sought to determine any rules or heuristics for determining an appropriate constant value for that preferred transformation. In order to conduct Experiment 2, data was needed that was representative of the problems previously discussed, but only a small number of data points with obvious behavior were considered. This was done in order to ensure generality of the results from this experiment and to provide clear context for any rules or heuristics that were developed. The data used for this canonical experiment is shown in Table 14 – each alternative has ten data points that create a distribution of results and the mean and maximum value for Alternative 2 are greater than those of Alternative 1, but both have the same variance. This means that when these alternatives are compared using Taguchi's S/N formulation for larger is better, Alternative 2 should be selected.

The first transformation applied to this data was the transformation given in Equation 36, which introduced a constant of γ to shift the data. The results from varying $1 \leq \gamma \leq 10$ are shown in Table 15. When $\gamma \geq 4$, then the results show that Alternative 2 was preferred, which was the expected results; however, when $\gamma = 1, 2,$ or 3 Alternative 1 had a higher S/N value and was therefore preferred.

Table 14: Notional data used for Experiment 2 to evaluate transformation techniques of nonpositive data using Taguchi's S/N formulation.

Data Point	**Alternative 1**	**Alternative 2**
1	-3.5	-3.25
2	-2.5	-2.25
3	-1.5	-1.25
4	-0.5	-0.25
5	0.5	0.75
6	1.5	1.75
7	2.5	2.75
8	3.5	3.75
9	4.5	4.75
10	5.5	5.75
Mean:	1	1.25
Variance:	9.17	9.17

Further analysis into this result showed that for values of γ less than the absolute value of the minimum of the data caused the results to be inaccurate. This finding was significant because it suggests values of γ and a heuristic that can be applied to other data sets. Another interesting trend seen in the results of Table 15 is that as γ increases, the separation between S/N values of Alternative 1 and Alternative 2 decreases. This result was expected from the results of the partial derivative shown in Equation 38, but has now been confirmed by experiment.

The second transformation applied to the data was the transformation given in Equation 37, which introduced a constant of Γ to serve as an arbitrary target from which all the data could be compared. The results from varying $-4 \leq \Gamma \leq 5$ are shown in Table 16. When $\Gamma \geq 2$, Alternative 2 had a higher S/N value and was preferred, which was the expected result. But, when $\Gamma \leq 1$, then Alternative 1 was the preferred option. The reason for this switch occurring around $\Gamma = 1$ was due to the means of the data set. As long as the target was set to a value higher than the mean of the data being analyzed, this transformation selected the correct distribution.

Table 15: S/N results from transforming the data by introducing a shift of γ.

Size of γ	**S/N(Alternative 1)**	**S/N(Alternative 2)**
1	0.270	-2.84
2	0.337	-2.80
3	0.543	-2.66
4	3.16	6.12
5	10.7	11.7
6	13.9	14.5
7	16.0	16.4
8	17.5	17.8
9	18.8	19.1
10	19.8	20.1

Another trend that was not as apparent from the data shown in Table 16 was the verification of Equation 39, which was verified by checking larger values of Γ. When $\Gamma = 40$, there was no difference, to the three significant figures, between the S/N values of Alternative 1 and Alternative 2 with both equal to -31.8. Interestingly, when $\gamma = 40$ in the shift transformation, the values of Alternative 1 and Alternative 2 are both equal to 32.2.

The results form Experiment 2 did not provide clear guidance about which transformation technique is preferred, but yielded three useful heuristics for these transformations. The results suggest that either technique could be used to mitigate the effects of negative data values in Taguchi's S/N formulation. This means that the preference of one of these transformation techniques is dependent on the user and the analysis being conducted. While the S/N values from the shift-transformation are positive and the S/N values from the target-transformation are negative, this might be indicative of the data set used and may not be the case for all data evaluated. However, the heuristics suggested below should be universally applicable to any data set. The first heuristic is applicable to both the shift-transformation and the target-transformation, but the second and third heuristics are specific to the transformation

Table 16: S/N results from transforming the data by introducing a target value of Γ.

Size of Γ	S/N(Alternative 1)	S/N(Alternative 2)
-4	-15.2	-15.5
-3	-13.8	-14.2
-2	-12.4	-12.7
-1	-10.9	-11.2
0	-9.66	-9.92
1	-9.16	-9.20
2	-9.66	-9.45
3	-10.9	-10.5
4	-12.4	-12.0
5	-13.8	-13.5

used.

Heuristic 1: Regardless of the transformation used, the values of γ or Γ should not exceed seven-times the maximum value for the data set for all alternatives, but values of the constant less than two- or three-times the maximum value may be preferred.

Heuristic 2: If performing a shift-transformation, the value of γ must be greater than the absolute value of the minimum of the data for all alternatives (i.e., $\gamma > |min(A_{ji})|$ for j alternatives with i data points in each).

Heuristic 3: If performing a target-transformation, the value of Γ must be greater than the largest mean of the data for all alternatives (i.e., $\Gamma > max(\bar{y}_j)$ for j alternatives.

These suggestion of these heuristics conclude Experiment 2. The following section discusses Experiment 3, which looks at applying the three hybrid techniques of Taguchi's S/N formulation and MCDM to data from the scenarios analyzed at the end of Experiment 1.

Table 17: k-factor values of two notional technologies evaluated in Experiment 3.

	Technology 1 (T1)	Technology 2 (T2)
Benefits	$k_{\text{ComponentWeights}}$ = -5%	k_{Drag} = -10%
Costs	$k_{\text{RDT\&E}}$ = +5% k_{Price} = +5%	$k_{\text{RDT\&E}}$ = +5% k_{Price} = +5%

4.3.2 Non-negative Value Metrics (Experiment 3)

Experiment 3 was conducted using data from the randomly generated scenarios examined in § 4.2.4. These scenarios were described in Table 12 and their resulting variability on the value metrics can be seen in Figure 81. However, it is important to note that the purpose of comparing alternatives is not to select an optimal scenario because aircraft OEMs have no control over the scenarios. Instead, the objective was to select optimal strategies in the presence of a given scenario. That is the main thrust of Experiment 3 – to determine which, if any, combination of Taguchi's S/N formulation and MCDM techniques would be best for selecting the preferred strategy(ies). The strategies considered for Experiment 3 were two notional technologies (T1 and T2) that are described in Table 17 using their k-factors.

T1 and T2 were then evaluated for each scenario in order to see their impacts on the variability of the value metrics. The results from Scenario 1 are shown in Figure 82 and the results for Scenario 2 are shown in Figure 83. The most obvious results from both scenarios was that the results of the technologies were not drastically different in terms of their value metrics; however, the difference of 1% in the normalized $/RPM metric for *one* aircraft that flew 1,000 nmi missions during the year could result in a difference of up to $330,000 in operating costs and when considering billions of dollars in potential profit for an aircraft a 1% difference could result in a difference of tens of millions of dollars. While the difference between these technologies may not seem significant, there are large consequences for making the wrong decision of selecting a non-optimal technology.

The inability to clearly distinguish the preferred technology based on the impacts shown in Figures 82 and 83 highlight the need for an appropriate technique to select the preferred technology. As previously discussed (§ 3.7.5), three alternative combinations of Taguchi's S/N formulation and MCDM techniques are candidates for preferred techniques: 1) OEC of S/N values, 2) S/N of OEC values (MRSN), and 3) TOPSIS of S/N values. Further complicating the issue was that preferences between value metrics may not be known or may change with time. To mitigate these effects an approach was adopted to show the relative sensitivities or elasticities of each approach for unknown weightings. This was accomplished by normalizing the weightings to a percentage value and then using those percentages to analyze each technology using the three different approaches. In all three approaches, w_1 was the preference towards normalized \$/RPM and w_2 was the preference towards normalized profit for making a decision. For example, if a decision-maker knew that \$/RPM was thrice as important as estimated profit for making their decision – this might be because the decision-maker would expect a lower \$/RPM value to increase the number of aircraft purchased which would further increase profit – then the weightings would be set to $(w_1, w_2) = (75\%, 25\%)$.

The first approach examined was the OEC of S/N values, which was defined by Equation 23 of § 3.7.5. The results from this approach are shown in Figure 84. This figure shows that the OEC values are linearly increasing, which is expected given the linear nature of the weightings. It can be seen that the weighting values of approximately (60%, 40%) represent an important point because values to the left (i.e., where profit is more or equally preferred to \$/RPM) show that T1 was preferred, but values to the right (i.e., where \$/RPM is at least 1.5x preferred to profit) result in T2 as the preferred strategy. It is important to note that a decision-maker would need to have some knowledge of their preferences in order to select an appropriate technology.

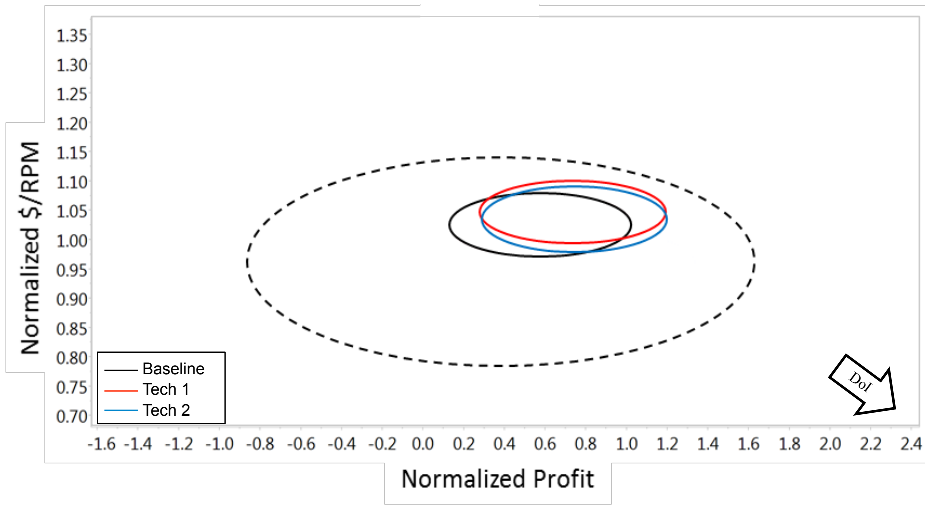

Figure 82: Ellipses showing variability in value metrics with infusion of T1 and T2 in Scenario 1.

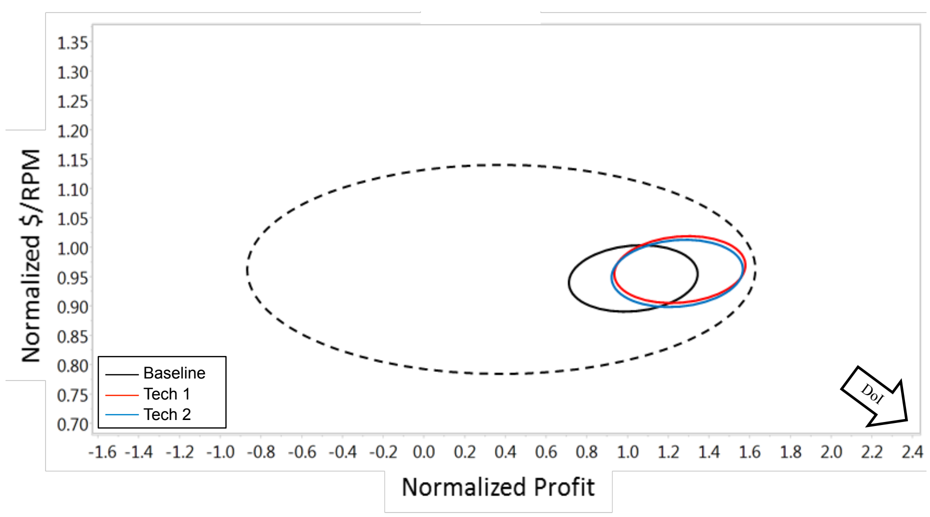

Figure 83: Ellipses showing variability in value metrics with infusion of T1 and T2 in Scenario 2.

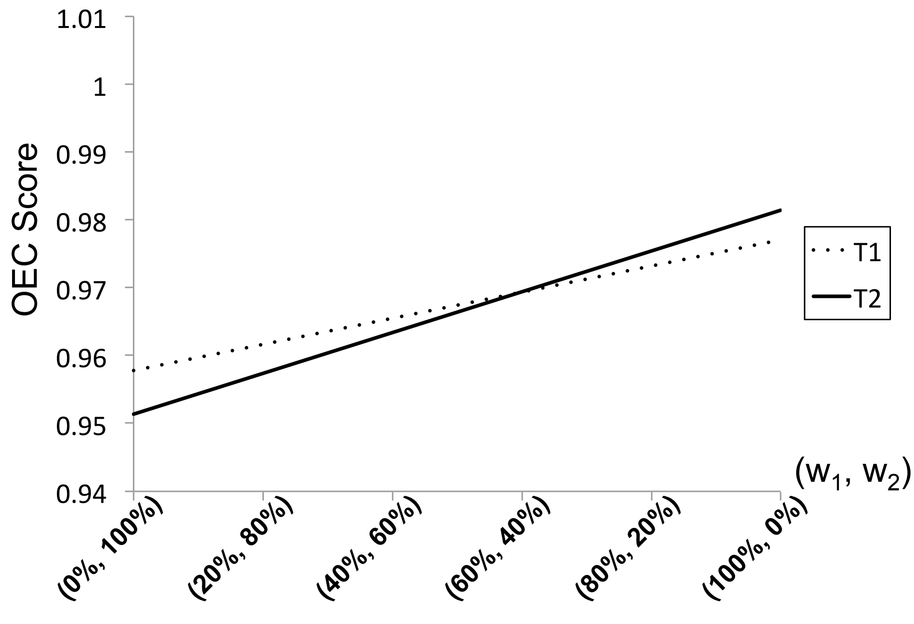

Figure 84: Scenario 1 with T1 and T2 being analyzed by an OEC of Taguchi's S/N values for each value metric with variable weightings.

This approach was also applied to the technologies in Scenario 2, which can be seen in Figure 85. The results from this figure show that T2 was generally preferred for all weightings to the right of (25%, 75%), which would mean that if profit was considered less than thrice as important as $/RPM, then T2 should be selected. While this result was not independent of the weighting values, T2 was shown to dominate for a larger range of weightings than T1 dominates in Scenario 1. However, this was only the result from one possible combination of Taguchi's S/N and MCDM techniques.

The second approach examined multi-response signal to noise ration (MRSN), which could be described as a S/N formulation of OEC values (i.e., second approach). This approach is described by Equations 25, 26, and 27 in § 3.7.5. The results from evaluating T1 and T2 in Scenario 1 are shown in Figure 86, which are drastically different than the results shown for the OEC of S/N values (Figure 84). One of the main observations that can be made about this figure was that the values of MRSN for T1 and T2 approach zero as the weightings shift towards focusing entirely on $/RPM. Secondly, the technologies have near-identical MRSN values for the range

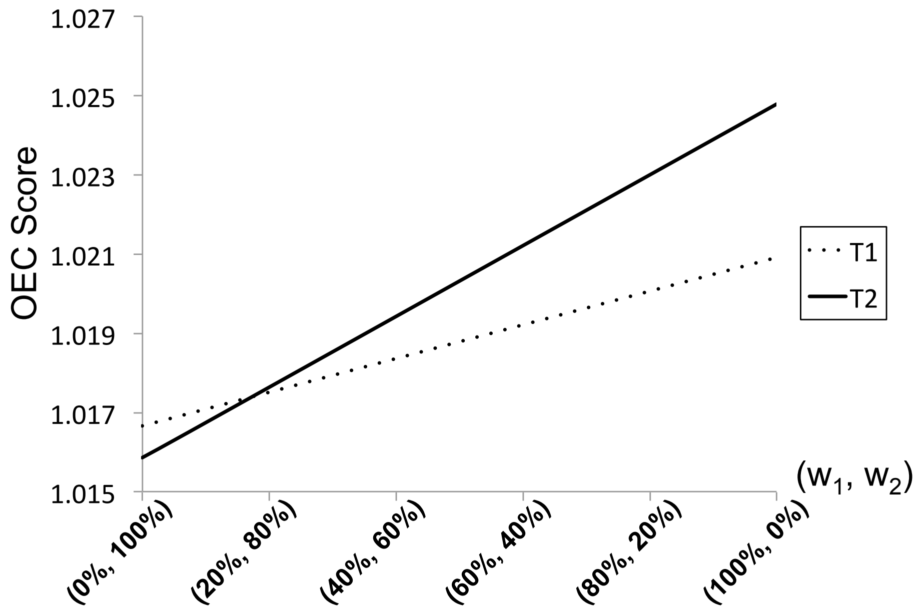

Figure 85: Scenario 2 with T1 and T2 being analyzed by an OEC of Taguchi's S/N values for each value metric with variable weightings.

of weightings (70%, 30%) to (90%, 10%). This result would suggest that for any weightings-preferences within that range, both technologies are equally preferred. A similar result is shown in Figure 87, which plots the MRSN values for the technologies in Scenario 2; however, this figure shows that the MRSN values are very similar for weightings that are between (30%, 70%) and (60%, 40%). While these results cannot be verified against real data, they were compared to the other approaches to provide some guidance. Before comparing these results, it was necessary to examine the results from the TOPSIS of S/N values (i.e., third approach).

Figure 88 show the results from the TOPSIS of S/N values (i.e., third approach) for the different technologies in Scenario 1. These results provide some interesting insight due to the TOPSIS formulation. Firstly, it is clear to see – from the slopes of the lines – that as the weightings shift towards preferring $/RPM compared to profit, T2 becomes more favorable and T1 exhibits the opposite behavior. This insight might be more beneficial to a decision-maker because it provides a clearer indication of the elasticities associated with each value metric. Secondly, a step in performing

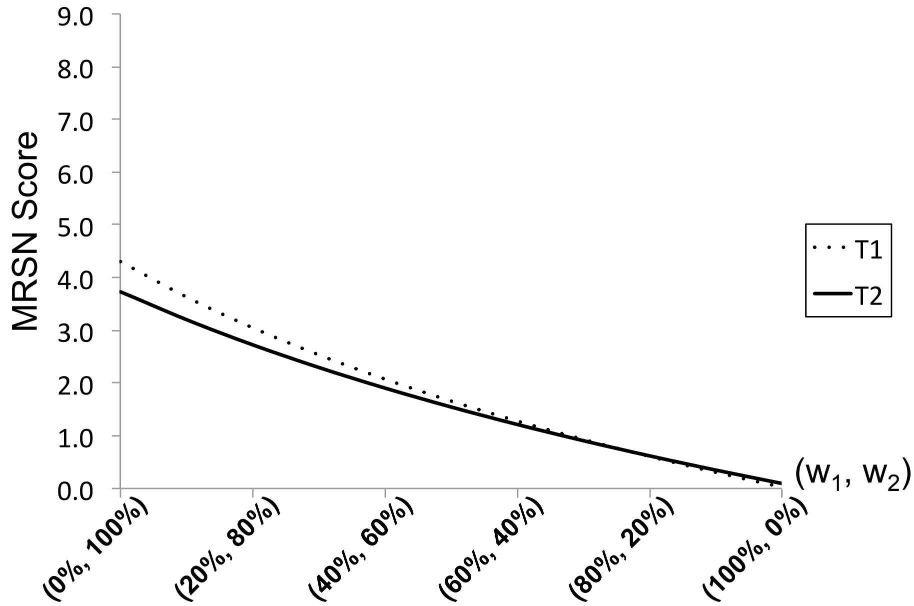

Figure 86: Scenario 1 with T1 and T2 being analyzed by MRSN with variable weightings.

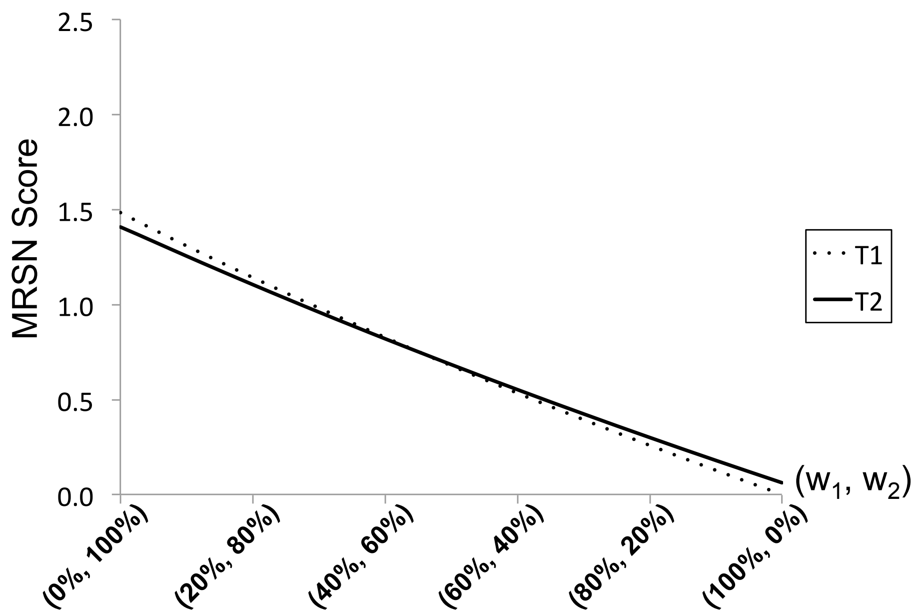

Figure 87: Scenario 2 with T1 and T2 being analyzed by MRSN with variable weightings.

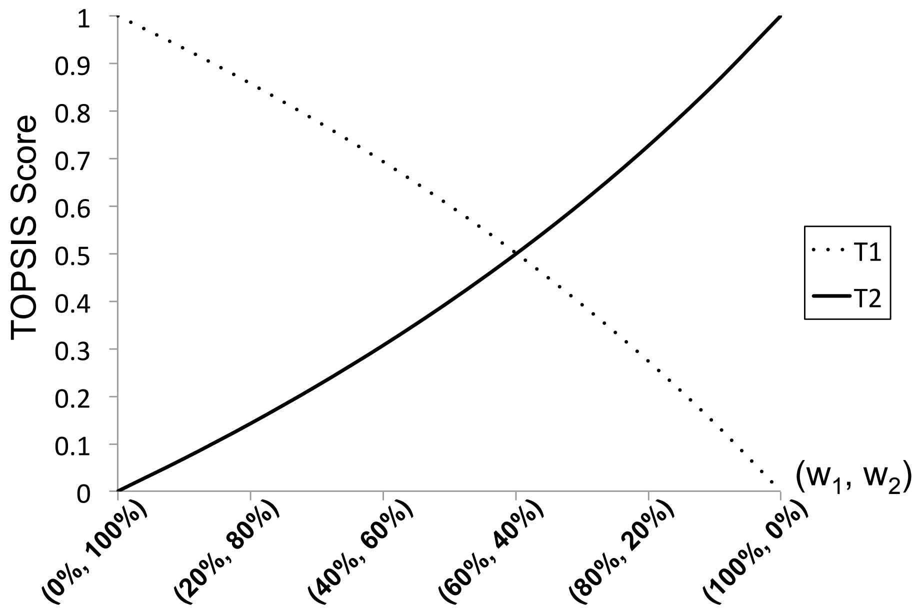

Figure 88: Scenario 1 with T1 and T2 being analyzed by a TOPSIS of Taguchi's S/N values for each value metric with variable weightings.

TOPSIS identifies a *positive ideal solution* from which to compare the data, and if an alternative was that *positive ideal solution* then it would have a TOPSIS score of unity. This means that for the weightings of (0%, 100%) T1 was the *positive ideal solution*, and for weightings of (100%, 0%) T2 was the *positive ideal solution*. Similar results are also seen in Figure 89, which shows the evaluations of the technologies in Scenario 2. The results from Scenario 2 show that T2 would be preferred as long as $w_2 \leq 4w_1$.

By showing and analyzing the results from the three different approaches of combining Taguchi's S/N formulation and MCDM techniques, these three techniques can be evaluated. While all three results show that the preferences of technologies for both scenarios is dependent on the relative weightings of the value metrics, the results from the OEC of S/N values and TOPSIS of S/N values show the same relative weightings for when T2 is preferred over T1 for each scenario. Not only does MRSN not show the same results, but it also shows lines that both approach zero as the weightings are shifted towards completely favoring profit. It was believed that this behavior was

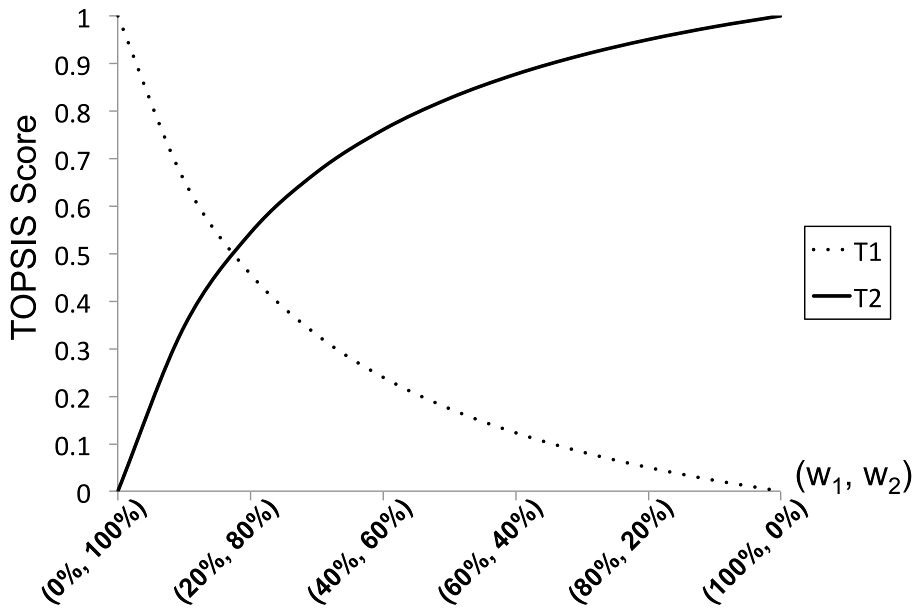

Figure 89: Scenario 2 with T1 and T2 being analyzed by a TOPSIS of Taguchi's S/N values for each value metric with variable weightings.

due to trying to maximize profit while trying to minimize $/RPM, which makes this approach not as favorable for the CoDeS Framework. Since none of the approaches could be verified as being ideal, the CoDeS Framework allows for any of the three techniques to be applied. However, since the OEC of S/N values and TOPSIS of S/N values produced the same result for this experiment, they may be preferred over the MRSN formulation. Furthermore, since TOPSIS is often cited as being a more robust technique compared to OEC, the TOPSIS of S/N values was selected as a preferred approach for the use cases analyzed in Chapter 5.

Before concluding Experiment 3, an enterprise solution was considered in order to examine its effects on the design space. The enterprise solution (E1) examined was assumed to be a manufacturing initiative that reduced the manufacturer's learning curve by 5% ($\lambda_{E1,MLC} = -5\%$). Instead of applying this enterprise solution to both technologies in each scenario, an optimal technology for each scenario was first selected. Since no prior information was known about the preferences of weightings, they were equally weighted at (50%, 50%) – examination of Figures 88 for Scenario

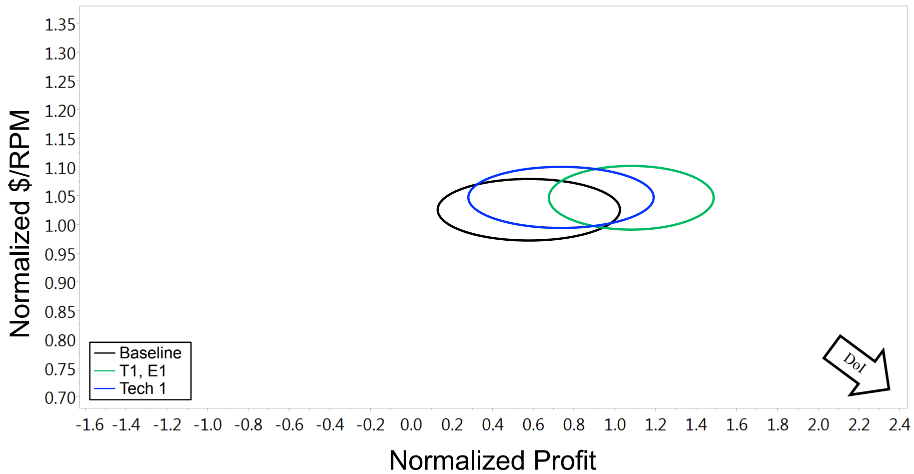

Figure 90: Ellipses showing variability in value metrics with infusion of T1 and implementation of E1 in Scenario 2 compared to both T1 and the baseline with no strategies.

1 and Figure 89 for Scenario 2 shows that at that weighting value T1 is preferred in Scenario 1 and T2 is preferred in Scenario 2.

Figure 90 shows the effects of the enterprise solution (E1) and T1 on the variability of the value metrics in Scenario 1. These effects were directly compared to the baseline (i.e., no strategies) result and the result of infusing on T1 in this figure. By coupling E1 and T1, the mean of normalized profit was higher than the geometric baseline. This is useful information because it means that further enterprise strategies, like decreasing the price to reduce $/RPM[†], could be infused to further improve the aircraft's performance in this scenario. The effects of this strategy was analyzed using the TOPSIS of S/N values approach and compared to the effects of T1 and T2 for variable weightings – these results are shown in Figure 91. The results from this analysis showed that T1 and E1 were almost always preferred to only T1 and T2, unless the weightings were heavily skewed towards favoring the $/RPM value metric.

The effects of E1 and T2 in Scenario 2 can be seen in Figure 92. The TOPSIS of S/N values technique was applied to this data and the results are shown in Figure 93.

[†]This specific strategy was detailed in Figure 23 of § 3.4.

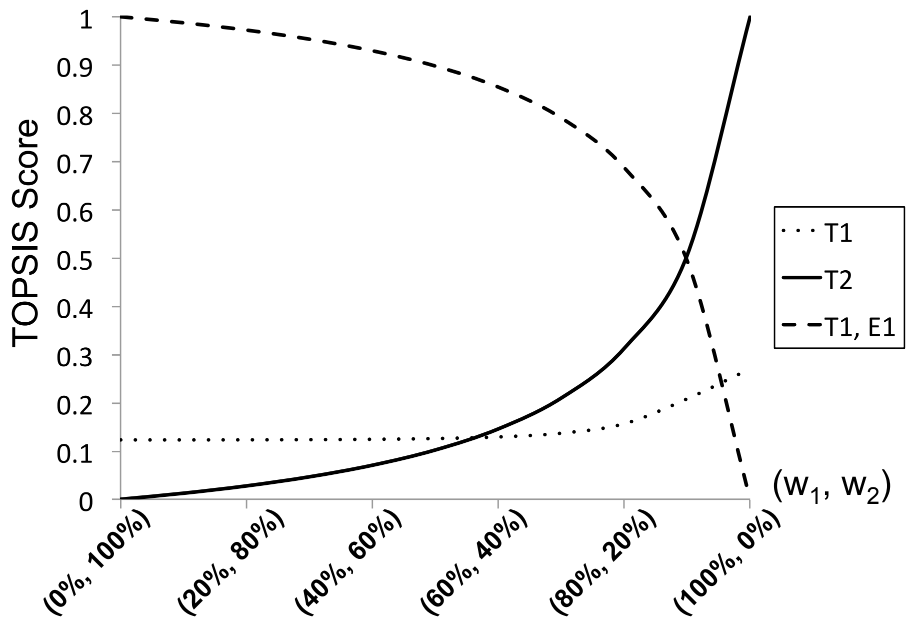

Figure 91: Scenario 1 with T1 and E1 being analyzed by Taguchi's S/N and TOPSIS with variable weightings.

The results were very similar to the results in Scenario 1 – the enterprise solution and technology combination were preferred to only technologies except for at extreme values of weighting $/RPM relative to profit. Further analysis of this result in both scenarios seems to be due to minute differences in $/RPM, which may be due to slight errors caused by the use of surrogate models. However, this error was not deemed to be a major concern because the extreme relationships between the weighting values are shown for theoretical completeness – if the $/RPM metric was weighted that heavily, there would be no need to consider the profit value metric.

The enterprise and technology combinations were also analyzed using the OEC of S/N values approach and the MRSN approach. The results from these analyses are shown in Appendix B. However, all of the approaches showed similar results for both scenarios. This was not expected based on the MRSN results from the evaluation of technologies. Regardless, the approach using TOPSIS was adopted as the preferred approach for this dissertation due to its prevalence in the aircraft design literature.

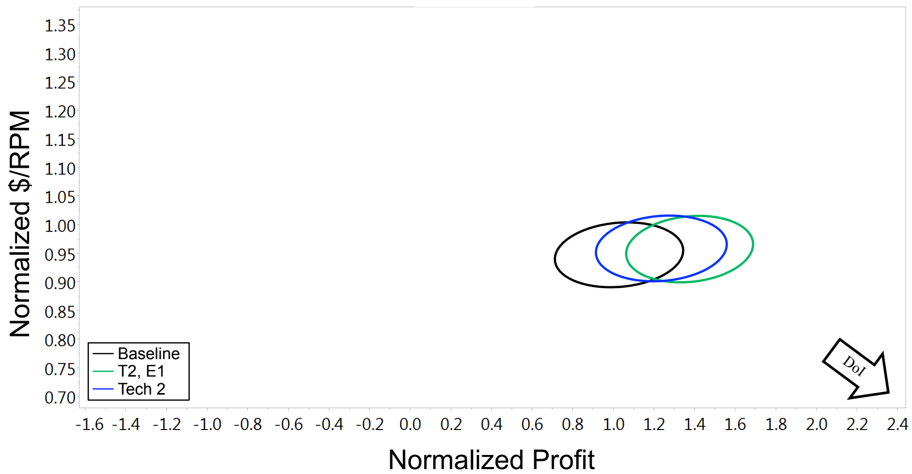

Figure 92: Ellipses showing variability in value metrics with infusion of T2 and implementation of E1 in Scenario 2 compared to both T2 and the baseline with no strategies.

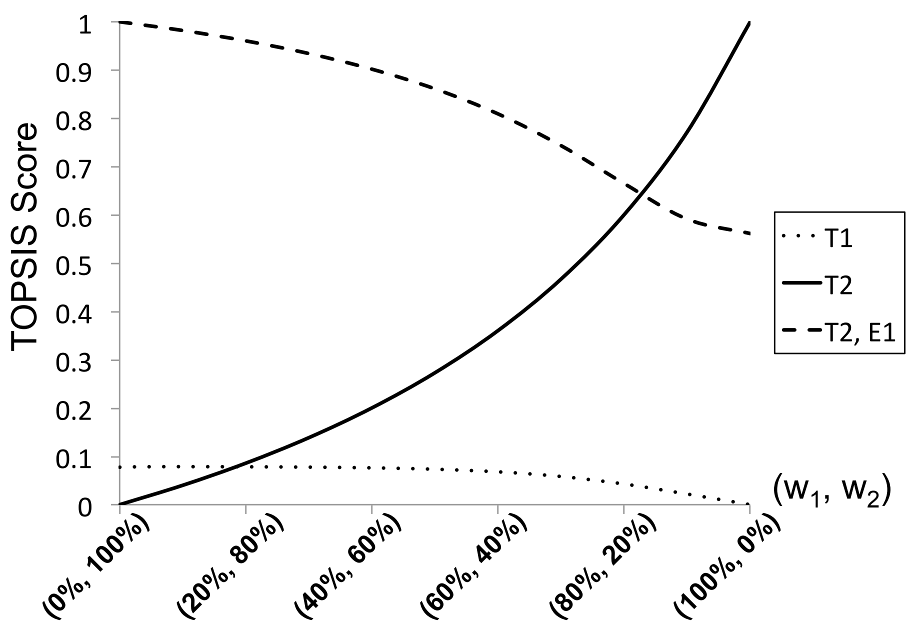

Figure 93: Scenario 2 with T2 and E1 being analyzed by Taguchi's S/N and TOPSIS with variable weightings.

While the results of Experiment 3 did not select a definitive approach, the results did highlight some differences that may influence the user's selection when applying the CoDeS Framework.

4.4 Summary of Chapter

This chapter described three experiments that were conducted in order to provide guidance in the implementation of the CoDeS Framework. Experiment 1 characterized the impacts of uncertainty by examining the impacts of single-variable, interactions, and different probability distributions on the variability of the value metrics. Furthermore, this experiment concluded showing the usefulness of scenario-based analysis. Experiment 2 was a canonical experiment that was conducted in order to determine a preferred approach for selecting between strategies that may have negative value metrics. While neither of the two transformations (shift-transformation and target-transformation) were shown to be superior, the experiment did allow for the development of three heuristics which should be applicable to any situation of analyzing negative value metrics with Taguchi's S/N formulation. Experiment 3 further analyzed the Taguchi's S/N formulation by examining three hybrid techniques that combined Taguchi's S/N and MCDM techniques. These techniques were: 1) OEC of Taguchi's S/N values, 2) Taguchi's S/N of OEC values (i.e., MRSN), and 3) TOPSIS of Taguchi's S/N values. While neither technique was shown to be superior, some differences between the results caused the third technique (TOPSIS of Taguchi's S/N values) to be selected for this dissertation; however, the CoDeS Framework could use either of the three techniques to select a strategy.

None of the experiments presented in this chapter examined the impacts of competition. This was intentionally done in order to increase the probability of gaining clear insight in to the results from each experiment. However, the main thrust of this dissertation was to analyze how accounting for competition may influence the conceptual design of an aircraft, which was the motivation for constructing the CoDeS Framework. To this end, the following chapter examined three *use cases* of the CoDeS Framework in order to demonstrate its capabilities and flexibility.

CHAPTER V

USE CASES

"I do not think that there is any other quality so essential to success of any kind as the quality of perseverance. It overcomes almost everything, even nature."
John D. Rockefeller [103]

The information presented in this chapter built on the results from the experiments discussed in Chapter 4. This chapter explored three example *use cases* of the CoDeS Framework. Each of these *use cases* examines a different aspect of the CoDeS Framework. Before analyzing these *use cases*, § 5.1 describes the general problem that was applied to all three *use cases* by describing the models used for the aircraft. In each *use case*, two OEMs are competing for market share. It is important to note that all three *use cases* represent notional scenarios, which may be motivated by real market data, but are not intended to represent actual behavior of any establish aircraft OEMs. The following is a brief description of each *use case*:

§ 5.2: Exploratory Enterprise Forecasting Explores an Ent-IES (§ 3.6.2) formulation to examine the application of the CoDeS Framework in a competitive duopoly – seeks to determine if a proposed enterprise solution for an entrant can *beat* the incumbent's design.

§ 5.3: Normative Enterprise Forecasting Explores an Ent-IF (§ 3.6.2) formulation to examine what enterprise solution would be necessary in order for an entant's design to *beat* the incumbent's design.

§ 5.4: Entering Asian Market Both firms are trying to enter the Asian market with competing aircraft, one already available in other markets and the other being developed – one utilizes only technologies, but the other seeks to use enterprise solutions in order to dominate this new market.

Each of these *use cases* is elaborated further in their respective sections. But it was necessary to describe the models that were used in each *use case*.

5.1 Background Information on Competitors

Some of the background information for each of the *use cases* was the same. All three examined examples of short-haul, single-aisle, narrow-body, 150-passenger class aircraft in the presence of a duopoly. The basic model used for these aircrafts was representative of a Boeing B737 [92], which was described in detail in § 4.1.1. While the Bertrand and Cournot duopoly models (§ 2.1) do often assume that firms are producing identical goods, this would not be a useful assumption to make for the analyzing the design of aircraft. While the basic model used was the same, modifications were made in order to simulate different OEMs and different aircraft. These differences are further elaborated by discussing the first four steps of the CoDeS Framework, which are identical for the first two *use cases* – the third *use case* mights slight modifications to the first four steps of the CoDeS Framework.

Step 1 – Establish the Need:

Airlines are looking to purchase a single-aisle, narrow-body, 150-passenger class aircraft. This aircraft is for domestic routes that average 1,000 nmi. This aircraft should be of conventional design in order to ensure ease of airport operations, decrease the difficulty for technicians to perform maintenance, and ensure a degree of commonality for operating the aircraft when compared to other aircraft.

Step 2 – Define the Problem:

While the five major areas of concerned were addressed in this section, one of the key elements – Define Scenarios of Interest – was not defined in this section. Instead, each *use case* included a definition for the scenario of interest.

1. **Define the Competitive Environment:** This market is characterized as a duopoly. An OEM (the Incumbent) already exist in this market and airlines are beginning to purchase their aircraft. Seeing an opportunity for growth, another OEM (the Entrant) begins the early phases of conceptual design to bring a concept to this market – the Entrant is using the CoDeS Framework so all analysis is from their perspective.

2. **Define the Geometric Variables & Their Ranges:** The thirteen geometric variables and their corresponding ranges are the same as the ones used in Experiment 1. This data can be seen in Table 8 of § 4.1.1.

3. **Define the Competitor's Geometric Baseline:** The Incumbent's aircraft is already in production. From reverse-engineering techniques, it was found that their geometric baseline was given by the third column of Table 19.

4. **Define Economic Noise Variables and Their Ranges:** Table 18 shows the economic noise values, their ranges, and the distribution shapes used to model them. A discussion about the distribution shapes can be found in § 4.2.4 – this discussion also motivated the particular ranges for some of the economic noise variables variables.

5. **Define Strategy Variables and Their Ranges:** The specific technology k-factors and enterprise λ-factors will be defined for each *use case*; however, the names of the technologies considered for both the Entrant and Incumbent are described below.

Table 18: Ranges and description of PDF used for Economic Noise Variables.

Economic Noise Variable:	Ranges	PDF Shape
Manufacturing Learning Curve	[-15%, +15%]	$\beta(5,2)$
Production Facility Costs	[0, $1 Billion USD]	$\beta(5,2)$
Inflation Rate	[-25%, 50%]	Uniform
Number of Aircraft Produced	[-50%, +15%]	Uniform
Price of Aircraft	[-15%, +15%]	$\beta(3,3)$
Load Factor	[-15%, +30%]	$\beta(5,2)$
Price of Fuel	[-25%, +50%]	$\beta(5,2)$

- Entrant
  - Composite Wing [88]
  - Natural Laminar Flow [65]
  - Geared Turbofan [95]
- Incumbent
  - New Engine Option (NEO) [92]
  - Winglets [176]

Step 3 – Establish Value Metrics:

The two value metrics that are used for this dissertation are normalized OEM profit and normalized $/RPM. The former serves as a surrogate metric for market share, and the latter as a surrogate metric for airlines' desire to purchase aircraft. This was discussed in detail in § 3.4.

Step 4 – Determine Geometric Baseline:

This step determines not only the Entrant's geometric baseline, but also establishes the Incumbent's geometric baseline. Since the Incumbent's design* was already in

*The Incumbent's design was modeled as being very geometrically similar to a Boeing B737.[92]

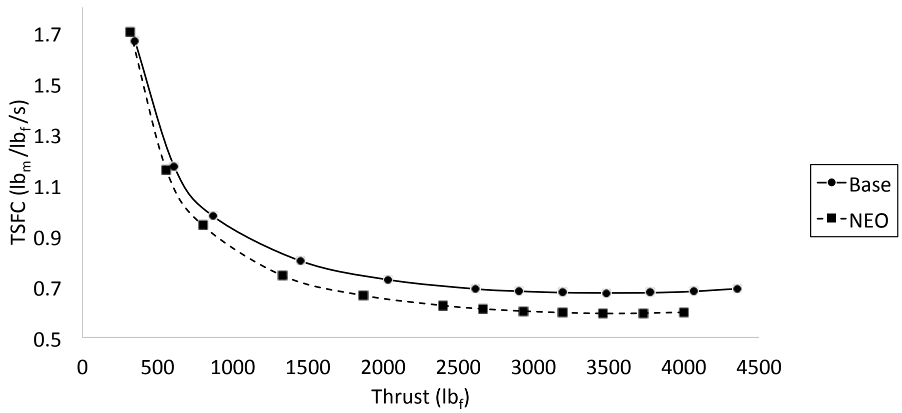

Figure 94: Comparison between the thrust and TSFC values at cruise conditions for the base engine and the NEO – each point represents a different throttle setting.

production, reverse engineering techniques were used to determine the values for each geometry variable. This table also shows the entrant's baseline geometry, which was the same as the one defined in § 4.2; as a reminder, this geometry was determined by using the NSGA-II process, which sought to optimize the profit and $/RPM values for the range of geometries specified in Table 8.

For simplicity, it was assumed that both aircraft use the same propulsion system. This was done in order to decouple the aircraft manufacturing competition problem from the aircraft engine competition problem. The propulsion system used has the same characteristics as the one described in § 4.1.1. The thrust and thrust-specific fuel consumption were described by Figure 43 at cruising altitude and speed. Each aircraft has two engines that each weigh 6,781.67 lb_m. Each engine has an installed thrust of 27,293.2 lb_f at sea-level. The NEO for the Incumbent produces the same thrust, but weighs only 6,403.77 lb_m. Furthermore, the NEO has a better thrust-specific fuel consumption, which can be seen in Figure 94.

Results of Model of Incumbent's Aircraft and Model of Entrant's Aircraft: A major difference in the models arose from the fact that one of the OEMs in all of the *use cases* already has an established design in market. Therefore, the model for

Table 19: Comparison between the incumbent's geometry and the entrant's geometry in the three *use cases*.

Geometric Variable	Entrant's Value	Incumbent's Value
Wing Area (ft^2)	1200	1408.48
Thrust to Weight Ratio	0.25	0.275
Aspect Ratio – Wing	10	9.741
Taper Ratio – Wing	0.34	0.284
Thickness to Chord – Wing Root	0.2	0.1693
Thickness to Chord – Wing Tip	0.15	0.0949
Wing Sweep Angle (^{o})	35	25.72
Aspect Ratio – Horizontal Tail	3	6.266
Taper Ratio – Horizontal Tail	0.155	0.203
Thickness to Chord – Horizontal Tail	0.07	0.109
Aspect Ratio – Vertical Tail	1.2	1.918
Taper Ratio – Vertical Tail	0.4	0.276
Thickness to Chord – Vertical Tail	0.09	0.115

this aircraft would not include the same RDT&E costs nor would it have the same baseline value of the manufacturer's learning curve. But this aircraft is still analyzed over the same twenty year production life cycle in order to ensure an "apples to apples" comparison between the profit value metrics.

In order to visualize the differences between these models, a deterministic analysis was conducted – this analysis assumed baseline values for all economic noise and strategy variables, except for the NEO strategy for the incumbent. The results of this analysis are shown in Figure 95. All of the results were normalized by the Entrant's geometric baseline. When comparing the Incumbent's geometric baseline to the Entrant's geometric baseline it is clear to see that the Entrant has a lower \$/RPM value. As stated previously in § 4.3.2, a difference of 0.01 in normalized \$/RPM equates to a difference of approximately \$330,000 per aircraft per year. If a relationship between \$/RPM and number of aircraft purchased were known, then it could be implemented in the model. This change in number of aircraft purchased would cause the Entrant's profit to increase (i.e., shift right), while causing the Incumbent's profit to decrease

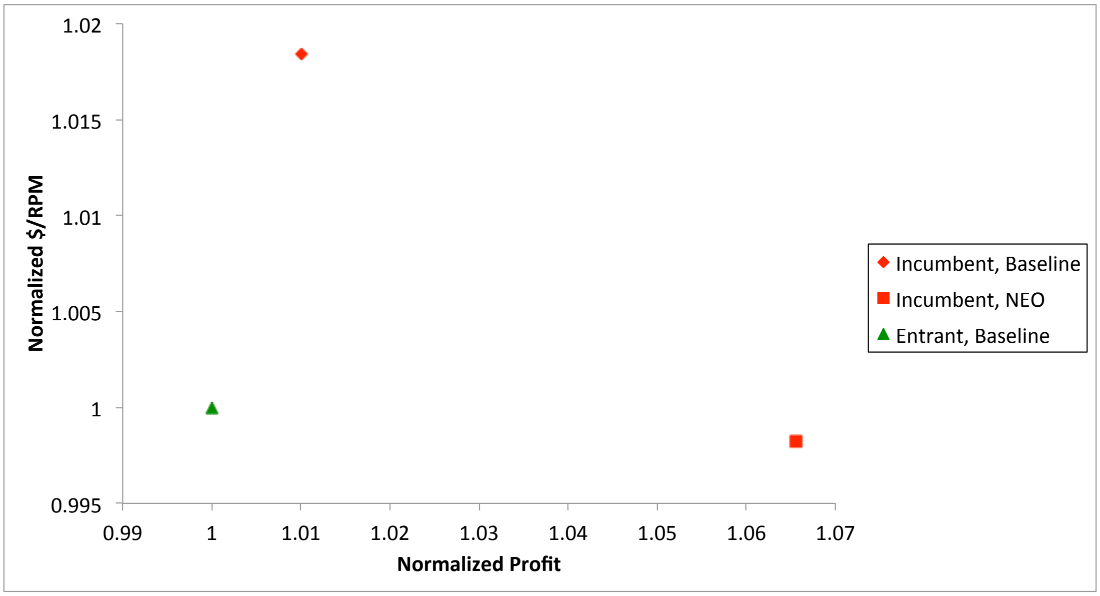

Figure 95: Deterministic comparison between Entrant's geometric baseline design, Incumbent's geometric baseline design, and the Incumbent's geometric baseline design with NEO.

(i.e., shift left). However, since it would be naïve to believe than an Incumbent would not try to oppose the Entrant from entering the market, Figure 95 also shows the deterministic result os a NEO strategy. Not only is the $/RPM value lower for the Incumbent's NEO, but the estimated profit is much higher – this could result in a situation where the Incumbent could offer price discounts to further incentivize airlines to purchase their aircraft. As previously stated in § 3.4 and shown in Figure 23, this could result in the Incumbent gaining even more market share.

While the deterministic results do provide some insight into the competitive nature of the problem, they do not fully address the difficulty associated with this problem – the uncertainty. The possible impacts from uncertainty are shown in Figure 96. From this figure, it is clear to see that the uncertainty, especially related to the competitor, is so large that it is almost impossible to have confidence in any decision made. While Figure 96 serves as a representation from what may happen in the presence of uncertainty, the *use cases* in the following sections more thoroughly address concerns associated with uncertainty.

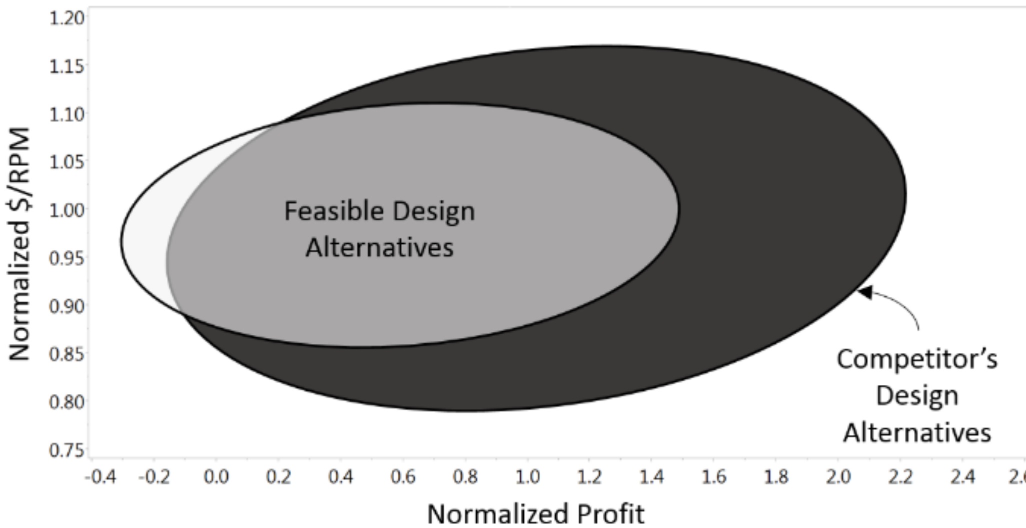

Figure 96: Depiction of how uncertainty can reduce the ability to make a decision.

Before examining the results of the *use cases* it was necessary to examine the general case of how uncertainty impacts this design from the Entrant's perspective only. Using the information from Table 18, the impacts from the economic noise variables was quantified. The variability of the value metrics from these economic noise variables are shown in Figure 97. It is important to note that the results in this figure represent a theoretical twenty-year production life cycle, but in actuality an OEM would probably cancel an aircraft program that did not reach its breakeven year after a certain period of time; however, this logic was not the focus of this dissertation so it was assumed all aircraft designs and strategies are evaluated over a twenty-year period. Regardless, the large variability shown in Figure 96, it is obvious that mitigating steps need to be taken in order for the Entrant to have confidence in their decisions. The results of Research Question 3, which were further examined in § 4.2.4, showed that scenarios could be used to mitigate the effects of this uncertainty. Therefore, each *use case* examined the implications of different scenarios and how they impacted the selection of a preferred strategy.

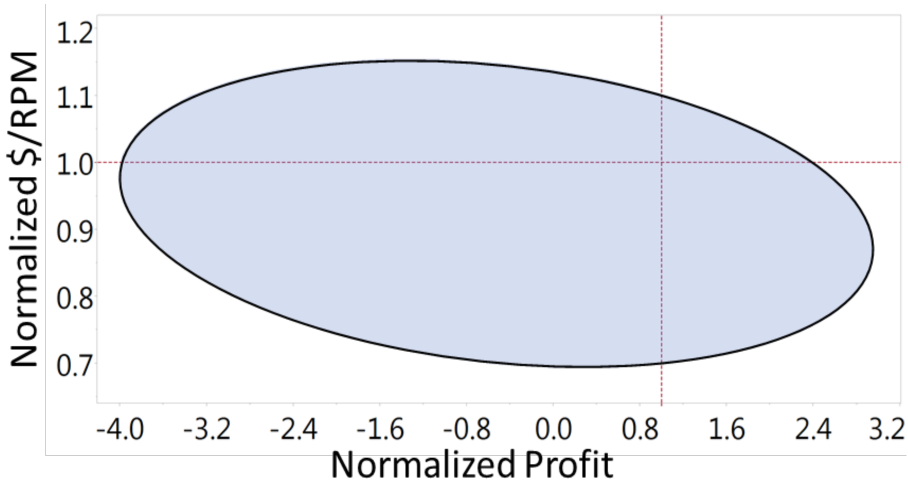

Figure 97: Effects from the full range of economic noise variables on both value metrics, which are described in Table 18.

5.2 Use Case 1: Exploratory Forecasting

Use Case 1 examined the use of exploratory forecasting for an enterprise solution. As discussed in the previous section, the effects from the full range of uncertainty associated with the economic noise variables causes significant variability in the value metrics. To mitigate the effects of this uncertainty, it was necessary to introduce a scenario, which was probabilistically-defined by the data in Table 20. This completes part of the missing information from Step 2 of the CoDeS Framework, which was mostly covered in § 5.1. The variability in the value metrics from this scenario are compared to the variability in the value metrics from the uncertainty in Figure 98 – Figure 99 shows a zoomed in version of just an ellipse defining the scenario.

There was still one element of information missing from Step 2 of the CoDeS Framework, and that was the definition of strategy variables and their ranges. The first strategies to be examined were technologies for infusion into the Geometric Baseline design. Three technologies were considered: Composite Wing (T1) [88], Natural Laminar Flow (T2) [65], and Geared Turbofan (T3) [95]. Since the scenario was probabilistically-defined, these technologies were deterministically-defined by using

Table 20: Description of probabilistic scenario evaluated in Use Case 1.

Economic Noise Variable	Range
Manufacturing Learning Curve	[-3%, +5%]
Production Facility Costs	[$800 Million, $1 Billion USD]
Inflation Rate	[-5%, +3%]
Number of Aircraft Produced	[700, 800]
Price of Aircraft	[-5%, +5%]
Load Factor	[0, +10%]
Fuel Price	[-5%, +5%]

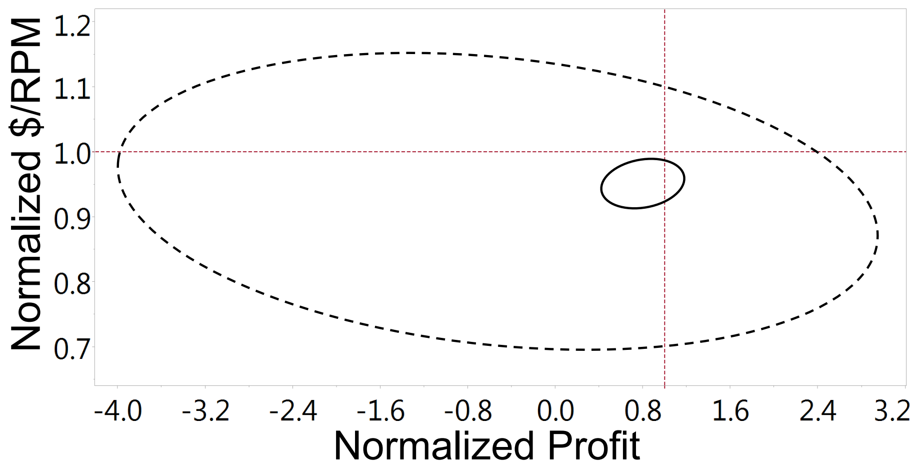

Figure 98: Variability in the value metrics from the full uncertainty of the problem (dotted line) compared to the variability from the scenario (solid line) described in Table 20.

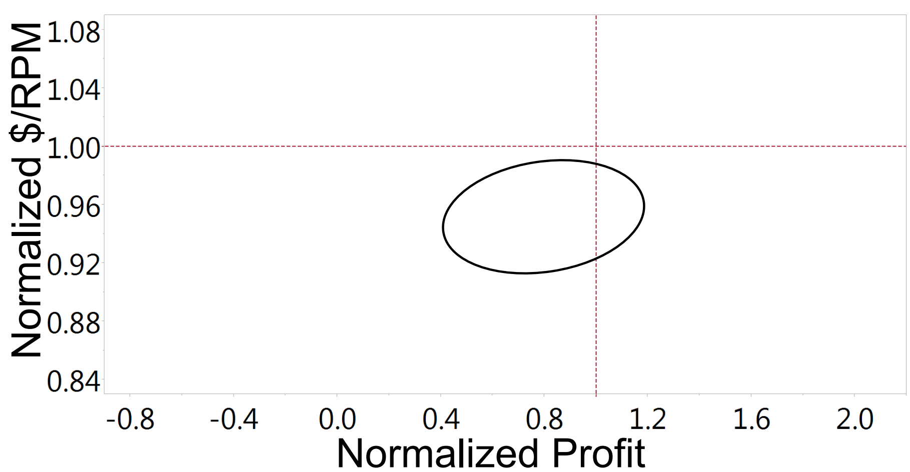

Figure 99: Zoomed in look at the probabilistically defined scenario of Use Case 1 described in Table 20.

Table 21: Description of three deterministic technologies evaluated for the entrant in Use Case 1.

Technology k-factor Value	Composite Wing (T1) [88]	Natural Laminar Flow (T2) [65]	Geared Turbofan (T3) [95]
$k_{RDT\&E}$	+0.5%	+5%	+3%
$k_{O\&S}$	+0.5%	–	+2%
k_{WingWt}	-10%	–	–
$k_{MLC-Wing}$	+2%	–	–
$k_{D,induced}$	–	-10%	–
$k_{D,profile}$	–	-5%	–
k_{EngWt}	–	–	-5%
k_{TSFC}	–	–	-10%
k_{Util}	-0.5%	–	-0.5%

point-estimates of their impacts – the values of the technology k-factors are shown in Table 21. While these technologies are not necessarily incompatible, it was assumed that the Entrant was only willing to invest in one technology.

Step 5 – Evaluate Strategy Alternatives:

These technology strategies were investigated using the M&S environment, which was composed of surrogate models created from the FLOPS and ALCCA M&S environments. The effects from each technology are shown in Figure 100 – as a reminder, profit should be maximized and \$/RPM minimized, which is indicated by the direction of improvement (DoI) arrow on the figure. This figure shows that T2 has lower \$/RPM values, on average, but that T1 and T3 may have slightly larger profit values. However, it is clearly seen that no technology clearly dominates the other technologies. As stated earlier, Taguchi's S/N formulation can be used in order to help discern differences between these technologies and then a MCDM technique, like TOPSIS, can be used to help select and optimal technology.

The results from applying TOPSIS to the S/N values for each technology are

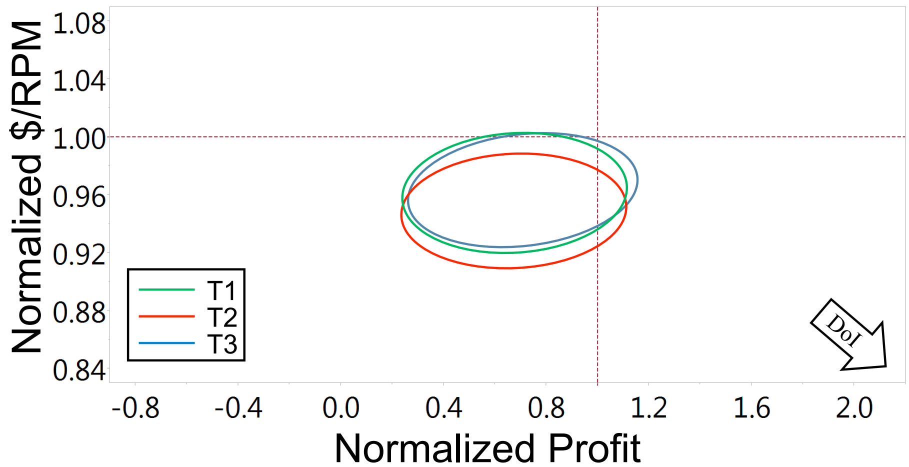

Figure 100: Ellipses that represent the impacts in Use Case 1 from each of the technologies defined in Table 21.

shown in Figure 101. The results from this figure indicate some interesting trends. Firstly, T1 seems to be almost completely dominated by the other two technologies, which suggest that T1 should not be selected, regardless of the weightings on the value metrics. Another interesting trend is the trade in preferences between T2 and T3 – at low preferences for $/RPM, T3 is strongly preferred, but as $/RPM has larger significance, T2 becomes preferred. Since knowledge of preferences were not known, an equal weighting for each value metric would result in T2 being preferred; this equal weighting is shown by the vertical black line in Figure 101. However, before finalizing selection of a preferred technology at this step, the technologies were first compared to the Incumbent's design – if one, two, or all of the technology options clearly dominated the Incumbent's design, then there would be no need to use TOPSIS.

Step 6 – Compare to Competitor's Design:

As previously stated, it would be naïve to assume that the Incumbent would not try to adopt some strategy to prevent the Entrant from entering the market. As previously stated, the Incumbent and Entrant have different technologies available based on their different phases of the product life cycle. The Incumbent cannot select

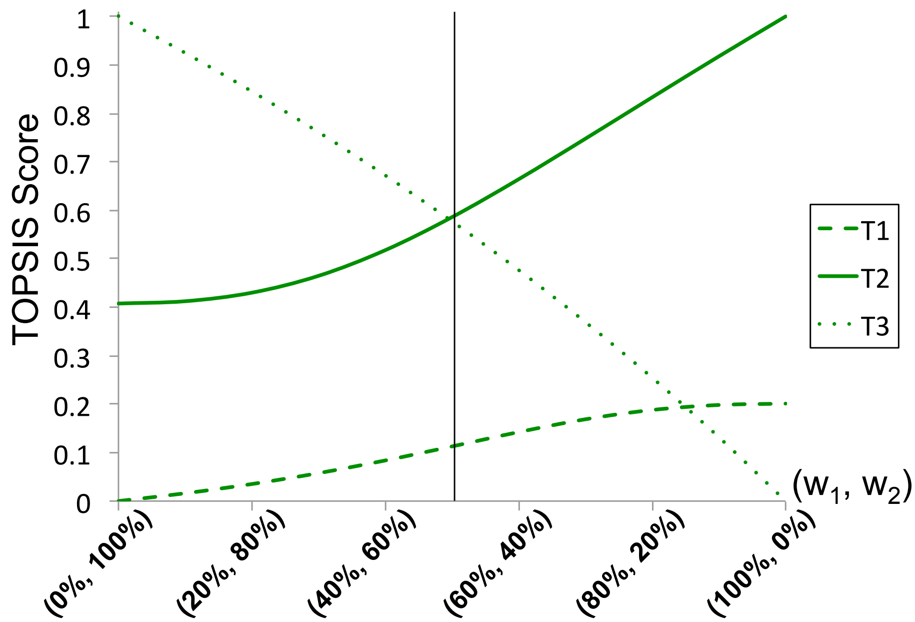

Figure 101: Results from TOPSIS of S/N values in Use Case 1 with variable weightings to select a preferred technology option for the Entrant. The vertical black line shows the point of both value metrics being equally weighted.

between the technologies in Table 21, but instead can use a new engine option (NEO) and winglet. A comparison between the NEO engine and the base engine were shown in Figure 94 of § 5.1. The winglet was assumed to reduce the induced drag by 5% (i.e., $k_{D,i}$=-5%) and increase the weight of the wing by 1% (i.e., k_{WingWt}=+1%). [176] This combination of strategies was referred to as NEO+ and only available to the incumbent.

Instead of comparing the Incumbent's NEO+ design to the Entrant's technology strategy options by showing their effects on the variability of the value metrics, Figure 102 shows these effects after applying Taguchi's S/N formulation. From this figure, it can be clearly seen that the Incumbent's NEO+ strategy dominates all of the technology options for the Entrant. There was no need to apply a TOPSIS analysis to these data because the results would clearly indicate that the Incumbent's NEO+ option is preferred, regardless of the weightings selected.

However, it was shown in Figure 101 that T2 would be preferred for the Entrant

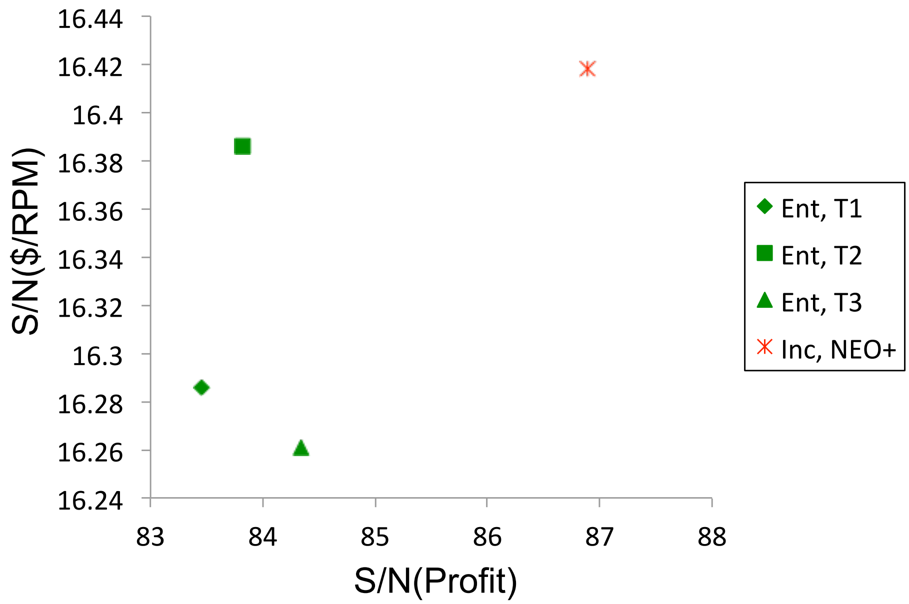

Figure 102: Scatter plot comparison of the S/N values of the value metrics for the technology options compared to the Incumbent's design with NEO and winglet technology strategies (NEO+) – the Incumbent's alternative dominates all technology strategies from the Entrant.

when equal weightings were applied to the value metrics. Figure 103 shows a direct comparison between only the Entrant's T2 strategy option and the Incumbent's NEO+ strategy option. This figure allows for clear examination of how each of these strategies impact the variability of the value metrics. It can be seen that the Incumbent's NEO+ option earns a higher profit on average and has better performance in \$/RPM values with a slightly lower mean and tighter variability.

To further examine the differences between these aircraft designs, a study was conducted in order to examine the effects of an uncertainty imbalance. Figure 104 shows the results of this study. The top graph in this figure shows the case where no uncertainty exists in the Entrant's T3 option compared to the scenario-uncertainty shown in the Incumbent's NEO+ option – this was done by collapsing the variability of the scenario to zero and using the midpoint for each economic noise variable to deterministically-define the scenario. The bottom graph in this figure shows the reverse case where no uncertainty exists for the Incumbent. While it is unlikely that

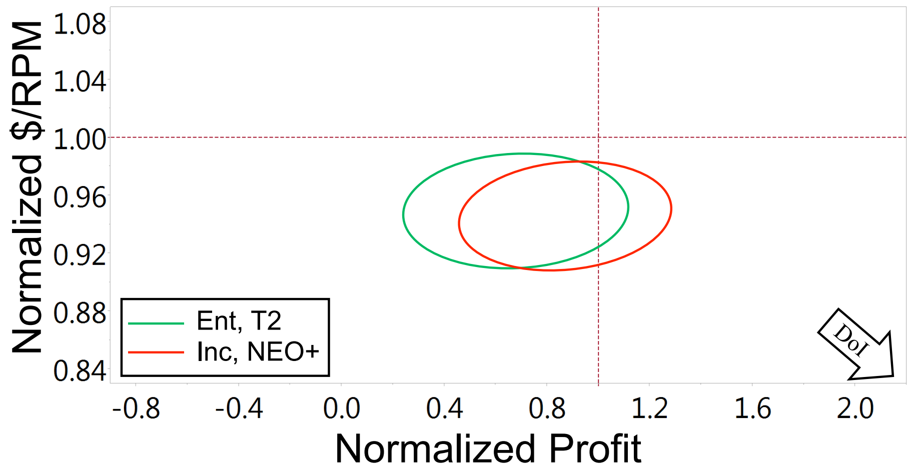

Figure 103: Ellipses showing variability in the value metrics in Use Case 1 for the Entrant with natural laminar flow strategy option compared to the Incumbent NEO+ option.

either of these situations would occur, it provides interesting insight into the nature of this problem. The top graph of Figure 104 shows that the Incumbent's ellipse completely dominates the Entrant's point. Furthermore, the bottom graph shows that a portion of the Entrant's ellipse is in the preferred direction compared to the Incumbent's point-solution.

Step 7 – Make a Decision:

The final step of the CoDeS Framework has two options: 1) Terminate, or 2) Iterate. Since the results from Step 6 of the CoDeS Framework showed that the Incumbent's design would be preferred, a rationale decision-maker would iterate in order to see if other strategies would result in a better design option for the Entrant. This should include the investigation of enterprise options.

***Re*-Step 5 & 6:**

Based on past experience, the Entrant knows that it could implement an in-house manufacturing initiative to reduce the learning curve by 5% (i.e., λ_{MLC}=-5%) – this

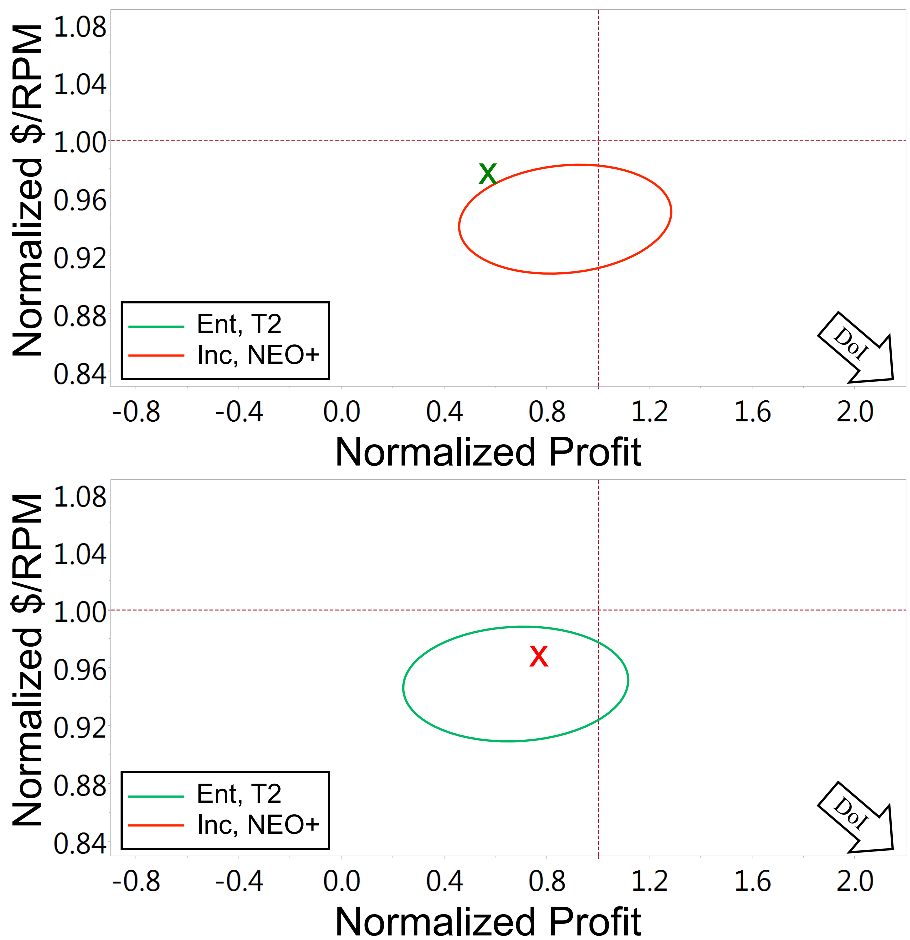

Figure 104: Comparison between Entrant's T2 option and Incumbent's NEO+ option by examining cases of uncertainty imbalance in Use Case 1.

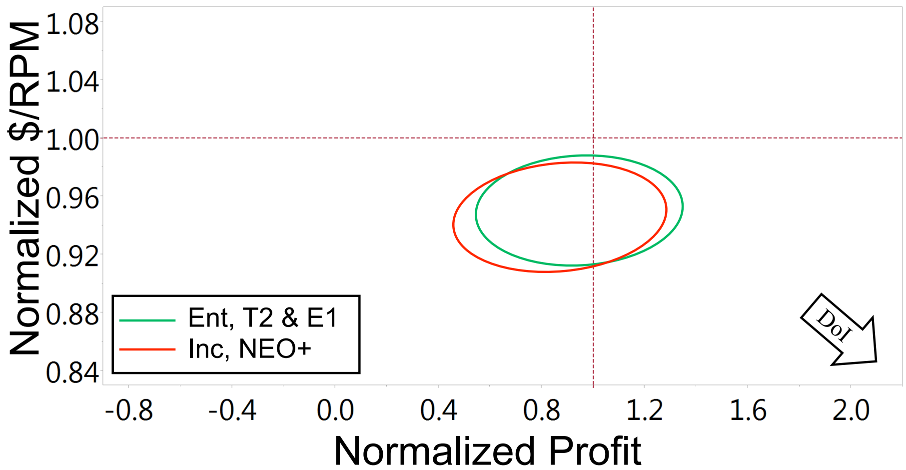

Figure 105: Ellipses showing variability in the value metrics in Use Case 1 for the Entrant with natural laminar flow technology and manufacturing initiative strategies compared to the Incumbent NEO+ option.

enterprise solution, which was called E1, was further investigated. The analysis of the manufacturing initiative was conducted using the M&S environment and the Ent-IES formulation. E1 was investigated in conjunction with T2 in order to keep the benefits of the natural laminar flow technology, but decrease the costs associated with manufacturing. The effects of E1 and T2 can be seen in Figure 105 where their impacts were also compared to the Incumbent's NEO+ option. From this figure, it can be seen that the profit of the Entrant has increased, but E1 did not affect the variability of the $/RPM value metric.

Even though E1 only improved the expected profit for the Entrant's design, this improvement was enough to make the design more preferred to the Incumbent's NEO+ option. This result is shown in Figure 106 where a TOPSIS analysis of Taguchi's S/N formulation for the value metrics was conducted with variable weightings. This figure shows that the Entrant T2 & E1 strategy options were preferred to the Incumbent's NEO+ strategy option for almost all values of the weightings.

***Re*-Step 7:**

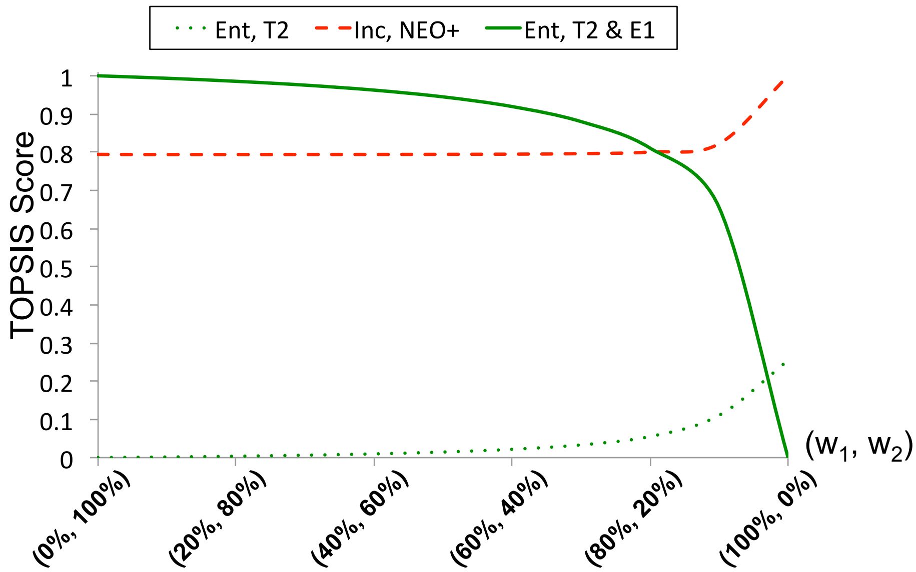

Figure 106: Results from TOPSIS of S/N values with variable weightings to determine if inclusion of manufacturing initiative in Use Case 1 causes Entrant's design to *beat* Incumbent's design.

While E1 did not improve the $/RPM value metric, it did offer significant improvement in the profit value metric. By comparing the strategy options to the Incumbent's strategy option, it was shown that the Entrant's design was more preferable for most weightings of the value metrics. Furthermore, it has been previously discussed that having a higher estimated profit could allow for the Entrant to reduce the cost of their aircraft, which would positively impact the $/RPM value metric – this could be considered another enterprise solution. While Use Case 1 did not examine any other enterprise options, Use Case 2 used an Ent-IF formulation in order to normatively explore the impacts of various enterprise strategies, including reduction of price.

5.3 Use Case 2: Normative Forecasting

Use Case 2 examined the impacts of normative forecasting in order to determine what enterprise solutions or combination of enterprise solutions would provide the highest likelihood of the Entrant's design being preferred over the Incumbent's design. Use Case 2 utilized the first four steps of the CoDeS Framework, which were described in

Table 22: Description of probabilistic and deterministic scenario evaluated in Use Case 2.

Economic Noise Variable	Probabilistic Ranges	Deterministic Value
Manufacturing Learning Curve	[+3%, +10%]	+6.5%
Production Facility Costs	[$100, $350 million USD]	$225 million USD
Inflation Rate	[0, +10%]	+5%
Number of Aircraft Produced	[600, 700]	650
Price of Aircraft	[-5%, +5%]	Baseline
Load Factor	[-10%, +10%]	Baseline
Fuel Price	[0, +15%]	+7.5%

§ 5.1. Also similar to Use Case 1, Use Case 2 used scenario-based analysis in order to mitigate the effects of uncertainty. The probabilistically-defined scenario is described in the center column of Table 22. The deterministically-defined scenario in the third column of this table is explained during Step 5 of the CoDeS Framework.

Step 5 – Evaluate Strategy Alternatives:

As opposed to Use Case 1, which evaluated deterministically-defined technologies, Use Case 2 used probabilistically-defined technologies. While the same three technologies were evaluated, the k-factor impacts of these technologies are shown in Table 23. The variability in the k-factors were approximated based on estimates about the time required to mature technologies – since a literature review described natural laminar flow (T2) has requiring more time to mature to the point of implementing on an aircraft, it has the largest variability in k-factor impacts. While a detailed discussion on the variability of k-factors was outside the scope of this dissertation, both Kirby [93] and Gaitan [69] provide detailed descriptions about these variabilities.

The impacts of the probabilistically-defined scenario and the probabilistically defined technologies on the design space are shown in Figure 107. While it can be seen that the probabilistically-defined scenario significantly reduces the variability in

Table 23: Description of three probabilistic technologies evaluated for the entrant in Use Case 2.

Technology k-factor Value	**Composite Wing (T1)**	**Natural Laminar Laminar Flow (T2)**	**Geared Turbofan (T3)**
$k_{RDT\&E}$	[0, +1%]	[+3%, +7%]	[+2%, +4%]
$k_{O\&S}$	[0, +1%]	–	[+1%, +3%]
k_{WingWt}	[-10.5%, -9.5%]	–	–
$k_{MLC-Wing}$	[+1.5%, 2.5%]	–	–
$k_{D,i}$	–	[-12%, -8%]	–
$k_{D,p}$	–	[-7%, -3%]	–
k_{EngWt}	–	–	[-6%, -4%]
k_{TSFC}	–	–	[-11%, -9%]
k_{Util}	[-1%, 0]	–	[-1.5%, 2.5%]

each value metric, compared to the effects of full uncertainty, this definition for the scenario was not used for the remainder of Use Case 2. Instead, the deterministically-defined scenario and probabilistically-defined technologies were used – a zoomed in figure of these impacts are shown in Figure 108. From this figure, it can be seen that this scenario results in the presence of negative values for the normalized profit value metric. This means that the insight gained from Experiment 2 (§ 4.3.1) was used in order to allow for accurate Taguchi S/N results for comparing the impacts of the technologies.

As stated in Experiment 2, either a shift-transformation or a target-transformation could be used to account for these negative values; however, it should be restated that either transformation must be applied to all of the data (i.e., each technology ellipse) in order to retain consistency in the results. While both transformation yielded the same results, only data from the shift-transformation was presented in order to maintain positive S/N values for plotting purposes. Using the heuristics suggest in § 4.3.1, the minimum of all the data from the technology ellipses was found to be approximately -15% of the Geometric Baseline so a shift of +20% of the Geometric

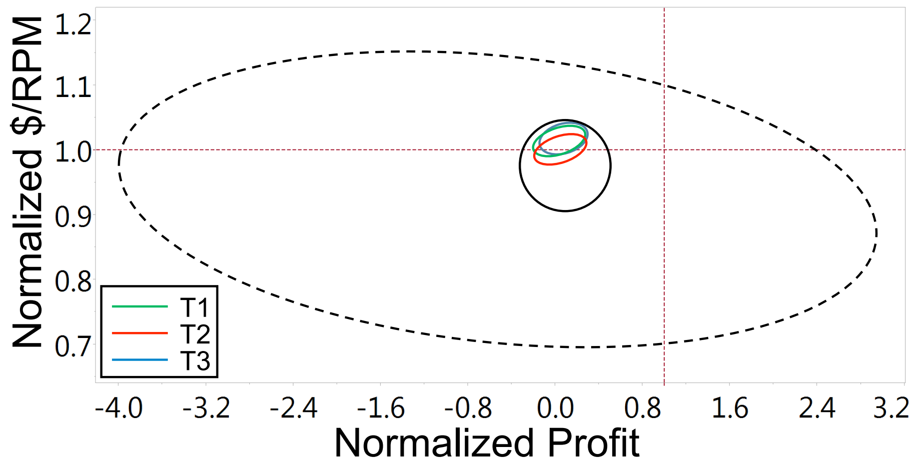

Figure 107: Comparing the variability in the value metrics from the full uncertainty (dotted line) to the probabilistically defined scenario from Table 22 (solid black line) to the combination of deterministically-defined scenario (Table 22) and probabilistically-defined technologies from Table 23.

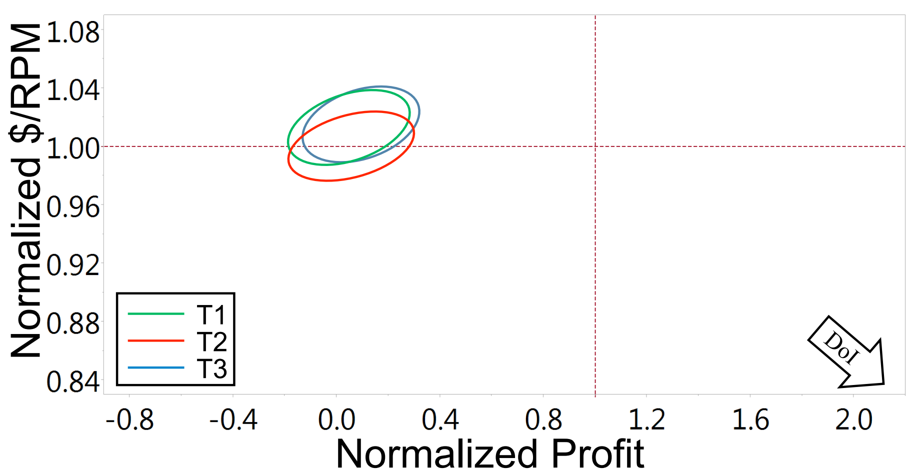

Figure 108: Evaluating impacts from probabilistically-defined technologies (Table 23) on the value metrics.

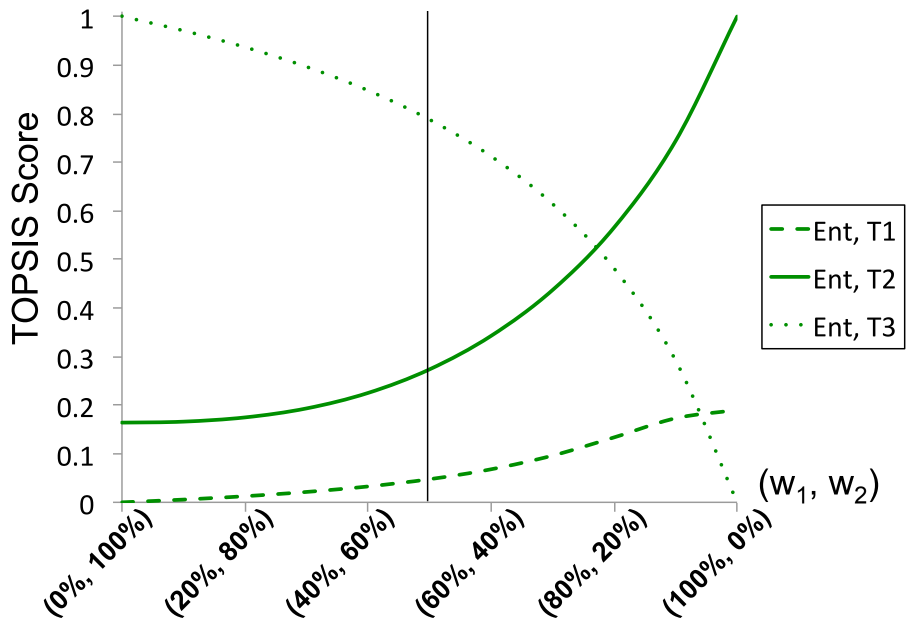

Figure 109: Results from TOPSIS of S/N values with variable weightings to select a preferred technology option for the Entrant. The vertical black line shows the point of both value metrics being equally weighted.

Baseline was used. After applying the shift-transformation to the data, a TOPSIS of S/N values was performed with variable weightings for all three technologies. The results from this evaluation are shown in Figure 109. These results show that T1 is dominated by both T2 and T3 and should not be selected, regardless of the weightings. Furthermore, these results show that T3 was preferred for most of the weighting values – when the weightings for each value metric are equal, which is shown by the black vertical line in Figure 109, then T3 (Geared Turbofan) was preferred. However, all three technologies were compared directly to the Incumbent's NEO+ strategy to see if any of the technologies would cause the Entrant's design to be preferred over the Incumbent's design.

Step 6 – Compare to Competitor's Design:

The Entrant's technologies were compared to the Incumbent's NEO+ alternative in the same manner as Use Case 1, but the same shift-transformation was applied to the

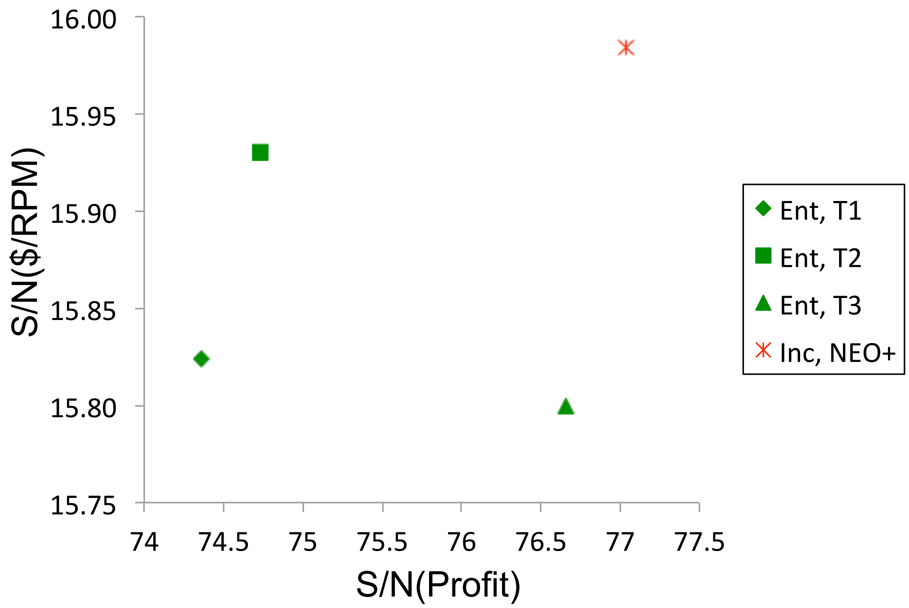

Figure 110: Scatter plot comparison of the S/N values of the value metrics for the technology options compared to the Incumbent's NEO+ design – the Incumbent's design dominates all strategy alternatives.

Incumbent's profit values for consistency. The Incumbent's technology k-factors were modified to represent uncertainty in their impacts – even though the technology was mature, the size of the winglet was unknown to the Entrant. Since the impacts of the winglet are dependent on its size [176], the Incumbent's technology k-factors were modified as follows: $k_{D,i}$ = [-7%,-3%] and k_{WingWt} = [+0.5%, +1.5%]. The results from this comparison are shown in Figure 110. This figure clearly shows that the Incumbent's NEO+ alternative dominates all of the Entrant's technology options.

Since T3 was selected from the TOPSIS analysis conducted in Step 5 of the CoDeS Framework, this technology's impact on the variability of the value metrics was directly compared to the Incumbent's NEO+'s impact. The resulting ellipses are shown in Figure 111. These results showed that the Incumbent's design was not only shifted in the direction of improvement (DoI), but also seemed to have a more narrow ellipse in general.

To further analyze these data, the variability in the technology k-factors for the

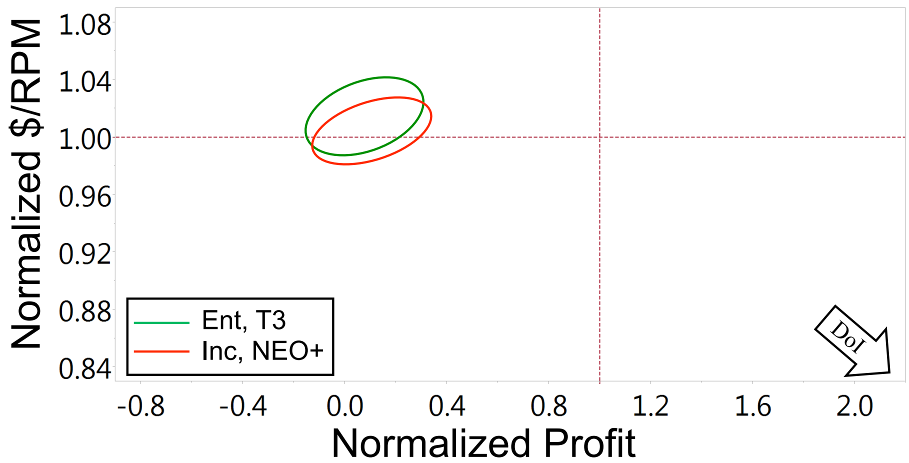

Figure 111: Ellipses showing variability in the value metrics in Use Case 2 for the Entrant with the geared turbofan strategy option compared to the Incumbent NEO+ option.

Entrant and Incumbent were reduced to zero. The effects of this study are shown in Figure 112. In the top graph of this figure, it can be seen that most of the Incumbent's ellipse dominates the Entrant's point-design. This graph most closely represents reality because it can be interpreted as the Entrant having complete knowledge of their design, but uncertain knowledge about the Incumbent's design. The bottom graph of Figure 112 describes the opposite situation where the Entrant has full knowledge of the Incumbent's design, but is uncertain about the impacts of their own design. From this graph, it can be seen that the Incumbent's NEO+ point-design dominates most of the Entrant's ellipse.

Step 7 – Make a Decision:

The final step of the CoDeS Framework has two options: 1) Terminate, or 2) Iterate. Since the results from Step 6 of the CoDeS Framework showed that the Incumbent's design would be preferred, a rationale decision-maker would iterate in order to see if other strategies would result in a better design option for the Entrant. This should include the investigation of enterprise options.

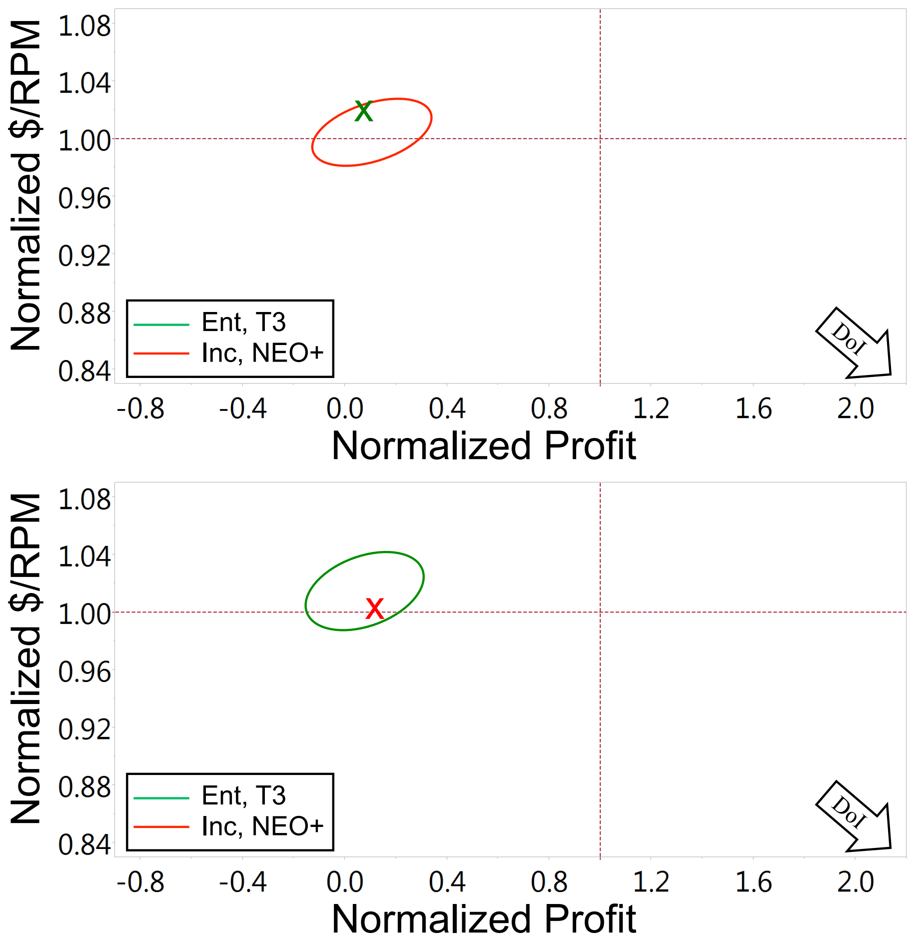

Figure 112: Comparison between Entrant's T3 option and Incumbent's NEO+ option by examining cases of uncertainty imbalance in Use Case 2.

Table 24: Description of three different normative enterprise manufacturing options' impacts.

Enterprise Number	λ_{MLC} **Value**
Enterprise 1 (E1)	-1%
Enterprise 2 (E2)	-3%
Enterprise 3 (E3)	-5%

***Re*-Step 5:**

Using the Ent-IF formulation, this step examined the impacts of three different enterprise solutions in order to determine whether they could help provide a more competitive alternative to the Incumbent's NEO+ option. All of these enterprise solutions examined notional manufacturing initiatives and their impacts are described in Table 24. This analysis was conducted in order to determine how much manufacturing would need to decrease in order to ensure that the ellipse was completely positive. This would allow for the OEM to utilize a fourth enterprise solution that is described at the end of this step.

Figures 113, 114, and 115 show the results of E1, E2, and E3, respectively. All of these figures compare the specific enterprise solution to the Entrant's design with T3. Figure 113 shows that E1 shifts the Entrant's ellipse to the right, but not enough for all of the profit values in the ellipse to be positive. Figure 114 illustrates how E2 causes a larger shift than E1 resulting in all of the profit values to be positive, but there is too small of a margin between the minimum value and zero. Figure 115 shows that E3 not only results in all of the profit estimates to be positive, but provides a margin of approximately 10% of the Geometric Baseline between the minimum value and zero.

Since E3 was shown to shift the Entrant's ellipse and provide a sufficient margin, it was combined with a fourth enterprise strategy (E4) in order to see if that combination would be preferred to the Incumbent's design. E4 was a price-reduction strategy

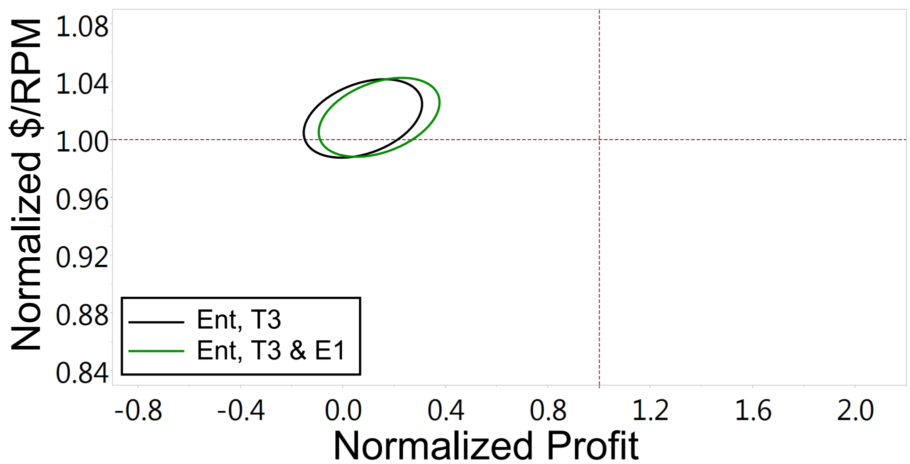

Figure 113: Exploring the impacts of including the first normative enterprise strategy (E1) in Use Case 2, compared to only the geared turbofan strategy.

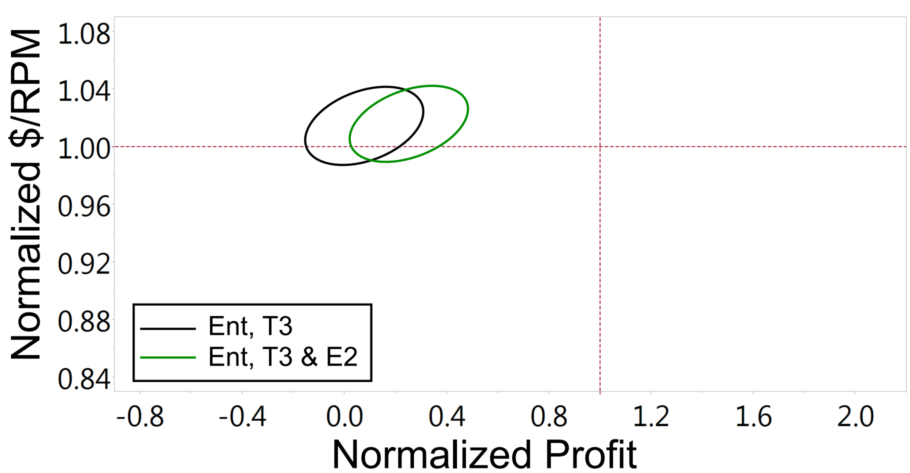

Figure 114: Exploring the impacts of including the second normative enterprise strategy (E2) in Use Case 2, compared to only the geared turbofan strategy.

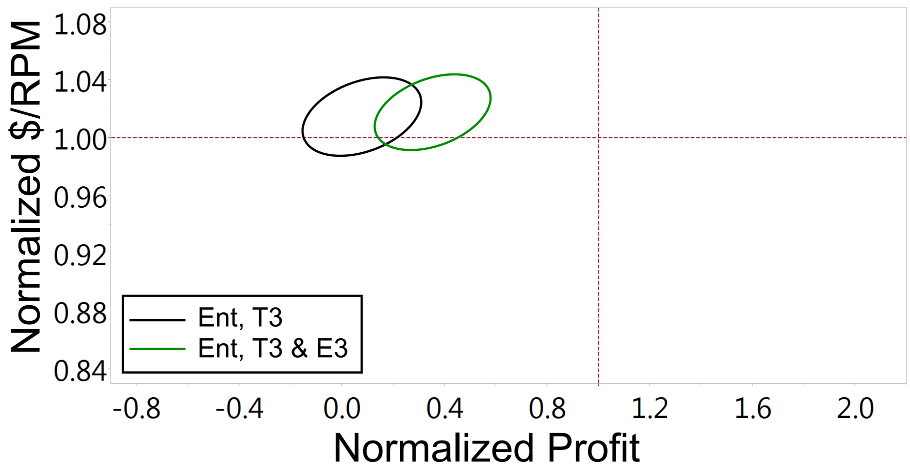

Figure 115: Exploring the impacts of including the third normative enterprise strategy (E3) in Use Case 2, compared to only the geared turbofan strategy.

that sought to capitalize on the increase in expected profit from utilizing E3. E4 was specifically defined as a 5% price reduction (i.e., λ_P = -5%). This price reduction was expected to decrease the $/RPM value; however, this price reduction would also decrease the expected profit, but it was desired that the margin from E3 would be sufficient in order to prevent any negative profit values. The results from combining E3 and E4 strategies for the Entrant are shown in Figure 116. This resulting combination was then compared to the Incumbent's NEO+ option in the sixth step of the CoDeS Framework.

***Re*-Step 6:**

Figure 117 shows a comparison between the Entrant's design with strategies of T3, E3, and E4 and the Incumbent's NEO+ design; the Entrant's T3 design was also shown for comparison. From this figure, it seems that the enterprise solutions have caused a significant increase in the competitiveness of the Entrant's design. To further examine this claim, a TOPSIS analysis of the S/N values was conducted. It should be noted that the normalized profit metrics were still shifted by 20% of the Geometric Baseline in order to account for nonpositive values and ensure consistency between

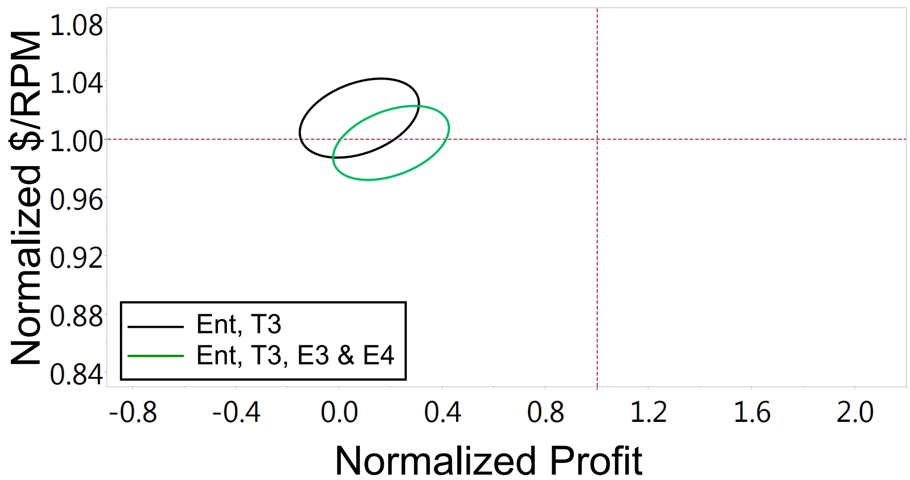

Figure 116: Exploring the impacts of including the third normative enterprise strategy (E3) and a fourth normative enterprise strategy (E4) in Use Case 2, compared to only the geared turbofan strategy.

the results presented in Use Case 2.

The results from the TOPSIS analysis are shown in Figure 118. This figure shows that the Entrant's combination of technology and enterprise strategies results in a design that was preferred over the Incumbent's NEO+ option for almost all values of the weightings. Furthermore, the slope of the Entrant's design with T3, E3 & E4 was more flat compared to the slope of the Incumbent's line. This suggest that the Entrant's design and strategy options were more robust to different weightings. While this figure also shows the Entrant's strategy option of only T3, it has a value of zero for all weightings, which suggest that this design is always completely dominated by the other strategy options.

***Re*-Step 7:**

Based on the results of the TOPSIS analysis presented in Figure 118, the Entrant's design option should be competitive against the Incumbent's design option. Therefore, the OEM should not only infuse T3 (geared turbofan) into their design, but

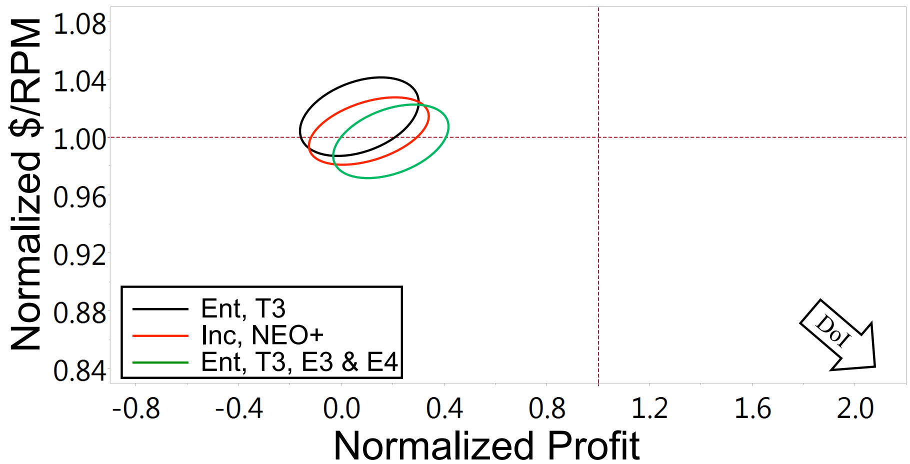

Figure 117: Exploring the impacts of including the third normative enterprise solution (E3) and a fourth normative enterprise solution (E4) in Use Case 2, compared to the Incumbent's NEO+.

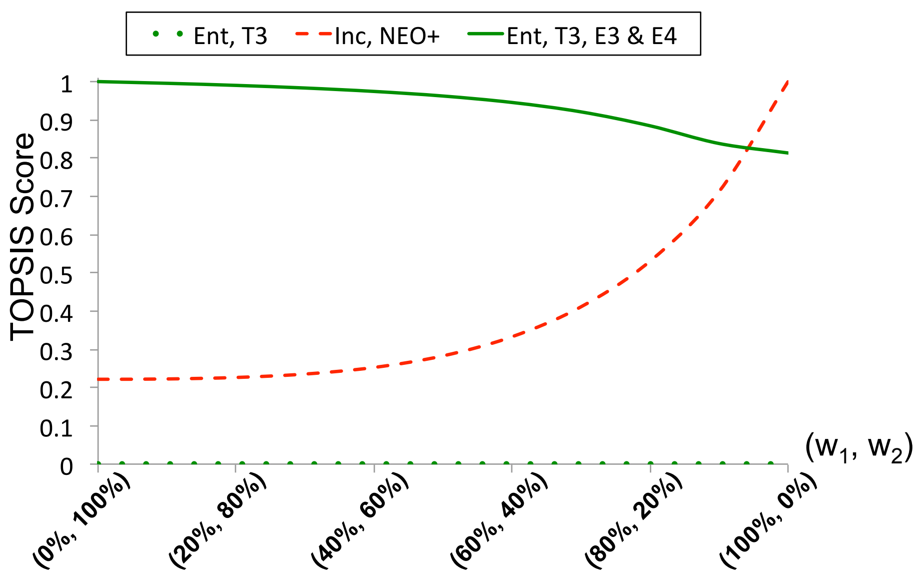

Figure 118: Results from TOPSIS of S/N values with variable weightings in Use Case 2 to determine whether the Entrant's geared turbofan with E3 and E4 strategies *beats* the Incumbent's NEO+ design.

should also explore an enterprise strategy that results in a 5% reduction in manufacturing costs (E3) and implement a 5% reduction in the price of their aircraft (E4) for the given scenario.

The analysis of Use Case 2 was missing an important element related to the 5% reduction in price – how this reduction in price (and $/RPM) propagates to changes in the number of aircraft desired. As previously stated in § 3.4, this relationship was not known for this dissertation, but it could be expected that an OEM would know or could estimate this relationship based on previous interactions with airlines. The third *use case* in the following section examines how that data could be used if it were known.

5.4 Use Case 3: Entering Asian Market

Use Case 3 explored a notional scenario of entering the Asian market; however, this scenario was motivated by current OEMs' predictions for strong growth in this market during the coming years. Both Airbus and Boeing predict significant growth in the Asian market between 2015 and 2034. [6, 27] Airbus estimates that majority of these aircraft will need to have passenger capacities between 154-183 seats for flights occuring within the Asian market (i.e., not between different continents). [6] Boeing estimates that approximately 11,000 single-aisle aircraft will be servicing the Asian market by 2034. [27] In fact, Airbus estimates that the Asian market will account for 39% of their deliveries between 2015 and 2034 [6], and Boeing estimates the entire Asian market has a value of approximately $2.2 Trillion USD[†][27].

To examine Use Case 3, some slight modifications were made to the general background information about the OEMs presented in § 5.1. The main difference was that neither aircraft is established in the market, but the names "Entrant" and "Incumbent" were still used to describe the OEMs in order to remain consistence since each

[†]Using USD valuation from 2015.

OEMs use the same Geometric Baselines described in Table 19. However, each OEM examined a different strategy in place for entering the Asian market. The Incumbent sought to utilize the NEO+ strategy previously described in Use Cases 1 and 2. But the Entrant sought to only utilize an enterprise solution to its Geometric Baseline – this enterprise solution (E1) is a maintenance initiative that seeks to also increase the OEM's physical presence in the Asian market.

E1 involved spending $1 billion USD to construct a maintenance facility in Asia that can service the aircraft. It was assumed that E1 would cause airlines to spend the same amount of money on the maintenance of aircraft (but they may be able to save costs by not having the overhead associated with a maintenance program), and that 10% of the money spent on maintenance would be a net profit to the OEM. The impacts and implications of this enterprise solution are discussed more in Steps 5 and 6 of the CoDeS Framework.

As with the previous *use cases*, the effects of uncertainty were mitigated by implementing a scenario-based analysis. Since both Boeing and Airbus have generally optimistic views about aircraft manufacturing between 2015 and 2034 [6, 27], the probabilistically-defined scenario used optimistic ranges for the economic noise variables. The exact ranges are shown in Table 25. In this table, no ranges are provided for the production facility costs because it was assumed that only the Entrant would spend money on a new production facility and that the value was deterministic. Also, it was assumed that both aircraft would be producing 50% of the total market share, before examining the impacts of enterprise strategies. The impacts of this scenario compared to the full range of uncertainty are shown in Figure 119.

A comparison of the Geometric Baselines, described in Table 19, is shown in Figure 120. This figure shows how each design impacts the variability of the value metrics in the presence of this scenario. It should be noted that this figure does not represent the infusion of any strategies.

Table 25: Description of probabilistic scenario evaluated in Use Case 3.

Economic Noise Variable	Range
Manufacturing Learning Curve	[-7%, +2%]
Production Facility Costs	–
Inflation Rate	[-15%, -5%]
Number of Aircraft Produced	50% market share
Price of Aircraft	[-5%, +5%]
Load Factor	[+10%, +15%]
Fuel Price	[-15%, -5%]

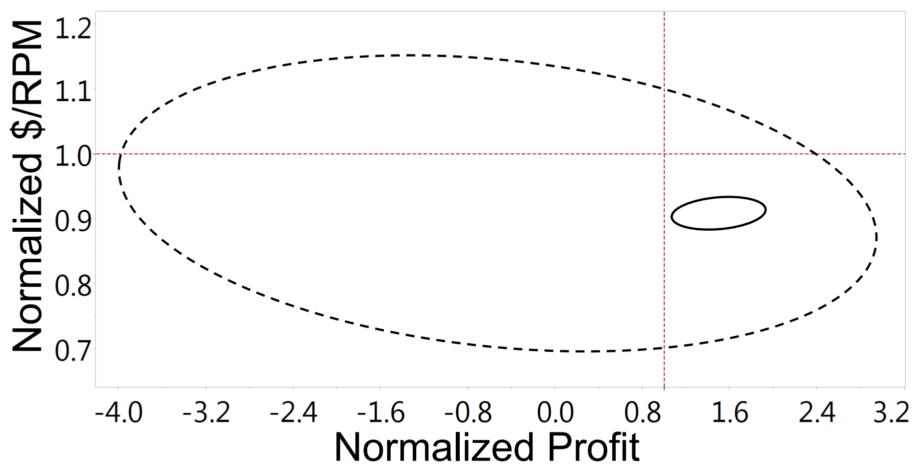

Figure 119: Variability in the value metrics from the full uncertainty of the problem (dotted line) compared to the variability from the scenario (solid line) described in Table 22.

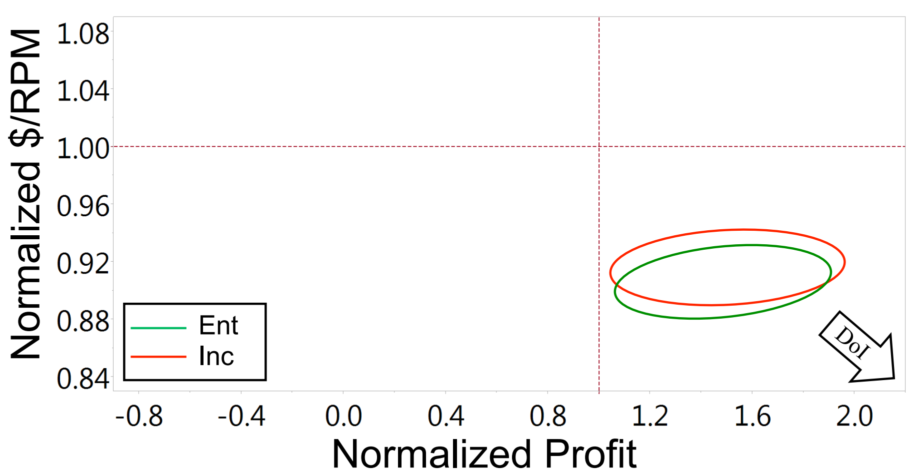

Figure 120: Comparison between the Entrant's baseline and Incumbent's baseline designs in Use Case 3.

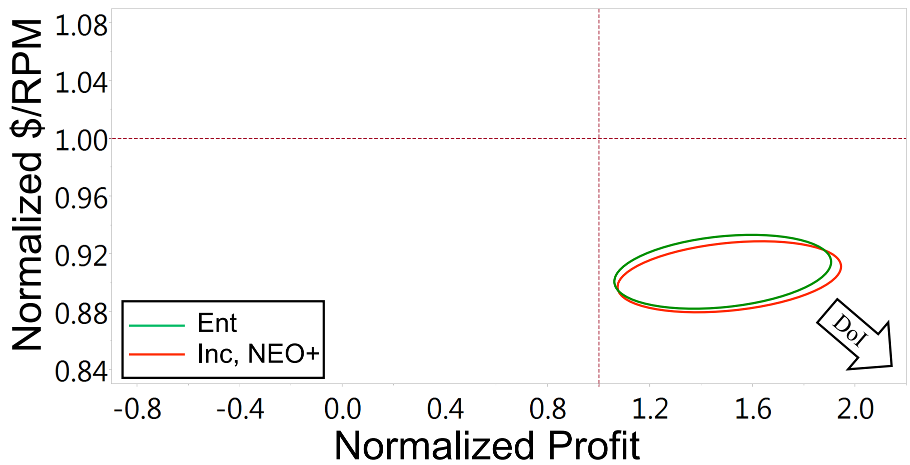

Figure 121: Comparison between the Entrant's baseline and Incumbent's NEO+ designs in Use Case 3.

Step 5 & 6:

Initially, Use Case 3 only examines the impacts of the Incumbent's NEO+ strategy, which was described in Use Case 1 (§ 5.2) and the Entrant not using any strategies. The resulting ellipses from this analysis are shown in Figure 123. When this figure is compared to Figure 120, it can be seen that the use of the NEO+ strategy causes the Incumbent's ellipse to move in the direction of improvement. These two ellipses were evaluated using Taguchi's S/N formulation in order to determine a preferred alternative. The result from this evaluation can be seen in Figure 122. The results in this figure show that the Incumbent's NEO+ strategy completely dominates the Entrant's Geometric Baseline.

Step 7 – Make a Decision:

The final step of the CoDeS Framework has two options: 1) Terminate, or 2) Iterate. Since the results from Step 6 of the CoDeS Framework showed that the Incumbent's design would be preferred, a rationale decision-maker would iterate in order to see if a strategy would result in a better design option for the Entrant. The strategy

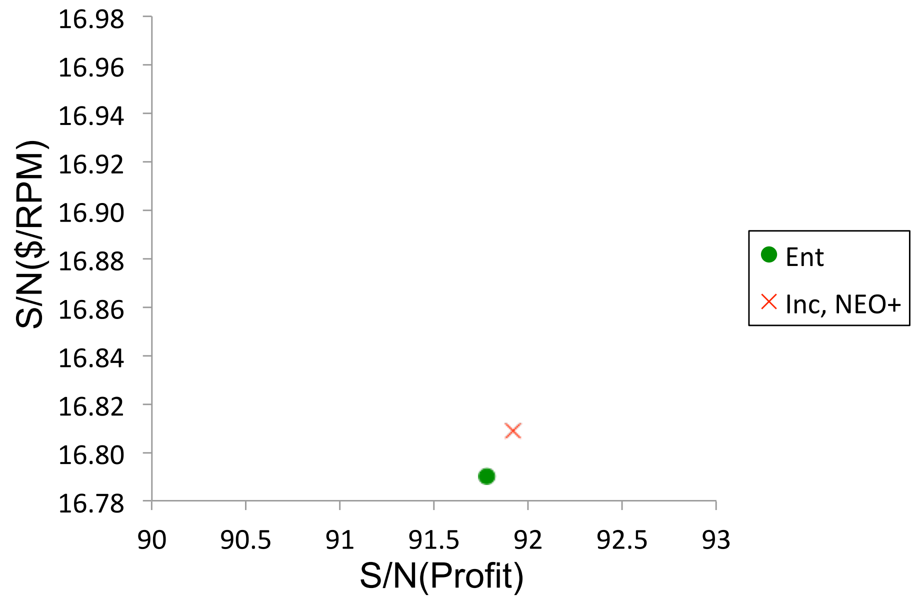

Figure 122: Scatter plot comparison of the S/N values of the value metrics in Use Case 3 for the Entrant's baseline design compared to the Incumbent's NEO+ design – the Incumbent's design dominates.

examined in Use Case 3 is the maintenance initiative (E1) previously described.

***Re*-Step 5 & 6:**

E1 is an enterprise strategy that sought to capitalize on making more money for the OEM throughout the life cycle of the aircraft. To model these effects, the total maintenance costs for the aircraft (not including the engine) were needed, which is a capability of the ALCCA code. The M&S environment was modified to incorporate these calculations into the total income for the aircraft OEM. Therefore, the effects of E1 were computed, and Figure 123 shows how it impacted the Entrant's ellipse relative to the Incumbent's NEO+ option.

S/N values were then computed for these ellipses in order to see whether the Entrant's use of E1 would be preferred to the Incumbent's NEO+ option. The results from this analysis are shown in Figure 124. This figure shows how the implementation of E1 caused the Entrant's point to shift to the right, but did not cause any significant

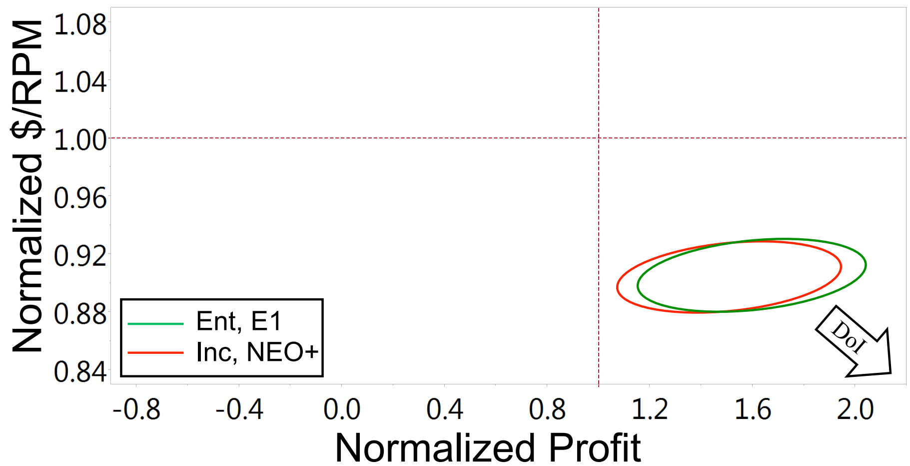

Figure 123: Comparison between the Entrant's use of a maintenance initiative (E1) and Incumbent's NEO+ designs in Use Case 3.

change in the values for \$/RPM. This result was expected since the maintenance initiative did not directly save airlines any money on maintenance costs. It should be noted that the slight variation in the \$/RPM metric is less than 0.02%, and was assumed to be due to the residuals of the surrogate models.

However, a key benefit of an OEM initiating a maintenance program is that they can then earn money during the life cycle of the aircraft and not just during the purchase of an aircraft. To this end, the Entrant then analyzed the impacts of second enterprise strategy (E2), which reduced the price of the aircraft by 5% (i.e., $\lambda_P =$ -5%). The effects of this price reduction are compared to the Incumbent's NEO+ strategy in Figure 125 using ellipses to show the variability in the value metric. When this figure is compared to Figure 123, it is clear that reducing the price caused the Entrant's ellipse to shift down and to the right, which is not in the preferred direction. By examining a plot of the S/N values, which is shown in Figure 126, it can be seen that the S/N of profit for the Entrant would lower when implementing E1 and E2 than for the Geometric Baseline.

While the enterprise strategy of reducing price was examined in Use Case 2, the resulting reduction in \$/RPM was not translated to increases in market share since

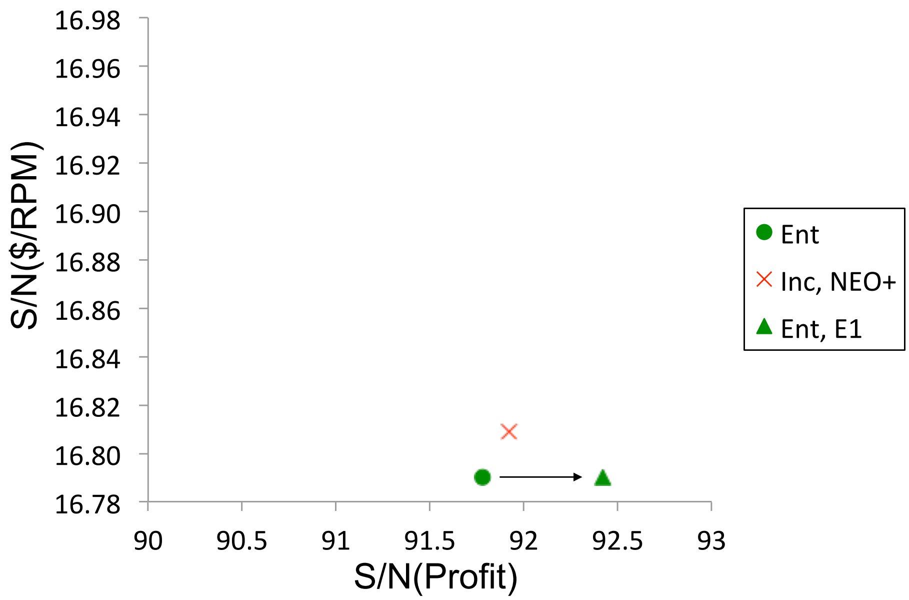

Figure 124: Scatter plot of S/N values of the value metrics showing how E1 shifts the Entrant's point to the right by increasing expected profit.

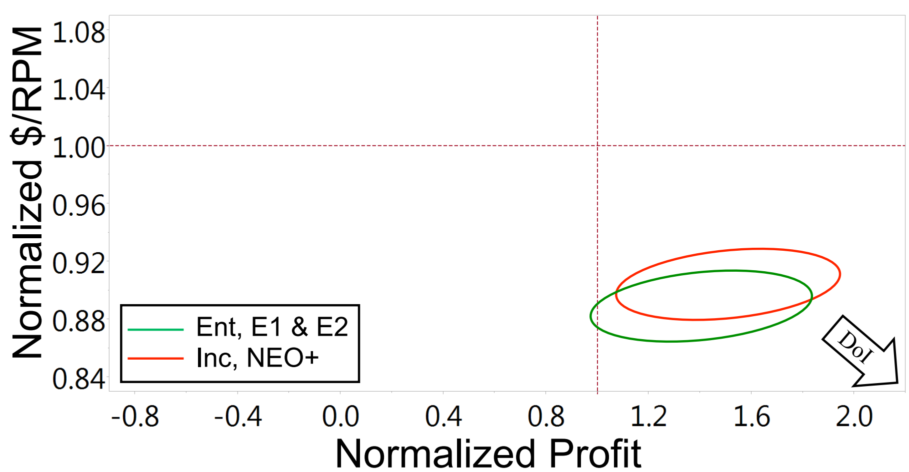

Figure 125: Comparison between the Entrant's use of a second enterprise strategy (E2) that lowers the price of the aircraft since higher values of profit were expected from Figure 123.

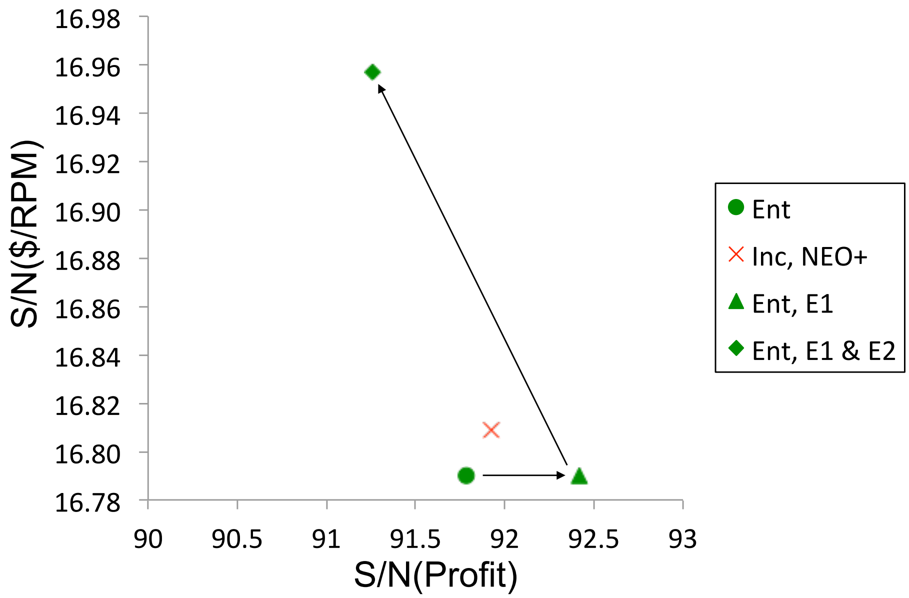

Figure 126: Scatter plot of S/N values of the value metrics showing how E2 shifts the Entrant's point to the left and up since the decrease in price lowers expected profit and $/RPM.

that relationship was unknown. Use Case 3 assumes a fixed relationship between relative $/RPM and percentage market share – a 1% lower $/RPM value equates to a 2% increase in market share between the Entrant and Incumbent. By examining the median values of the normalized $/RPM metric for the Entrant's E1 & E2 strategies compared to the Incumbent's NEO+ strategy, it was found that there was a 2% difference. By the assumed relationship between $/RPM and quantity desired, the Entrant's market share would increase to 54% and the Incumbent's would decrease to 46%. The effect of these change in market share can be seen for the Entrant in Figure 127 and for the Incumbent in Figure 128. The direct comparison between the Entrant's E1 & E2 strategies against the Incumbent's NEO+ strategy are shown in Figure 129.

The results from Use Case 3 can be summarized in Figure 130, which shows the impacts from the different strategies on a plot of S/N of the value metrics. If the entrant did not use any strategies, their design would be dominated by the Incumbent's

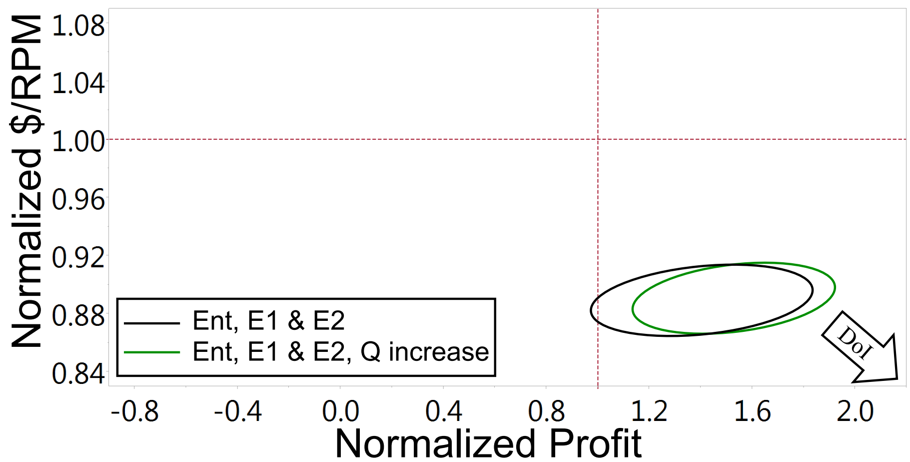

Figure 127: The Entrant's use of E1 and E2 to decrease $/RPM causes more aircraft to be demanded based on the assumed relationship between $/RPM and quantity desired.

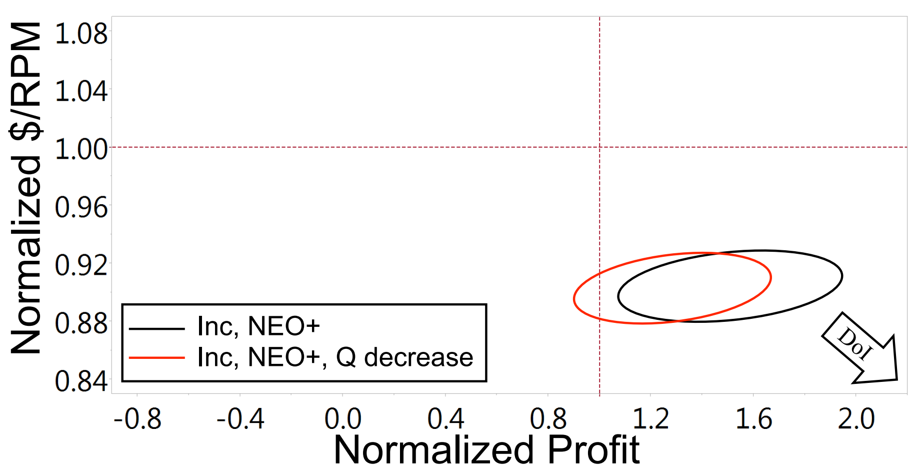

Figure 128: The Entrant's use of E1 and E2 causes their aircraft to be preferred over the Incumbent's NEO+ option, which causes the Incumbent's quantity desired to decrease.

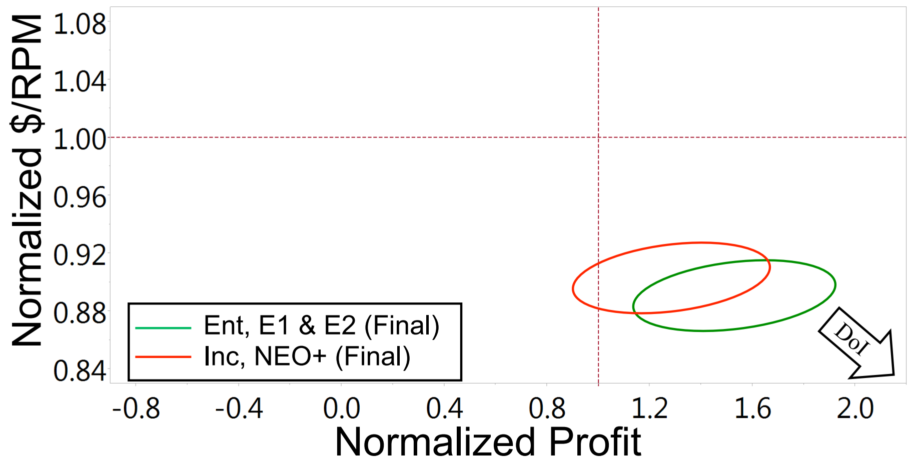

Figure 129: Comparing the variability of the value metrics from the Entrant's use of E1 and E2 and the Incumbent's NEO+ after accounting for changes in market share.

NEO+ strategy; furthermore, since the Incumbent's NEO+ strategy has a better S/N value for $/RPM, the Incumbent would have gained more market share. If the Entrant were to only use the maintenance initiative (E1), then their estimated profits would increase. As previously stated, this increase in expected profit means that another enterprise strategy of a price reduction (E2) can be implemented in order to lower the $/RPM values of an aircraft. Since Use Case 3 assumed a relationship between changes in $/RPM and quantity demanded, a more accurate representation of the effects from E2 can be seen. It should be noted that the decrease in $/RPM seen between "Ent, E1 & E2" and "Ent, Final" in Figure 130 represents a change of less than 0.03% and was assumed to be due to residuals associated with the surrogate model used. The opposite effect can be seen between "Inc, NEO+" and "Inc, Final" in the same graph – a decrease in market share causes a marginal increase in $/RPM.

***Re*-Step 7:**

By implementing enterprise strategies of E1 and E2, the Entrant is able to create a design option that dominates the Incumbent's NEO+ design option. Based on the assumed relationship between $/RPM and quantity demanded in the Asian market,

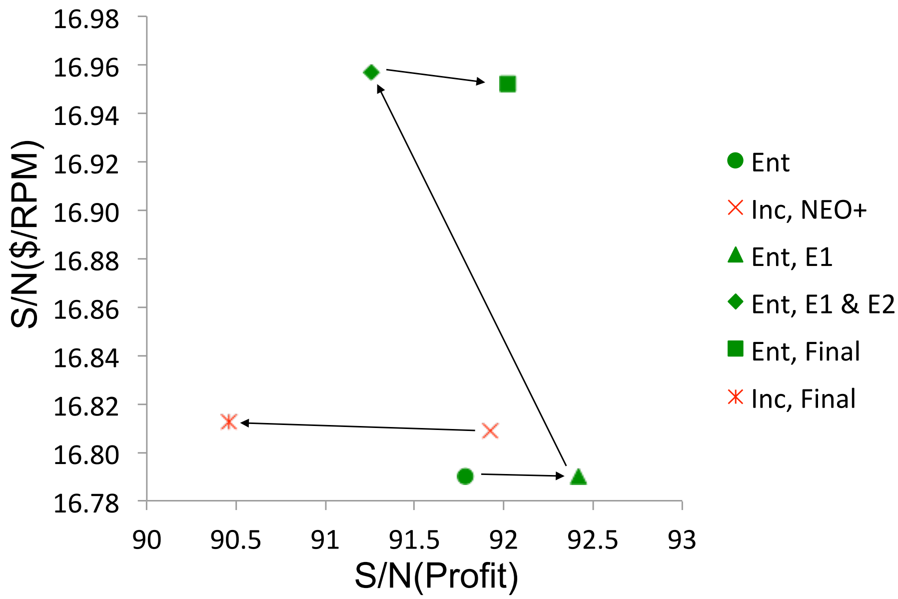

Figure 130: Scatter plot of S/N values of the value metrics showing how the Entrants use of E1 and E2 dominates the Incumbent's NEO+ strategy.

these strategies would also provide the Entrant with a majority of the market share. However, one aspect of Use Case 3 that was not accounted for in this analysis was any effects that result from opening a maintenance facility directly in the Asian market. Implementing this strategy may have political, economic, or other implications that were outside the scope of this dissertation.

5.5 Summary of Chapter

This chapter examined three *use cases* for the CoDeS Framework. While each *use case* examined slight variations of duopoly competition using the same geometric aircraft, the resulting strategies implemented were different. Use Case 1 used exploratory forecasting to examine the impacts of a known manufacturing initiative. This was important because this strategy was only considered after it was seen that the proposed design and technology would have not been sufficient to *beat* the competitor's design. Use Case 2 examined the impacts of normative forecasting to evaluate the amount of cost reduction that would need to occur in a manufacturing initiative so that a price reduction initiative could be implemented. This price reduction would result in a decrease in the \$/RPM value, which may cause more airlines to desire that aircraft. Finally, Use Case 3 examined the notional situation of entering the Asian market. This *use case* explored the impacts of a maintenance initiative that would allow for an OEM to make income throughout the life cycle of an aircraft and not just during sale of an aircraft.

One important aspect to note about all of the *use cases* is that significant insights were gained when comparing a proposed design to a competitor's design. In Use Case 1, the Entrant's selection of an optimal technology (Natural Laminar Flow) would have not been sufficient to compete against the Incumbent's NEO+ design. In Use Case 2, only the benefits gained from infusing a Geared Turbofan and two enterprise strategies allowed for the Entrant's design to *beat* the Incumbent's design. Finally, Use Case 3 demonstrated how a combination of only enterprise solutions may result in a better design alternative without the need to infuse technologies. While these results are specific to the three *use cases* described in this chapter, the flexibility of the CoDeS Framework allows for a decision-maker to analyze a large variety of alternative strategies, whether they are technology-based or enterprise-based.

CHAPTER VI

CONCLUSIONS

"The natural function of the wing is to soar upwards and carry that which is heavy up to the place where dwells the race of the gods."
Plato [133]

This chapter concludes this dissertation work. By constructing the CoDeS Framework and evaluating several *use cases*, the research objective has been sufficiently addressed. To fully address the research objective, three research questions were posed and answered either through a literature review or experimentation. The first of these research questions is restated below:

> **Research Question 1:** How to ensure a decision-maker has confidence in their decisions in the presence of uncertainty from economic factors and the competitive market?

In order to address Research Question 1, a deeper understanding of the impacts from uncertainty was needed. This lead to the development of Research Question 2 and Experiment 1, which sought to characterize the effects of uncertainty from controllable and uncontrollable factors. Research Question 2 is restated below:

> **Research Question 2:** How can the impacts of uncertainty be determined with regards to controllable and uncontrollable factors?

This second research question was addressed through Experiment 1, which conducted sensitivity analyses of the individual noise variables, interactions between noise variables, and the effects of different probability distribution shapes. The insight gained from this experiment lead to the development of Research Question 3:

> **Research Question 3:** What technique is most appropriate to mitigate the impacts of uncertainty?

An in-depth literature review resulted in the adoption of scenarios to address Research Question 3. The effects of these scenarios were further shown at the end of Experiment 1 by quantifying the reduction in variability of the value metrics that occurs by adopting scenarios. These scenarios were probabilistically-defined in Experiment 1, but the *use cases* of Chapter 5 examined both probabilistically- and deterministically-defined scenarios.

By addressing Research Questions 2 and 3, Research Question 1 could be fully answered. Due to the effects of uncertainty, a modified Taguchi's signal-to-noise ratio was adopted and coupled with a multi-criteria decision making technique. To fully understand how this approach should be implemented, Experiment 2 examined a canonical example involving nonpositive value metrics. From these results, Experiment 3 explored the results associated with implementing different multi-criteria decision making techniques with the modified Taguchi's signal-to-noise ratio.

Based on the results from these experiments, the CoDeS Framework was formalized. It was evaluated against three *use cases* in order to examine its capabilities. By addressing these *use cases*, it was shown that the Research Objective (which was formulated in detail in § 2.4, but is also restated below), was accomplished.

> **Research Objective:** Develop a framework to aid in the conceptual design of aircraft by parametrically accounting for uncertainty from the economic market and competitive environment through an integrated and interactive design approach. This approach should allow for analysis of various strategies (e.g., technology and enterprise-based) that can be used

by the designer or the competitor. Furthermore, this framework should allow for a direct comparison between proposed solution(s) and possible competitors solution(s).

The CoDeS Framework addressed all of the elements described in the Research Objective. The CoDeS Framework provides an approach to parametrically vary factors related to both the competitive environment and the economic market. These factors are addressed through the direct comparison to a competitor and the economic noise variables. This was accomplished using an integrated M&S environment that not only accounted for the physics associated with the physical design of aircraft, but also the economics associated with this design and external factors throughout the life cycle of the aircraft. Furthermore, the CoDeS Framework was constructed in a manner that allows for interactions to occur throughout the process – a decision-maker and/or SMEs can easily assess different strategies, whether technologies or enterprise solutions and rapidly compare the results from these strategies to a competitor.

Besides the development of the specific steps in the CoDeS Framework, this dissertation addressed several other key aspects of competition-influenced aircraft design. These aspects were addressed through synthesizing elements from the literature, experimentation, and the specific application of the CoDeS Framework. These specific contributions are described in further detail in § 6.1.

Finally, this chapter concludes with suggestions for future work. While most of these suggestions focus on further refinement of the CoDeS Framework, other competition-related aspects are also addressed. Specifically, these recommendations focus on incorporating a more refined model for the customers' preferences and steps towards developing an approach that accounts for market segmentation.

6.1 Contributions

The main contribution of this dissertation work was the development of the CoDeS Framework, which can be used to analyze the influences of competition during the early phases of conceptual design. The use of this framework can provide more detailed knowledge to a decision-maker earlier in the design process. Furthermore, it was shown through the three *use cases* in Chapter 5 that inclusion of a competitor during the evaluation of a potential design can result in different strategies being selected. In the first two *use cases*, the Entrant may not have investigated any enterprise solutions without the realization that their optimal technology would be dominated by the Incumbent's use of their own technologies. This problem represented the main motivation of the construction of the CoDeS Framework – a design that is optimal against *nature* may not be preferred compared to a competitor. However, the CoDeS Framework would not be effective, without several other specific contributions that were made during its development.

One of the key contributions made from a literature review was a detailed analysis of the ways in which aircraft OEMs compete. The identification of these competitive strategies drove the framing and underlying analysis of the CoDeS Framework. Two of the key aspects of competition were the use of technologies and enterprise solutions that are incorporated into a design in order to make it more appealing to customers. While the general assessment of these strategies could be qualitatively performed, there was a need to quantify their impacts especially during the early parts of the conceptual design phase. The use of a well-established k-factor approach for modeling the impacts of technologies was used and also modified to account for enterprise strategies. This adaptation used λ-factors in order to account for the impacts of enterprise strategies. While both of these techniques are useful, a difficulty arises in trying to quantify the values of k-factors and λ-factors, which means that input from SMEs might be solicited.

If SMEs were only used to help quantify values for k-factors and λ-factors, then established techniques could be used to adapt an M&S environment; however, the use of SMEs may not be limited to strategy assessment. SMEs could also be used to quantify metrics that cannot be captured through an M&S environment. Some examples of these metrics include, but are not limited to: desirability, manufacturability, ease of certification, potential for furture growth, etc. To include these assessments, a technique needed to be identified that could identify optimal alternatives based on the values of inputs and outputs without the knowledge of an underlying equation. A technique, Data Envelopment Analysis (DEA), from the fields of economics and operations research was cross-fertilized to address these concerns. The use of DEA allowed for SMEs to be easily incorporated in the assessment of potential designs. This increased the flexibility of the CoDeS Framework because it allowed for more problems/designs to be analyzed. While this dissertation did not utilize SMEs, a notional example was presented in § 3.5.2 that described how to solicit and incorporate data from SMEs into the CoDeS Framework.

While the use of strategies and SMEs helps capture the effects of factors that are under the control of the OEM, they are not as useful for factors that are not under the control of the OEM. A significant contribution from this dissertation was the characterization of how these factors can affect the value metrics and limit the ability to make decisions. These effects were mitigated by using a two-step approach. The first step involved the use of scenario-based analysis, which was highlighted by the literature as a preferred approach for mitigating uncertainty. The second step required the use of Taguchi's S/N formulation with MCDM techniques. Three of these hybrid techniques were identified – the OEC of S/N values, the MRSN, and the TOPSIS of S/N values techniques were identified from literature. Experiment 3 (§ 4.3.2) showed that all of these techniques produced similar results, but could not identify which technique was most appropriate. Instead, the CoDeS Framework allowed for any of the three techniques to be used, depending on the preferences of the decision-maker. Regardless of which technique is selected, the possibility of nonpositive value metrics can impact the accuracy of the results.

Experiment 2 (§ 4.3.1) examined a canonical example in order to determine an approach for mitigating the effects of negative value metrics used in Taguchi's S/N formulation. Two transformation techniques were identified from the literature: 1) a shift-transformation which added a constant to data in order to make all of the data positive, or 2) a target-transformation which introduced a notional target from which all the data would be evaluated. The results of this experiment showed that both techniques can be applied, but that certain heuristics must be used when applying either technique. The first heuristic is applicable to both technique and seeks to limit the size of the constant or target relative to the data. The second and third heuristics are related to the specific approach taken – a shift-transformation requires a shift that is slightly larger than the minimum of the data, whereas a target-transformation requires a target that is slightly larger than the mean of the data. While either transformation can be used, the heuristics must be followed in order to ensure accuracy in the results.

While most aircraft design approaches implicitly assume a monopoly (by not directly accounting for a competitor), the CoDeS Framework uses a direct comparison with the competitor's design. This allows for significant insight to be gained during the early parts of the conceptual design of the aircraft. These insights were shown in the *use cases*. Use Case 1 highlighted the ability of the CoDeS Framework to perform exploratory forecasting using known technologies and enterprise strategies. Use Case 2 explored the CoDeS Framework's ability to perform normative forecasting in order to identify the minimum requirements of a strategy in order to make a design more competitive. Finally, Use Case 3 examined a situation where two OEMs are simultaneously trying to enter a new market – one OEM used technologies to increase the competitiveness of their derivative design, but the other OEM used enterprise solutions in order to compete. The results of Use Case 3 highlight how a "real-world" game could be interactively analyzed using the CoDeS Framework.

In summary, the CoDeS Framework represents a necessary step that was required to gain detailed insight into the design of aircraft in the presence of competition. The following section offers suggestions for future work.

6.2 Suggestions for Future Work

Several *use cases* were presented in Chapter 5 that sufficiently demonstrated the capabilities of the CoDeS Framework. However, there are a large number of other *use cases* that can be evaluated in order to further test and refine the CoDeS Framework. This could include the incorporation of other technologies and enterprise solutions in order to quantify their impacts. Alternatively, analysis could be conducted into different passenger-classes of aircraft, which may cause changes in the type of competitive environment being analyzed. However, with the recent announcement of Delta purchasing seventy-five CS100 aircraft from Bombardier [131], the competitive market of manufacturers creating 150-passenger class aircraft has changed. While this third OEM means this market is still regarded as a duopoly, the responses from Boeing and Airbus should offer significant insight into the future of large aircraft OEMs. By evaluating more *use cases*, new insight can be gained into the development of utility functions that accurately represent OEMs' preferences. These utility functions could then be used to analyze competition in a specific market using a game theoretic approach.

Besides analyzing different *use cases*, the CoDeS framework could be expanded to include a robust model for the customer. Use Case 3 showed the powerful insights that could be gained if a direct relationship between \$/RPM and market share was known – by incorporating an accurate representation of the market, more detailed insight can be gained. For this to occur, the value metrics need to be accurately linked to the customers' preferences in order to estimate demand functions. By incorporating this insight, demand-based analysis could be performed on possible aircraft designs and different strategies. By incorporating this analysis into the existing supply-based analysis of the CoDeS Framework, an accurate representation of a market for a specific type of aircraft can be generated.

While the CoDeS Framework can assess competition between two OEMs competing in the same market, it is currently unable to assess general OEM competition across multiple markets. For this to occur, a robust representation of both utility functions and customer demand curves would need to be incorporated for different classes of aircraft and different markets. This would allow for a global assessment of the OEM to occur from a bottom-up perspective that truly captures the competitive nature of each market. This would allow for higher-level games to occur because OEMs could then examine consequences from leaving a particular market to more heavily invest in a different market.

APPENDIX A

NUMERICAL EXAMPLE OF DIFFERENT FORMS OF COMPETITION

This example is a notional example intended to provide insight into the difference between monopoly, duopoly (Cournot), duopoly (Bertrand), and perfect competition. The equations used in this example are notional and not particular to aircraft manufacturers. A list of notation specific to this example is first provided:

- p – Price
- Q – Quantity
- Π – Profit
- ρ – Revenue
- Co – Cost
- MC – Marginal Cost
- MR – Marginal Revenue
- R – Reaction Function
- Ma – Market
- M – Monopoly
- PC – Perfect Competition
- C – Cournot Duopoly

- B – Bertrand Duopoly

Cournot Duopoly:

Begin by assuming an inverse demand curve:

$$p(Q) = 100 - Q$$

Assume that $y = y_1 + y_2$, which means the market quantity is equal to the sum of the quantity produced by firm 1 and firm 2.

$$p(Q_1, Q_2) = 100 - Q_1 - Q_2$$

Assume that the costs for each firm are equal:

$$\begin{aligned} Co_1(Q_1) = &\ 10Q_1 \\ Co_2(Q_2) = &\ 10Q_2 \\ MC_1 &= \tfrac{dMC_1}{dQ_1} \\ MC_2 &= \tfrac{dMC_2}{dQ_2} \\ \therefore\ MC_1 &= MC_2 = 10 \end{aligned}$$

Find Q_1 that maximizes $\Pi_1(Q_1, Q_2)$, assuming Q_2 is constant:

$$\begin{aligned} \Pi_1 = &\ PQ - C_1 \\ \Pi_1(Q_1, Q_2) = &\ (100 - Q_1 - Q_2)Q_1 - 10Q_1 \\ \tfrac{\partial \Pi_1}{\partial Q_1} = &\ 100 - 2Q_1 - Q_2 - 10 = 0 \\ \therefore\ y_1 &= R_1(Q_2) = 45 - \tfrac{Q_2}{2} \end{aligned}$$

Find Q_2 that maximizes $\Pi_2(Q_1, Q_2)$, assuming Q_1 is constant:

$$\Pi_2(Q_1, Q_2) = PQ - C_2$$

$$\Pi_2(Q_1, Q_2) = (100 - Q_1 - y_2)Q_2 - 10Q_2$$

$$\frac{\partial \Pi_1}{\partial Q_2} = 100 - 2Q_2 - Q_1 - 10 = 0$$

$$\therefore \; Q_2 = R_2(Q_1) = 45 - \frac{Q_1}{2}$$

Solve the system of equations, based on the reaction functions:

$$Q_1 = 45 - \frac{Q_2}{2}$$

$$Q_2 = 45 - \frac{Q_1}{2}$$

The resulting solution is the Cournot equilibrium, $(Q_{1,C}, Q_{2,C}) = 30$. When these values are plugged into the inverse demand function initially assumed:

$$p(Q_{1,C}, Q_{2,C}) = 100 - 30 - 30$$

$$p_{Ma} = 40$$

$$\therefore \; \Pi_1 = \Pi_2 = 900$$

The Reaction

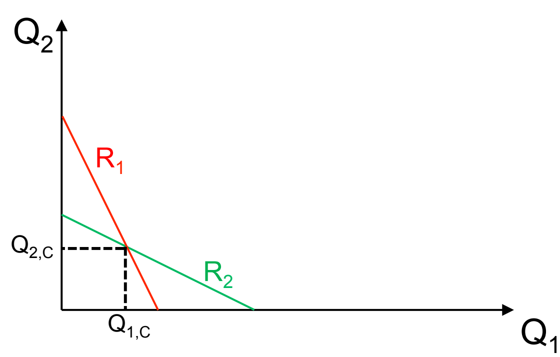

Figure 131: Cournot's model of a duopoly – reaction functions result in identification of the equilibrium quantities of $Q_{1,C}$ and $Q_{2,C}$

Perfect Competion:

Firms in perfect competition are *price takers*. The "invisible hand" of the market also drives the price of the goods to be equal to marginal costs of the firm, in the long run. If it were assumed that the firms had the same marginal cost function and the market had the same inverse demand function as described in the Cournot example:

$$\begin{aligned} p_{PC} = & \quad MC = 10 \\ p = 100 - Q & \quad \rightarrow Q_{PC} = 90 \\ \Pi_{PC} = & \quad 0 \end{aligned}$$

Monopoly Competion:

Monopolies act as *price setters*. This is done by determining where $MC = MR$ to find Q_M and then finding p_M based on that quantity. This problem assumed a simplified version of monopoly competition where the cost function is the same for the monopoly as for either firm in the Cournot duopoly. If the monopoly had the same inverse demand function as previously described:

$$\begin{aligned} \Pi = & \quad \rho - Co \\ \Pi = & \quad (100 - Q)Q - 10Q \\ \therefore & \quad \rho = 100Q - Q^2 \\ MR = & \quad \frac{d\rho}{dQ} \\ MR = & \quad 100 - 2Q \end{aligned}$$

By setting $MC = MR$:

$$\begin{aligned} MC = &\ MR \\ 10 = &\ 100 - 2Q \\ \therefore &\ Q_M = 45 \\ P_M = &\ 100 - Q_M \\ P_M = &\ 55 \\ \therefore &\ \Pi_M = 2,025 \end{aligned}$$

The monopoly profit is greater than the total profit earned in the Cournot Duopoly $(900 + 900 < 2,025)$.

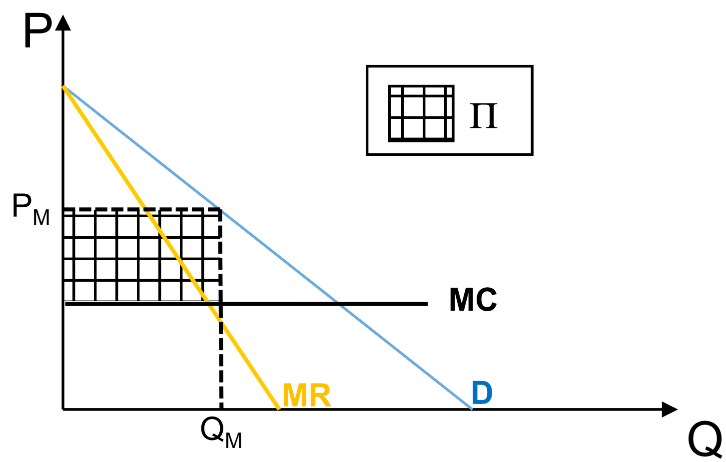

Figure 132: Graph of monopolistic competition as described in the above example.

Bertrand Duopoly:

Assume that the same cost functions for Cournot Duopoly also apply to this example.

Further assume that each firm has a demand function:

$$Q_1(p_1, p_2) = \quad 50 - p_1 + \tfrac{p_2}{2}$$

$$Q_2(p_1, p_2) = \quad 50 - p_2 + \tfrac{p_1}{2}$$

Firm 1 wants to choose p_1 that maximizes their profit, given that p_2 is fixed:

$$\Pi_1(p_1, p_2) = \quad p_1(50 - p_1 + \tfrac{p_2}{2}) - 10(50 - p_1 + \tfrac{p_2}{2})$$

$$\tfrac{\partial \Pi_1}{\partial p_1} = \quad 60 - 2p_1 + \tfrac{p_2}{2}$$

$$\therefore \quad R_1(p_2) = 30 + \tfrac{p_2}{4}$$

$$\Pi_2(p_1, p_2) = \quad p_2(50 - p_2 + \tfrac{p_1}{2}) - 10(50 - p_2 + \tfrac{p_1}{2})$$

$$\tfrac{\partial \Pi_2}{\partial p_2} = \quad 60 - 2p_2 + \tfrac{p_1}{2}$$

$$\therefore \quad R_2(p_1) = 30 + \tfrac{p_1}{4}$$

By solving the system of equations ($R_1(p_2)$,$R_2(p_1)$), $p_{1,B} = p_{2,B} = 40$.

$$Q_{1,B} = Q_{2,B} = 30$$

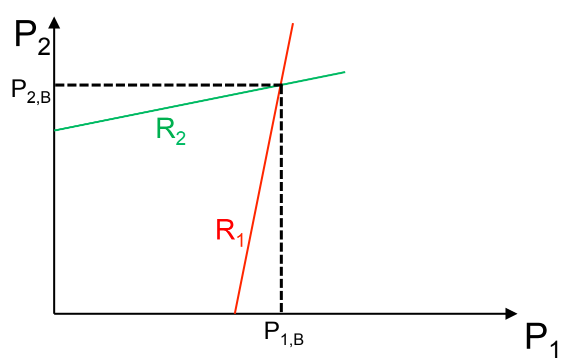

Figure 133: Bertrand's model of a duopoly – reaction functions result in identification of the equilibrium quantities of $p_{1,B}$ and $p_{2,B}$

The results from the Bertand model of a duopoly and the Cournot model of a duopoly yield the same equilibrium quantity, prices, and profit. This was due to the assumed demand function used for the examples. One of the most difficult problems associated with these analysis is accurately estimating the demand functions for a given firm, regardless of the type of competition (monopoly, duopoly, perfect competition) present.

APPENDIX B

FIGURES OF RESULTS FROM DIFFERENT S/N AND MCDM APPROACHES

These figures pertain to the analysis conducted in § 4.3.2. The figures shown are for the other methods of combining Taguchi's S/N formulation and MCDM – OEC of S/N values and S/N of OEC values (i.e., MRSN). The results are presented for the enterprise strategy options from both Scenario 1 and Scenario 2. Figures 134 and 135 show the OEC of S/N values for Scenarios 1 and 2, respectively. Similarly, Figures 136 and 137 show the results of the MRSN approach. These figures show that for most of the weighting values, the enterprise solution had a higher score. The results from these figures are similar when compared to the TOPSIS results, which are shown in Figure 91 for Scenario 1 and Figure 93 for Scenario 2 of § 4.3.2.

While the results are similar, the adoption of the MRSN approach still yields results that may be harder to interpret. The difficulty arises because the scores tends to zero as $w_1 >> w_2$. This was most likely due to the combination of trying to minimize one value metric while trying to simultaneously maximize the other value metric. Regardless, the general trend between the MRSN and the OEC of S/N values show that the enterprise solution would be preferred for almost all different values of the weightings. It should also be noted that the graphs in Figures 134, 135, 136, and 137 should not be compared to each other – the relative values of the weightings between graphs are not useful for two reasons: 1) they are evaluating different scenarios that a decision-maker cannot control, and 2) the scores between MRSN and the OEC of S/N values are not the same formulation which would result in different magnitudes of scores.

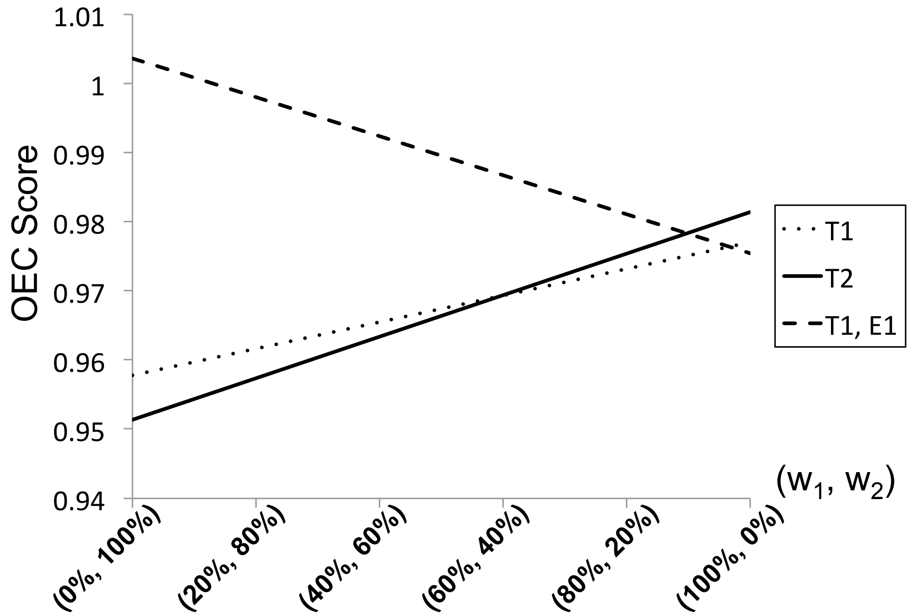

Figure 134: Scenario 1 with T1 and E1 being analyzed by an OEC of Taguchi's S/N values for each value metric with variable weightings.

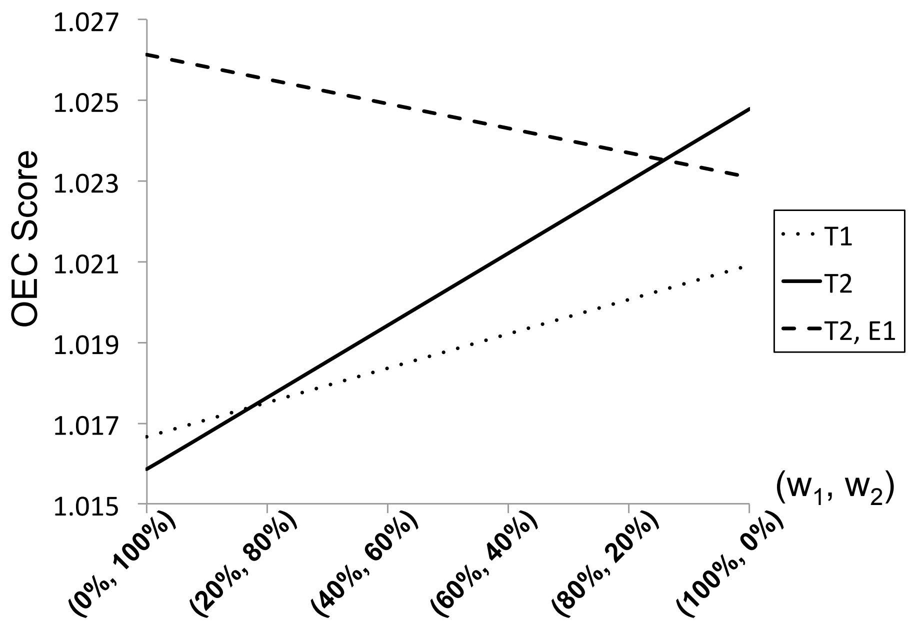

Figure 135: Scenario 2 with T2 and E1 being analyzed by an OEC of Taguchi's S/N values for each value metric with variable weightings.

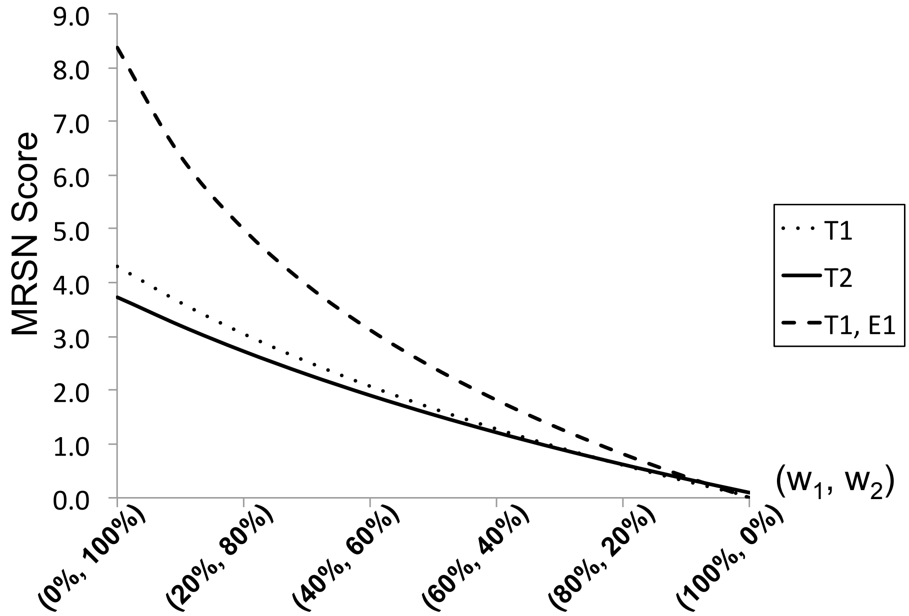

Figure 136: Scenario 1 with T1 and E1 being analyzed by MRSN with variable weightings.

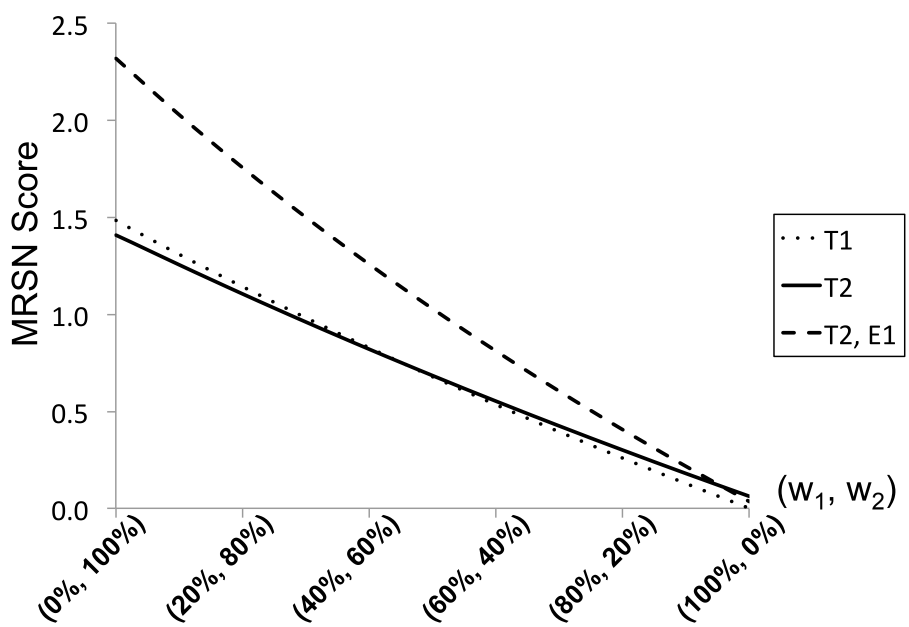

Figure 137: Scenario 2 with T2 and E1 being analyzed by MRSN with variable weightings.

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VITA

Michael (Mike) Miller was born in Jacksonville, Florida in 1985. He moved to Atlanta in 2003 to begin his undergraduate studies at the Georgia Institute of Technology. He earned both a B.S. in Aerospace Engineering and a B.S. in Economics in 2008. He joined the Aerospace Systems Design Laboratory (ASDL) in 2008. He completed his M.S. in Aerospace Engineering in 2010. He is a member of the International Council on Systems Engineering (INCOSE). He is also a member of the American Institute of Aeronautics and Astronautics (AIAA), where he was accepted to the Systems Engineering Technical Committee in 2016.