150 Passenger Commercial Aircraft

Deliverable V – Complete Report
AE8804A-7

Submitted to Dr. Michelle Kirby

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By

Adrian Bucovsky

Fairuz I. Romli

Jessica Rupp

Formal Declaration of Authenticity

The work and ideas contained in this report are solely those of the team members except where explicitly referenced or cited from another source.

Signed:

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Adrian Bucovsky

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Fairuz I. Romli

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Jessica Rupp

List of Team Member Contributions

List of Contributions

Adrian Bucovsky

- **Step 1: description of performance metrics and their targets/constraints**
- **Step 2: baseline and alternative concepts identification**
- **Step 3: requirement 7A, last bullet**
- **Step 4: requirements 3-12**
- **Step 7: All of Requirements 3, 4, 5, 6, 9 and Parts of Requirements 1, 7**
- **Step 8: requirements 3, 4, 11**
- **Closing the Loop: all**
- **Conclusions**
- **Put together presentation**
- **Final editing of report**

Fairuz I. Romli

- **Step 1: introduction and market research**
- **Step 3: requirements 1, 2, 3, & 4 (design mission description and assumptions)**
- **Step 4: requirements 1-3**
- **Step 6: all**
- **Step 7: All of Requirements 2, 8 and Part of Requirements 1, 3, 12**
- **Step 8: requirements 2**
- **Project Work Plan Assessment**
- **Closing the Loop: discussion of "goodness of fit" and CDF's**

Jessica Rupp

- **Step 1: all things relating to economic and misc. metrics**
- **Step 3: all of requirements 5, 6, & 7 (except part 7A, last bullet)**
- **Step 5: all**
- **Step 7: part of requirement 7, 12 and all of requirements 10, 11, 14**
- **Step 8: requirements 1, 8, 9, 10**
- **Project Work Plan Assessment**
- **Conclusions**
- **Put together presentation**
- **Overall Report: Combined all member's contributions into one report**
- **Final formatting and editing of report**

Team Evaluation Form

Please rank each team member on a scale of 1 to 5, with 1 being the lowest (worst), and 5 being the highest (best) and then print and sign your name below.

	Member #1		Member #2		Member #3	
	#2	#3	#1	#3	#1	#2
Professionalism						
Involvement with meetings						
Contributed towards deliverables						
Contributed to reports						
Quality of contribution						
Self-motivated						
Able to solve problems independently						
Ability to work as a team						
Other:						
Other:						
Other:						

Adrian Bucovsky
Team Member #1 Type Name

Team Member #1 Signature

Fairuz I. Romli
Team Member #2 Type Name

Team Member #2 Signature

Jessica Rupp
Team Member #3 Type Name

Team Member #3 Signature

Executive Summary

It has been projected that the need for a short-range mid-sized, aircraft is increasing. The future strategy to decrease long-haul flights will increase the demand for short-haul flights. Since passengers prefer to meet their destinations quickly, airlines will increase the frequency of flights, which will reduce the passenger load on the aircraft. If a point-to-point flight is not possible, passengers will prefer only a one-stop short connecting flight to their final destination. A 150-passenger aircraft is an ideal vehicle for these situations. It is mid-sized aircraft and has a range of 3000 nautical miles. This type of aircraft would market U.S. domestic flights or inter-European flight routes.

The objective of the design of the 150-passenger aircraft is to minimize fuel consumption. The configuration of the aircraft must be optimized. This aircraft must meet CO_2 and NOx emissions standards with minimal acquisition price and operating costs.

This report contains all the work that has been performed for the completion of the design of a 150 passenger commercial aircraft. The methodology used is the Technology Identification, Evaluation, and Selection (TIES) developed at Georgia Tech Aerospace Systems Design laboratory (ASDL). This is an eight-step conceptual design process to evaluate the probability of meeting the design constraints. This methodology also allows for the evaluation of new technologies to be implemented into the design.

The TIES process begins with defining the problem with a need established and a market targeted. With the costumer requirements set and the target values established, a baseline concept is created. Next, the design space is explored to determine the feasibility and viability of the baseline aircraft configuration. If the design is neither feasible nor viable, new technologies can be implemented to open up the feasible design space and allow for a plausible solution. After the new technologies are identified, they must be evaluated to determine the physical compatibility of integrating multiple technologies and then the impact on the design, both improvements and degradations, must be determined. These technologies are assessed deterministically. Again, Response Surface Equations (RSEs) are developed to allow for a full-factorial evaluation of the combinations of the technologies. The best combination of technologies is selected and then the design space is again reevaluated for feasibility and viability.

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List of Acronyms

$/RPM	Average Required Yield per Revenue Passenger Mile
Acq $	Acquisition Price
ADECS	Adaptive Engine Control System
ALCCA	Aircraft Life Cycle Cost Analysis
AR	Aspect Ratio
ARHT	Horizontal Tail Aspect Ratio
ARVT	Vertical Tail Aspect Ratio
ASDL	Aerospace Systems Design Laboratory
ASM	Available Seat Mile
BIOSANT	Biologically-Inspired Smart Nanotechnology
CAA	Civil Aviation Authority
CLF	Coach Load Factor
CO2	Carbon Dioxide
COFL	Fuel Cost
CDF	Cumulative Distribution Function
DOC+I	Direct Operating Cost plus Interest
DoD	Department of Defense
DoE	Design of Experiments
FAA	Federal Aviation Administration
FAR	Federal Aviation Regulations
FLF	First Class Load Factor
FLOPS	Flight Optimization System
FPI	Fast Probability Integration
GA	Genetic Algorithm
GWP	Global Warming Potential
ICAO	International Civil Aviation Organization
IOC	Indirect Operating Cost
LEARN1	Airframe Learning Curve Factor for first lot
LEARN2	Airframe Learning Curve Factor for second lot
LEARNA1	Avionics Learning Curve Factor for first lot
LEARNA2	Avionics Learning Curve Factor for second lot
LEARNAS1	Assembly Learning Curve Factor for first lot
LEARNAS2	Assembly Learning Curve Factor for second lot
LEARNFE1	Fixed Eq. Learning Curve Factor for first lot
LEARNFE2	Fixed Eq. Learning Curve Factor for second lot
LdgFL	Landing Field Length
MADM	Multi-Attribute Decision Making
NGP	Next Generation Fire Suppression Technology Program
NOx	Oxides of Nitrogen
NV	Production Quantity
ODP	Ozone Depleting Potential

PAI	Propulsion-Airframe Integration
PDF	Probability Density Function
QFD	Quality Function Deployment
RDT&E	Research, Development, Testing, and Evaluation
RPM	Revenue Passenger-Miles
RTM	Revenue Ton-Miles
RTRTN	Manufacturer Return on Investment
RTRTNA	Airline Return on Investment
SHT	Horizontal Tail Area
SL	Economic Stage Length
SMA	Shape Memory Alloys
SPF	Superplastic Forming
SPGG	Solid Propellant Gas Generator
SVT	Vertical Tail Area
SW	Wing Area
TAROC	Total Airplane Related Operating Costs
TCHT	Horizontal Tail Thickness to Chord Ratio
TCM	Technology Compatibility Matrix
TCVT	Vertical Tail Thickness to Chord Ratio
TIES	Technology Identification, Evaluation, and Selection
TIM	Technology Impact Matrix
TOC	Thickness to Chord Ratio
TOFL	Take Off Field Length
TOGW	Take Off Gross Weight
TOPSIS	Technique for Order Preference by Similarity to Ideal Solution
TR	Taper Ratio
TRHT	Horizontal Tail Taper Ratio
TRL	Technology Readiness Level
TRVT	Vertical Tail Taper Ratio
TWR	Thrust-to-Weight Ratio
U	Utilization
UEET	Ultra Efficient Engine Technology
Vapp	Approach Speed
WAWt	Wing Aerial Weight

INTRODUCTION

An aircraft is a complex system consisting of a combination of propulsion, aerodynamics, structures, control, and other subsystems. Similar to other complex systems, the development of a new aircraft is very cost significant. Traditionally, the design process of an aircraft starts with the sizing of the aircraft via the initial estimate of its design takeoff gross weight. This approach, however, becomes inapplicable when the design concept in hand is revolutionary in nature as the traditional method heavily depends on making crude estimations and approximations from the database of previously existing designs. Moreover, the method involves too many vague assumptions that could affect the reliability of the end product of the conceptual design stage. This situation will cause changes being made to the design in later stages.

As being investigated in the product design process from manufacturing point of view, changes in later stages will correspond to higher added costs compared to that incurred if changes were made in early stages [1]. To avoid this from happening, the knowledge of the design should be increased in the early stages as to ensure that the generated design concept will have high compatibility with the downstream process.

In order to explore the design space, a new method of concept assessment in aircraft design, namely the Technology Identification, Evaluation and Selection (TIES), has been developed at the Georgia Tech Aerospace Systems Design Laboratory (ASDL). TIES is defined as a "comprehensive, structured, and robust methodology for decision making in the early phases of aircraft design" [2]. This allows the designer to determine if there is a feasible and viable design for the given requirements available within the existing level of technology. If the design space does not exist for the current technology, TIES allows for the evaluation of new or upcoming technologies and their impact on the design and will assess different technology combinations. This method will enable "the designer or the decision maker to easily assess and trade-off the impact of various technologies in the absence of sophisticated, time-consuming mathematical formulations" [2]. The TIES method in general comprises of eight steps as listed below:

1. Problem definition
2. Baseline and alternative concepts identification
3. Modeling and simulation
4. Design space exploration
5. System feasibility and viability determination
6. Technology alternatives specification
7. Technology alternatives assessment
8. Selection of best family of alternatives

The generic process of the TIES method is shown in Figure 1 [3].

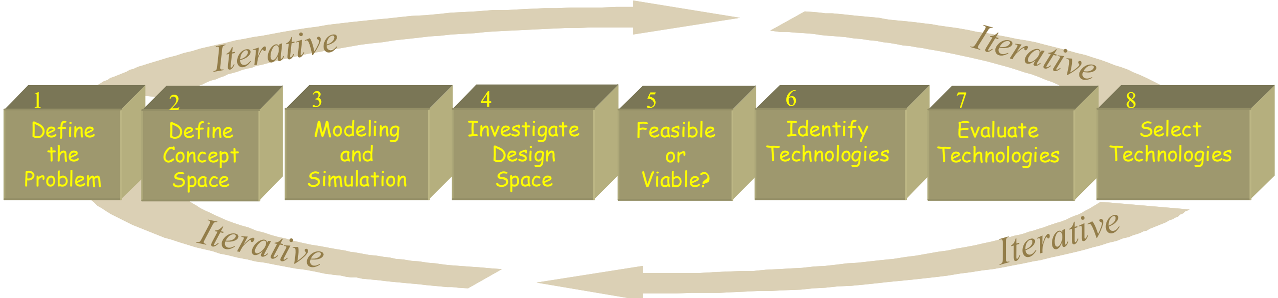


Figure 1: TIES Technical Approach

For this project, the task for the team is to design a 150-passenger commercial transport aircraft by utilizing the TIES method. The project will go through each of the steps of the method as presented in this report. Please, note that all costs and prices are in 1996 dollars.

PROBLEM DEFINITION

The first step in the TIES process is to define the problem. There must be a distinct societal need to drive the design of a new commercial aircraft. The markets that can utilize this type of aircraft as well as competitors must be clearly outlined. In developing a new aircraft, the design must be tailored to the customer requirements as to suit the existing market needs and this is usually achieved by using the Quality Function Deployment (QFD) [1]. This is a method of converting the 'voice of customers' and correlating them to the corresponding 'voice of the engineers'. These system metrics can be objective (maximize, minimize, etc.) or constrained with target values. These requirements will merit if a design is adequate or poor.

The problems that create the need for a new design of a 150-passenger aircraft category can be identified through the assessment of the related operational markets. The important parameters (engineering characteristics of the product) that need to be achieved have been given as results of QFD from previous market studies. These parameters are important in establishing the advantages of the new design against its competitors. Thus, the target or constraint values for the new design are derived by investigating the target markets and the existing competitive aircrafts.

Design Need Identification

The operational markets for a 150-passenger aircraft have been investigated and from the outcome from this assessment, it can be concluded that a need for a new aircraft is tightly related to the growth of both the world Revenue Passenger-Miles (RPM) and Revenue Ton-Miles (RTM), and also the world's air traffic flow pattern. In addition to these factors, the changes in the aviation regulations and airlines operational trend will also drive the development of a new aircraft design. The impacts of these factors in contributing towards the need for a new aircraft design are further discussed.

Growth of Revenue-Passenger Mile (RPM)

A positive future global market forecast has been made by both Boeing and Airbus which runs over the next 20 years period of study. The report published by the former predicted an annual growth of about 4.5% for the world's RPM over the study period [4] while that of the latter put forward an estimated annual increase of 4.9% [5]. It should be noted that both figures were derived by using the year 2000 as the base reference year and changes may occur due to the abnormality trend of the industry with the September 11 tragedy.

A further look into these figures indicates that a larger share of the world's added ASM by the year 2021 will be in the short-haul markets, taking as large as 96% of the total [4]. Short-haul markets in general correspond to the regional and domestic flight operations, which are being dominated by regional jets and intermediate-size aircraft. To further solidify this, Boeing has predicted that by the year 2021, the regional short-haul markets will increase its market share to about 2,736.57 (RPM in billions) as compared to only 1,059.91 (RPM in billions) in 2001 [5].

The future strategy of fragmenting more long-haul flights and airport-pairings is one of the reasons for the projected increase in demand of short-haul flights. Aircraft passengers will prefer to reach their destinations as quick as possible, with reduced number of hub connections and numerous flight segments [4]. "Where possible, airlines will provide passengers point-to-point service on busy routes. When this is not economically feasible, passengers will prefer carriers who move them over a single hub with one-stop connecting service to their final destination" [1]. Generally, the long-haul flights will be fragmented into one long-range flight (maybe inter-regional route) and a short domestic or regional connecting flight. In order to provide a competitively quick connecting service, the airlines will have to increase the frequency of its short-haul flights service and this strategy has been touted as the future "primary form of non-price competition" between airlines [4]. The anticipated consequence impact from this prediction will be an increase in the number of passenger fleets required to cope with the upward trend of the market demand. This also takes into consideration that most of the current fleets will be retired from service by the year 2021. An estimated total of 23,248 new deliveries of passenger aircraft will be needed by the year 2021 to meet the capacity demand, replacing more than 7,327 of the current fleets that are predicted to be removed from service [6]. Figure 2 shows how the flight frequency and airport pairs have increased from 1980 to 2000 [4].

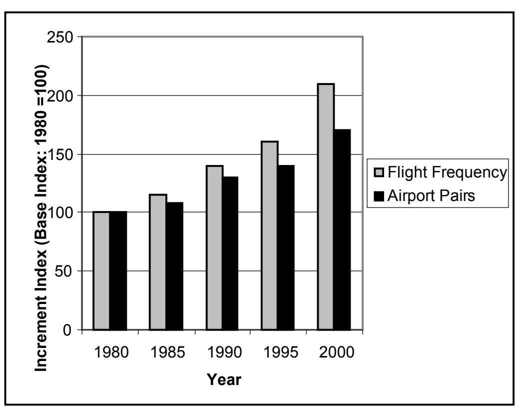


Figure 2: Airlines Provide Passengers with More Frequencies and Airport Pairs

Since the short-haul markets are predicted to take up the biggest portion of the future world's RPM, the future need for new aircraft to operate in these flight routes will be the most demand. Boeing has predicted sales of more than 7,883 single-aisle, 121-170 seats capacity category aircraft for the year 2002-2021, the highest of all seats categories [6]. On the other hand, the highest projected sales for Airbus aircraft are in the 100-175 seats capacity category, with an estimated of 7,570 new deliveries by the year 2019 [5] as shown in Figure 3. These facts correspond well with the predicted short-haul markets growth, as these aircraft types are the current dominant choices for the short-range operations.

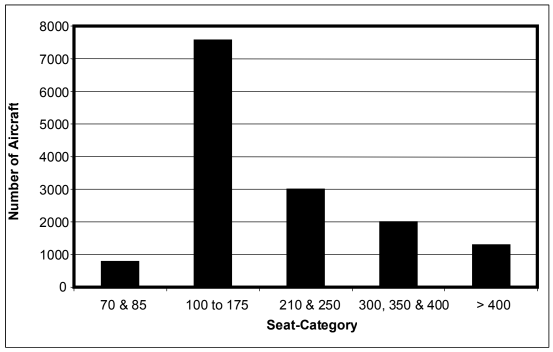


Figure 3: New Passenger Deliveries of Airbus Aircraft

Growth of Revenue-Ton Mile (RTM)

Another factor that creates the need of new aircraft is the increase in the projected world cargo growth. A significant percentage of the revenue of the commercial systems came from the cargo operations, which uses converted transport aircraft. Boeing has predicted that the world cargo will increase at 6.4% annual rate for the next 20 years, which implies an increase from 85.19 billion RTM in 1999 to approximately 292.04 billion RTM in 2019, as illustrated in Figure 4 [6].

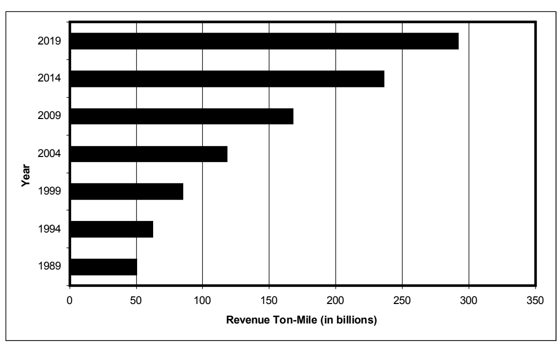


Figure 4: Projected World Air Cargo Growth

The Airbus company, on the hand, predicted a slightly less annual growth rate of 5.7% through the year 2019 [5]. This increase is mainly "stimulated by the development of global e-commerce and manufacturing trends" [5] with the likes of services by UPS, FedEx, and other major carriers.

In parallel response with the projected growth and anticipated retirement for some of the current freighter fleets, Airbus predicted an additional 3,090 total new aircraft will be needed to cope with the cargo market demands by the year 2019, which consist of 2,390 conversions and 700 new freighter aircraft [7]. The forecast by Boeing also put forward a need for about 2,600 new freighters by year 2019, with an estimated 70% of the additional fleets will be from modified passenger and cargo aircraft [5].

A 150-passenger aircraft, as discussed before, is taken as a medium size aircraft category. By looking at the Figure 5 [5], the midsize aircraft, which consists of the medium standard-body and medium wide-body aircrafts, is predicted to have a significant operational market share. This indirectly implies a need for new medium size aircraft (also converted passenger aircraft) to fill in the operational cargo market demands.

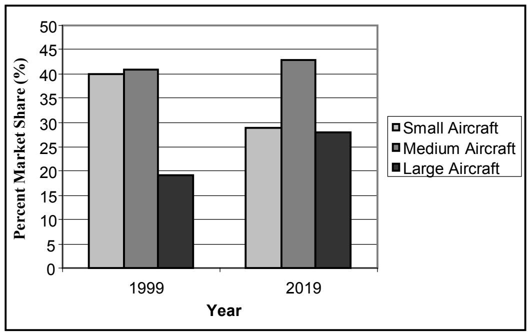


Figure 5: Predictions of World Freighter Fleet Units

Regulation Changes

In addition to the anticipated increase in both RPM and RTM growth, the changes in commercial aviation regulation also imposed a need for a new design of aircraft. It is well known that a major constraint in flight operation is the aviation regulations put forth by the governing bodies in the industry. These include International Civil Aviation Organization (ICAO) and other aviation governing organizations such as Federal Aviation Administration (FAA), Civil Aviation Authority (CAA) and the European Union. One of the most widely used regulations is the Federal Aviation Regulations (FAR) by the FAA. For a transport aircraft, FAA has specified that the aircraft must be aligned with the FAR Part 25, 34, 36, 33, 91 and 121 [8].

For future commercial transport operation, environmental compliance will be a major force in designing a new aircraft. Stricter changes have been made regarding the environmental criteria of the codes by which the emission and the noise levels from the commercial aircraft operation will have to decrease significantly to continue operating. Although these changes will only be effectively employed in the near future, they have already constrained the future operation of most current passenger fleets. Thus, the airlines will need a new ‘environmentally friendly’ design that satisfies the new codes to avoid any complication in their future operation.

From the discussion above, it has been shown that there exists a need for a new design of aircraft to suit the future operational requirements. The design should not just be tailored to provide the capacity for the increased passengers demand or expected cargo growth but also have the performance criteria that follow the governing operational regulations. A new design of a 150 seats capacity passenger aircraft is then found to be relevant to the needs of the market, especially in serving the high demand of short-haul passenger markets with the new regulation constraints.

Target Markets

From the market outlook by Boeing, the domestic flying in North America and Europe have the two largest market shares for the total world's air traffic by the year 2021, with 1,007.02 (RPM in billions) and 694.54 (RPM in billions) respectively [4]. Airbus also predicted that the US domestic sector would have the largest share of the world's traffic at the end of year 2019 with 17% of the total [5]. Therefore, the two main target markets for utilization of the new design will be the North America and Europe regional sectors. This selection of target markets is well justified as the two markets are projected to make up almost 40% of the future total air traffic demand in year 2021[4]. Figure 6 shows the comparisons between the RPM in year 2001 and the predicted RPM in year 2021 for the top five operational commercial transport markets in the world [4].

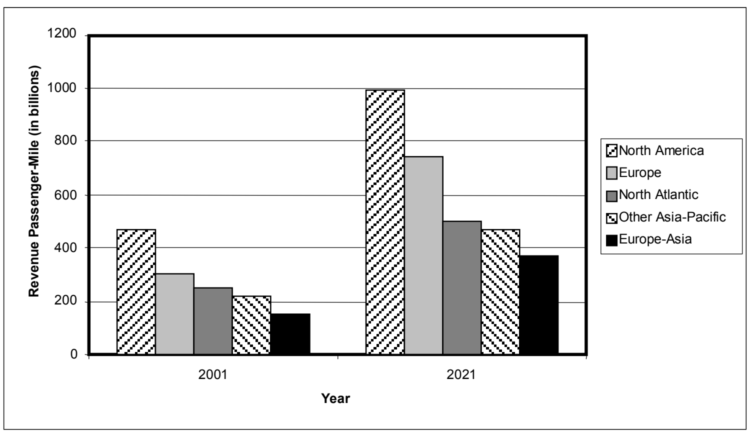


Figure 6: Air Travel Growth by Region

A more thorough investigation on the flight operations in each of these two sectors is required as to capture all the requirements needed for the design to be successfully operational. An airline operates on the basis of the idea of profit optimization. To be competitive in the market, one has to make a good strategy regarding fleets selection and the operational service routes.

Typical flight destinations served coverage in the North America regional sector, taking Boston as the center airport and the capability of a B737-800 aircraft is shown in Figure 7 [12]. In general, the longest short-haul markets flight routes range will be around 1620 nm with the common practice of airport pairings such as Seattle-Chicago (1500 nm) [6].

Figure 7: Typical North American Flight Destinations

For the European sector, the common flight routes coverage are shown in Figure 8 [12], which is configured by using Brussels as the center airport and using the capability of a B737-800 aircraft. The flight routes are shorter than the ones for US domestic flight sector, with the longest being just around 815 nm. Typical airport pairings as shown in the figure are London-Rome (756 nm [9]) and London-Stockholm (810 nm [9]).

Figure 8: Common European Flight Destinations

From the cargo operation point of view, the North America regional market is predicted to undergo a steady growth of 4.3% annually from 2001 to 2019 [6] whereas for the Intra-Europe sector, the growth is expected to be at a base of 5.6% annually for the same study period [6].

Figure 9 shows the predicted trend of cargo traffic growth from the year 2001 to year 2021, with the inclusion of the year 1991-2001 data, for the North American market [6]. On the other hand, Figure 10 shows the predicted trend of cargo traffic growth from the year 2001 to year 2021, with the inclusion of the year 1991-2001 data, for the Intra-European market [6].

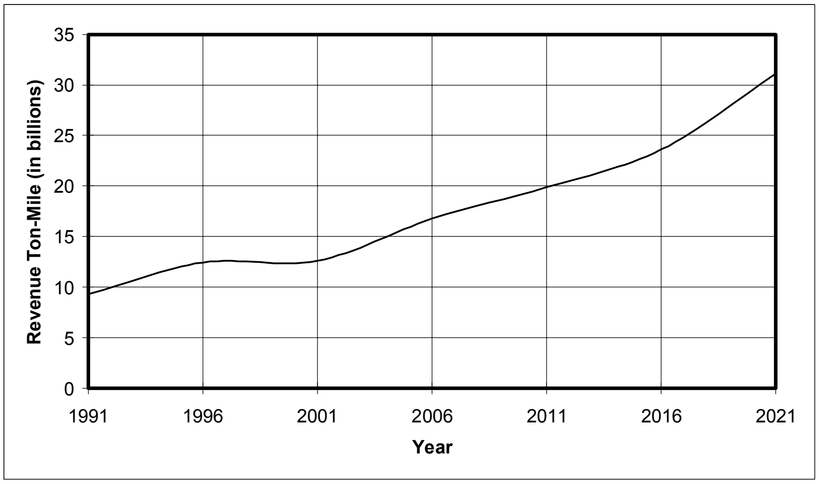


Figure 9: Predicted North American Cargo Market Growth

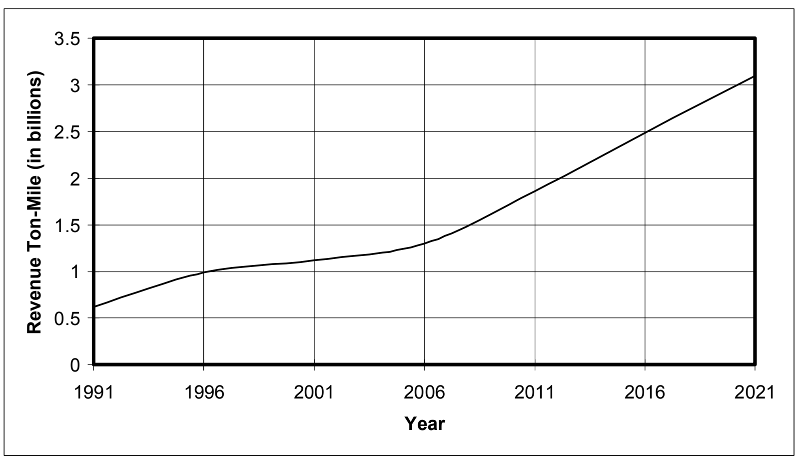


Figure 10: Predicted Intra-European Market Growth

Therefore, the selection of these two target markets, although mostly based on passenger transport operation rather than cargo, still in a good shape since both markets are predicted to have an increase in both operations.

Competitor Aircraft

The competition for the design will come from the existing designs that are currently being utilized in the target markets. It is therefore essential for the design to have the edge against its competitors as to operate in the two markets.

To have a more accurate idea on the competitive existing designs that are currently filling up the operations of intended target markets, one could look through the current fleet utilized by the regional airlines in the respective markets. Southwest Airlines (North America) and Ryanair (Europe) are the two airlines taken as examples for their respective operational flight markets. They are good references since their operations are limited to regional sector only.

The current fleet for Southwest Airlines is summarized in Table I [10]. In similar response, Ryanair also utilizes 44 B737-series aircraft in its operations [11]. Thus, it appears evidently that the current Boeing 737 series are the ones that are heavily utilized for the short-haul markets.

Table I: Current Southwest Airline Fleet

Type	Number	Seats
737-200	27	122
737-300	194	137
737-500	25	122
737-700	120	137

However, apart from the B737 series, there are also other intermediate-size aircraft that are being used to operate the short-haul markets. Among the designs are the A320 family and the MD-80 series aircraft.

A summary of comparison between the A320, MD 82 and B737-800 (the latest in B737-series) in few performance characteristics is shown in Table II [12, 13 &14]. These aircraft are chosen for their similar passenger capacity range as the intended new design. These characteristics would be regarded as references in designing the new design, as the goals of the design is to produce a new design that tops all the existing design in suiting the future market needs.

Table II: Competitive Aircraft Performance Characteristics

Characteristics	B737-800	MD 82	A320
Passengers 2-class configuration 1-class configuration	 162 189	 152 172	 150 164
Max. Cargo Capacity	1,555 ft^3	1,253 ft^3	1,097 ft^3
Maximum Fuel Capacity	6,875 US gal.	5,840 US gal.	7,835 US gal.
Maximum Takeoff Weight	174,200 (lb.)	149,500 (lb.)	162,000 (lb.)
Max. Range	2,945 nm	2,046 nm	3,050 nm
Typical Cruise Speed (at 35000 ft)	530 mi/h (0.785 Mach)	504 mi/h (0.76 Mach)	545 mi/h (0.82 Mach)

System Level Metrics

The customer requirements (as given by the results of previous market studies) can be organized into quantifiable system metrics. These are categorized into performance, economics, and miscellaneous metrics. These metrics are defined below and are summarized in Table III, with their associated constraints.

Performance Metrics

Approach Speed (Vapp) is defined as the stall speed of the aircraft times a safety factor (1.3 for commercial aircraft). The approach speed is important to passenger, crew, and ground safety while landing. Enough speed is necessary to control the aircraft while landing and is greatly affected by the wing area; therefore a minimization of the approach speed induces an increased wing area. A lower approach speed could also be accomplished using control surfaces for increasing the lift of the aircraft produced while landing.

Landing Field Length (LdgFL) is defined as the horizontal distance traveled by an aircraft from the point at which the aircraft is 50 feet high from the ground to the point at which the aircraft reaches a complete stop. FAR requirements include a 66.7 % additional field length to account for irregular landing procedures [15]. The landing field length limits the aircraft to airports that have a field length distance of at least the same length required by the aircraft. This metric is directly related to approach speed. A higher approach speed requires a longer runway and vice-versa.

Takeoff Field Length (TOFL) is defined as the distanced horizontally traveled by an aircraft from the point of initial acceleration to the point at which the aircraft is 35 feet high from the ground. It is also taken in consideration the distance required for a complete stop in case of engine failure or other emergencies during takeoff. This metric also limits the aircraft to airports with a minimum field length distance equal to the takeoff field length required by the aircraft. Takeoff field length is largely affected by the wing area and thrust. A shorter takeoff field length requires a combination of more thrust and a larger wing area.

CO_2/ASM (CO_2) is the amount (lb) of CO_2 per available seat mile. Laws concerning the environment limit the emissions of this greenhouse gas. It is important to minimize it in order to create a cleaner aircraft complying with all regulations. The 150-passenger aircraft design must consider the reduction of CO_2 emissions by 25% of the baseline value by 2007 and a 50% reduction by 2022. $CO_2$is defined as [16]:

$$CO_2 / ASM = 3.155 \frac{Mission\_Block\_Fuel}{(Total\_Pax\_Capacity) * (Range)} \quad \text{Eqn. (1)}$$

NOx are the oxides of nitrogen emissions, which includes NO and NO_2. NO_2 is a reddish brown gas and is an active compound in the photochemical smog formation. NO is a precursor to the formation of NO_2. It is also important to minimize this parameter for environmental reasons. Mostly airlines are concerned with this metric because of regulations that each aircraft has to comply with. The goal for the design of the 150-passenger aircraft is to reduced the NOx emissions baseline 25% by 2007 and 50% by 2022.

Takeoff Gross Weight (TOGW) is the total weight of the aircraft before starting the specified mission. It is equal to the sum of the empty weight, fuel weight, crew weight, and payload weight. It is closely related to all the economics of the aircraft and closely related to the operation costs. It is typically used as a minimizing factor in design. The gross weight of the aircraft is used for specifying what kind of aircraft it will be, its size, range, payload capabilities, thrust required, and what airports can handle that size of aircraft.

Economics Metrics

The Acquisition Price (Acq $) is the cost for the airline to purchase the airplane from a manufacturer. The less expensive the aircraft is for the manufacturer to build, the less the price must be to the airline. The cheaper it is to acquire an airplane, the lower ticket prices for passengers can be allowed for airlines to make a certain profit and decrease their investment. It is desirable to minimize the acquisition price that the airline must pay for an aircraft.

Research, Development, Testing, and Evaluation Costs (RDT&E) are costs to the manufacturer for the research and development required for the design of the aircraft as well as flight-testing and FAA certification. The acquisition price is influenced by the amount the manufacturer spends on RDT&E costs and that too is then reflected on how much airlines must charge passengers for tickets.

The Average Required Yield per Revenue Passenger Mile ($/RPM) is the amount of money that the airline must charge each passenger-per-mile of flight to achieve a particular return on investment. The lower this amount is, the more money the airline can collect as profit. This also affects the amount that the airline must charge the passenger for a ticket.

The Direct Operating Cost plus Interest (DOC+I) reflects on the affordability of the airplane. This cost incorporates all costs associated with the operation of the aircraft for each one-way flight including: fuel, oil, crew salaries, airframe maintenance, depreciation, insurance, and landing fees plus the interest the airline pays on the loan for the purchase of the aircraft. These costs are measured in cost per aircraft seat mile. The amount of the DOC+I consists of 55% of the passenger's ticket price [17]. The larger the DOC+I, the more passengers must pay for a ticket or more passengers must be on the airplane for the flight to be profitable for the airline.

The Total Airplane Related Operating Costs (TAROC) includes all costs associated with the aircraft except for passenger and cargo related costs. This includes the DOC+I plus all ground handling, property, maintenance, depreciation, communication and control, and general and administrative costs, which accounts for 10% of the passenger's ticket price [17]. This is measured in dollars per aircraft seat mile, which is similar to revenue passenger mile except that it includes both empty and occupied seats. The lower this cost is, the cheaper it is for the airline to operate the aircraft.

The objective for each economic parameter will be minimization in this design study. By reducing any of the costs associated with the aircraft, either in RDT&E, acquisition price, or operating costs, the overall life-cycle-cost for the airplane can be reduced. This will increase the yield for the airline, decrease the passenger's ticket price, and increase the number of aircraft sales for the manufacturer.

Miscellaneous Metrics

The only miscellaneous parameter that must be considered is the Wing Aerial Weight (WAWt). This is a parameter on the structural performance merit of the wing. The calculation for WAWt [16] is:

$$WAWt = \frac{WingWeight}{WingArea} \qquad \text{Eqn. (2)}$$

In aircraft design, weight has a large effect on the performance of the aircraft. The less each component weighs, the less lift required to fly the airplane. Therefore, it is desirable to minimize the WAWt because the less the wing weighs with the same wing area; the larger the lift is for that configuration. The material of the wing, which is directly linked to its weight, determines the process necessary for manufacturing.

The values of the baseline aircraft and the desired targets are displayed in Table III.

Table III: System Level Metrics

Metric	Baseline	Target/Constraint	Units
Performance			
Approach Speed (Vapp)	106.8	< 130	knots
Landing Field Length (LdgFL)	4897	< 7000	ft
Takeoff Field Length (TOFL)	5367	< 7000	ft
CO_2/ASM (CO_2)	0.24605	-25 % for 2007 -50 % for 2022	lb/ASM
NOx (NOx)	456	-25 % for 2007 -50 % for 2022	lb
Takeoff Gross Weight (TOGW)	148,219	< 175,000	lbf
Economics			
Acquisition Price (Acq $)	59.259	Minimize	M$
Research, Development, Testing & Evaluation Costs (RDT&E)	4,721.8	Minimize	M$
Average Required Yield per Revenue Passenger Mile ($/RPM)	0.134	Minimize	$
Total Airplane Related Operating Costs (TAROC)	6.752	Minimize	¢/ASM
Direct Operating Cost plus Interest (DOC+I)	5.279	-25% for 2007 -50% for 2022	¢/ASM
Miscellaneous			
Wing Aerial Weight (WAWt)	10.48	Minimize	lb/ft^2

BASELINE AND ALTERNATIVE CONCEPTS IDENTIFICATION

In the conceptual design of a commercial transport, there are a plethora of combinations of subsystems that could satisfy the requirements. This next step in the TIES process involves the identification of possible alternatives for the configuration of the aircraft and its performance by looking at the trend of operation of its intended target markets and its competitors. This can be achieved through brainstorming and organizing the options in a Morphological Matrix. From the options, a baseline is chosen. Then, the design variables of importance are chosen and baseline values are assigned to them for initial sizing. This step also involves choosing ranges for the design variables.

Alternatives for the baseline that were considered are listed in Table IV. The main configuration of the aircraft (wing and tail, dihedral wing, conventional fuselage, and low wing) was chosen to be similar to the current aircraft in the market. The morphological matrix also shows alternatives for the materials used in the production of the aircraft, and for the study, aluminum was chosen for the wing and fuselage. The concept selected is just one of the possible 12 million combinations.

Table IV: Morphological Matrix

	Alternatives Characteristics	1	2	3	4
Configuration	Vehicle	Wing and Tail	Wing And Canard	Wing, Tail, and Canard	Wing
	Dihedral Angle	Dihedral	Anhedral	Flat	
	Fuselage	Conventional	Non-conventional		
	Wing Position	Parasol Wing	High Wing	Mid Wing	Low Wing
	Pilot Visibility	Synthetic Vision	Conventional		
	Cabin Layout	1 class	2 classes	3 classes	
Mission	Range (nm)	2000	3000	4500	
	Passengers	100	150	200	250
	Cruise Mach Number	0.700	0.785	0.830	0.900
Propulsion	Type	Turbojet	Turboprop	Turbofan	
	Engines	2	3	4	
	By-pass	N/A	Low	High	
Structures	Wing Materials	Aluminum	Composites	Titanium	Aluminum and Composites
	Fuselage Materials	Aluminum	Composites	Titanium	Aluminum and Composites

The design variables of importance are those shown in Table V. These variables represent the design space to be investigated in the study. Once the baseline description is chosen, a sizing and synthesis code was run and the baseline variables were obtained as those representing an airplane that could be built in the year 1997. A range for these variables was carefully chosen in order to maintain the sizing and synthesis code from producing invalid data or crashing (also shown in Table V). The sizing and synthesis code used is very sensitive to large variations of parameters, especially T/W and W/S, therefore high attention when establishing the for T/W ratio and wing area. The table shows that the ranges vary between 5% and 20% for most cases.

Table V: Design Variable Ranges and Baseline Values

Design Variable	Description	Low Limit	Baseline	High Limit	Units
SW	Wing area	1000	1310	1500	ft^2
TWR	Thrust to weight ratio	0.3	0.3098	0.34	~
AR	Wing aspect ratio	7.0	8.78	11.0	~
TR	Wing taper ratio	0.2	0.25	0.3	~
TOC (1)	Wing thickness-to-chord ratio at root	0.1	0.13	0.14	~
TOC (3)	Wing thickness-to-chord ratio at tip	0.1	0.13	0.14	~
SWEEP	Wing quarter-chord sweep	20	20	30	deg
ARHT	HT aspect ratio	4	5.67	7.5	~
TRHT	HT taper ratio	0.2	0.281	0.36	~
TCHT	HT thickness-to-chord ratio	0.06	0.09	0.12	~
SHT	HT area	150	201	250	ft^2
ARVT	VT aspect ratio	0.9	1.24	1.6	~
TRVT	VT taper ratio	0.27	0.386	0.5	~
TCVT	VT thickness-to-chord ratio	0.06	0.09	0.12	~
SVT	VT area	100	153	200	ft^2

The baseline aircraft for this study is a medium range commercial transport, carrying 150 (12 first class, 138 tourist class) passengers up to 3000 nm. It has two turbofan engines with high by-pass ratio. The aircraft is designed to cruise at a Mach number of 0.785 at 40,000 feet in altitude. Figure 11, which shows the exterior physical dimensions of the 737-800, is taken as a valid representation of the baseline aircraft of this study [12]. Table VI, compares some of the features of the baseline aircraft to the competitors.

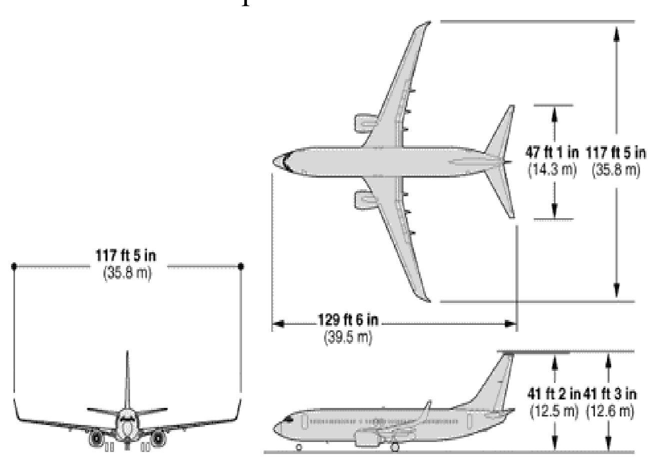


Figure 11: Exterior Dimensions of Boeing 737-800

Table VI: Baseline Aircraft Dimensions and Parameters

Dimension	Boeing 737-800	Airbus A320	Study Aircraft
Overall Length	129ft 6in	123ft 3 in	117ft 10in
Wing Span (geometric)	117ft 5in	111ft 10in	107ft 3in
Wing Area	1341 ft^2	1320 ft^2	Varies
Maximum Takeoff Weight	174,200 lbs	162,000 lbs	Varies
Typical Seating (first, economy)	12, 150	12, 138	12, 138
Range	2,945 nm	3,050 nm	3,000 nm
Maximum Operating Mach Number	0.82 M	0.82 M	0.825 M

MODELING AND SIMULATION

For the concepts identified in the Morphological Matrix, a modeling and simulation environment is needed for rapidly assessment so that tradeoffs can be performed. The use of a vehicle sizing and synthesis code allows for these tradeoff studies.

The modeling and simulation environment is provided by the usage of the Flight Optimization System (FLOPS). This is an aircraft sizing code which includes subprograms for weights, aerodynamics, engine cycle analysis and performance, mission performance, takeoff and landing, and program control [18]. This program has been developed by NASA Langley Research Center for assistance in the conceptual phase of design and analysis in aircraft concepts. FLOPS is linked to Aircraft Life Cycle Cost Analysis (ALCCA) for the prediction of the economics involved with the aircraft design, manufacturing, and service.

ALCCA has been modified by Georgia Tech Aerospace Systems Design Laboratory and has been seamlessly linked to FLOPS. The user inputs economic variables into the FLOPS input file and ALCCA computes economic metrics including RDT&E costs, manufacturer and airline return on investment (ROI) and cash flows, acquisition costs, direct and indirect operating costs, and annual interest rates [19].

Design Mission

The main goal in the design of the 150-passenger aircraft is to minimize the fuel consumption. The mission for the design aircraft is that of a typical commercial transport aircraft mission. In other words, the aircraft will generally be used to transport passengers from one airport to another. In a nominal flight operation, the design is supposed to do the sequential mission segments of taxi out-takeoff-climb-cruise-descent-land-taxi in. In addition to that, a reserve segment is also taken into consideration in sizing the aircraft. The reserve segment of the mission profile will consist of additional climb-cruise-descent-hold mission legs, in sequential order.

There are different optimization approaches to the aircraft operation for the climb, cruise and descent segments of the mission. For the climb segment, the aircraft is expected to climb to a maximum cruise altitude of 40,000 feet in a minimum fuel-to-climb manner. However, the climb speed will be governed by the FAA regulation, which limits the climb speed to a maximum 250 knots calibrated airspeed below 10,000 ft altitude.

The two cruise segments for the main mission and the reserve mission are subjected to different optimization approaches. For the cruise segment of the main mission, the aircraft operation will try to achieve cruise at optimum altitude for specific range at a fixed Mach number of 0.785. The optimization is done while also trying to minimize the fuel consumed. On the other hand, for the cruise segment of the reserve mission, the cruise altitude is fixed at 25,000 ft and the aircraft is expected to fly at an optimum Mach number for endurance, which relates to the minimization of the fuel flow, at that particular cruise altitude. The maximum cruising Mach number for this segment is taken as 0.6 and similar to the main mission cruise, the approach should also try to minimize the emission level of NO_X instead of just fuel. For both cruise segments, the instantaneous rate of climb for cruise ceiling calculation will be at 300 ft/min.

For the descent segment, the aircraft is to descent at an optimum lift-to-drag ratio. The descent speed will also be governed by the FAA regulation, which limits the maximum of 250 knots calibrated airspeed below 10,000 ft altitude. All the mission segments are summarized in the design mission profile as depicted in Figure 12 and listed Table VII.

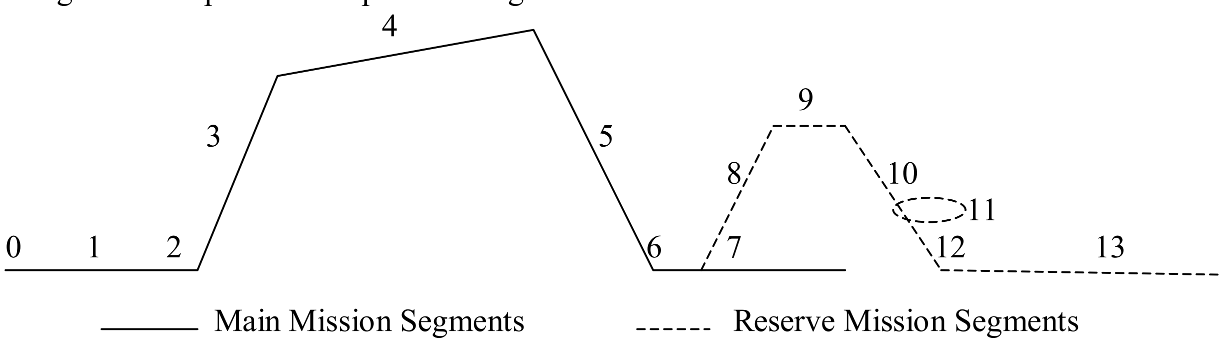


Figure 12: Mission Profile

Table VII: Summary Description on Each Mission Segment Profile

Leg No.	Segment	Description
0	Warm-up	Allocated time: 9 minutes
1	Taxi-out	
2	Takeoff	Takeoff time: 2 minutes at maximum 7000ft takeoff length.
3, 8	Climb	Climb with minimum fuel-to-climb profile optimization.
4	Mission Cruise	Cruise climb to optimum altitude (1000ft $\leq h \leq$ 40000ft) at M=0.785
5, 10	Descent	Descent with optimum lift-to-drag ratio.
9	Reserve Cruise	Cruise at optimum Mach number at fixed 25000ft cruise altitude and M≤0.6. (minimization of the fuel flow)
11	Hold (loiter)	Hold at optimum altitude, h at fixed cruise speed (M=0.785 and 1000ft $\leq h \leq$ 40000ft) for 45 minutes.
6, 12	Landing	Approach time allocated is 5 minutes and missed approach time is 4 minutes.
7, 13	Taxi-in	Allocated time: 5 minutes

Some assumptions have been made in association to the sizing of the design and for assessing the economic feasibility of the design in hand. These assumptions, especially from the sizing point of view, are closely related to the outcome of the Morphological Matrix completed in Step 2.

The design of a 150-passenger vehicle (12 business class and 138 economy class), requires 2 people for the flight crew and 4 people for the cabin crew in a 3000nm mission flight range. The weight for each passenger is assumed to be 165 pounds with an additional 44 pounds for baggage. As can be seen from the optimization approach discussed before, the maximum cruise altitude is taken as 40,000 ft and the fixed cruise Mach number is 0.785.

Also included into consideration are the reserve mission segments, where additional range of 150nm to alternate airport, with cruise at fixed altitude of 25,000 ft at an optimum Mach number and also a hold time of 45 minutes with Mach 0.785 at optimum altitude.

The aircraft configuration will be conventional, as defined by the result of the Morphological Matrix, which indicates a wing-tail-fuselage configuration combination, with 2 engines mounted on the wing (one on each side), and the baseline values for the variables in Table III. A more detailed summary on these sizing assumptions, in addition to those specified above, is provided in Appendix A.

In addition to the sizing assumptions, the design also has to be assessed from the economic point of vie to ensure that the resulting design is profitable and economically feasible. The assumptions that have been made in investigating the economic feasibility of the design are tabulated in Appendix A.

Engine Performance

The engine that has been selected for this aircraft is a NASA Lewis engine. There are two wing-mounted engines that have 26,000 lbf of thrust each at sea level static (SLS). The fuel tanks are located in the wings with a total fuel capacity of 41,050.7 lbm. The thrust versus Mach number at different altitudes for this engine is located in Figure 13. The plot shows that the thrust available decreases with altitude and Mach number. As the altitude increases, the density of the air decreases. From the continuity equation $\dot{m}_{air} = \rho_\infty A_i v_\infty$ and thus a lower density means a lower mass flow rate, resulting in less thrust. Similarly, the mass flow rate is increased by a larger velocity, or Mach number. However, from the thrust equation [20]:

$$T = \dot{m}_{air}(v_e - v_\infty) + (p_e - p_\infty)A_e \qquad \text{Eqn. (3)}$$

as v_∞ increase, the term $(v_e - v_\infty)$ decreases, thus decreasing the thrust. According to Anderson in reference 20, the two affect essentially cancel each other out, resulting in an almost constant thrust for subsonic speeds. For the design point at 40,000 feet in altitude and a Mach number of 0.785, the thrust approximately 5100 lbf. The fuel flow for this engine decreases with altitude as shown in Figure 14. For the design point, the fuel flow is roughly 3000 lb/hr. These are both plotted at maximum power.

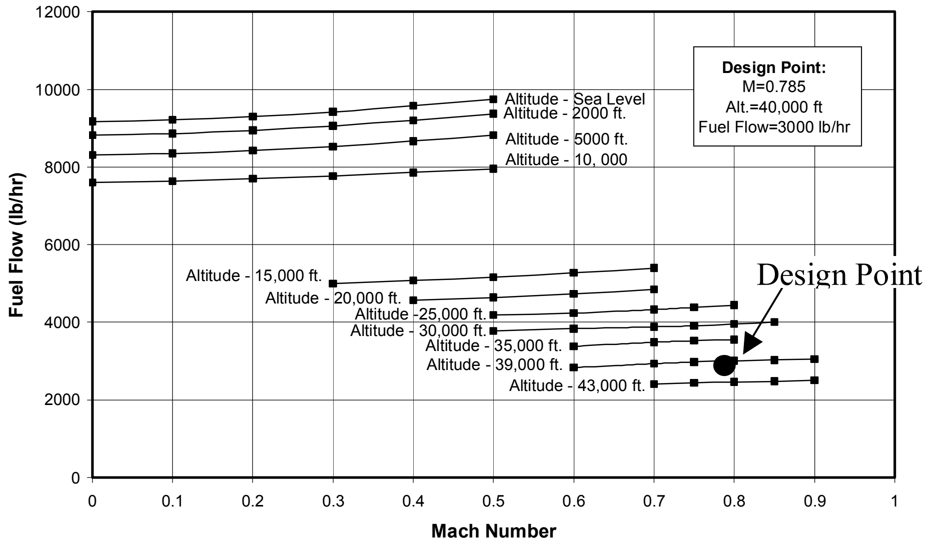


Figure 13: Thrust vs. Mach Number at Different Altitudes at Maximum Power

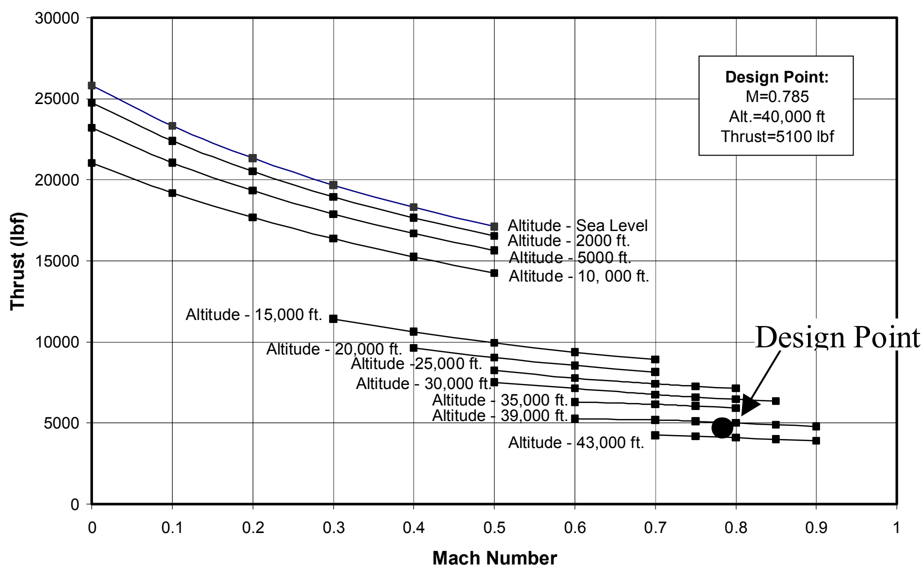


Figure 14: Fuel Flow vs. Mach Number at Different Altitudes at Maximum Power

Drag Polars

Drag polars for the baseline aircraft at different Mach numbers at sea level and at a cruise altitude of 40,000 ft. are located in Figure 15 and Figure 16, respectively. At a Mach number of 0.85, the effects of transonic flow are visible by the large increase in the drag coefficients.

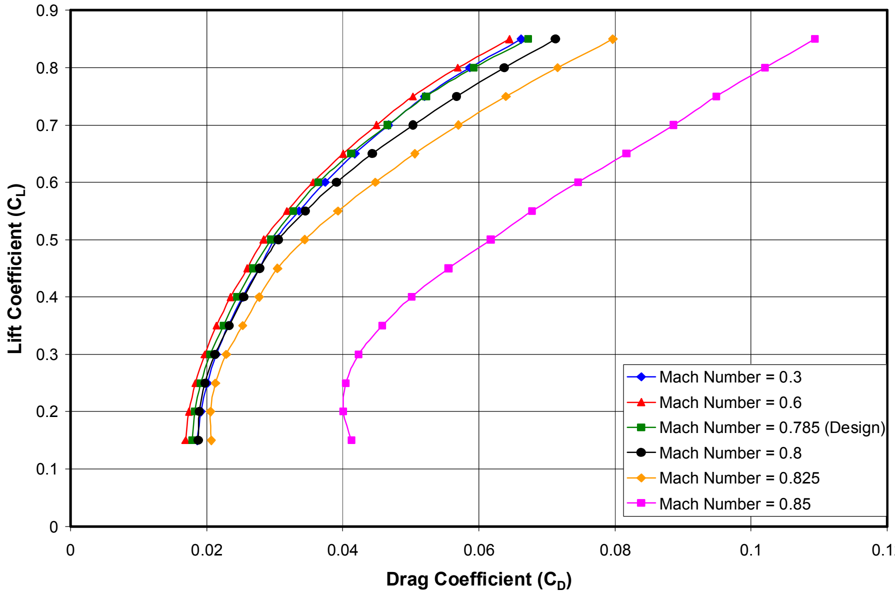


Figure 15: Drag Polar at Sea Level for Different Mach Numbers

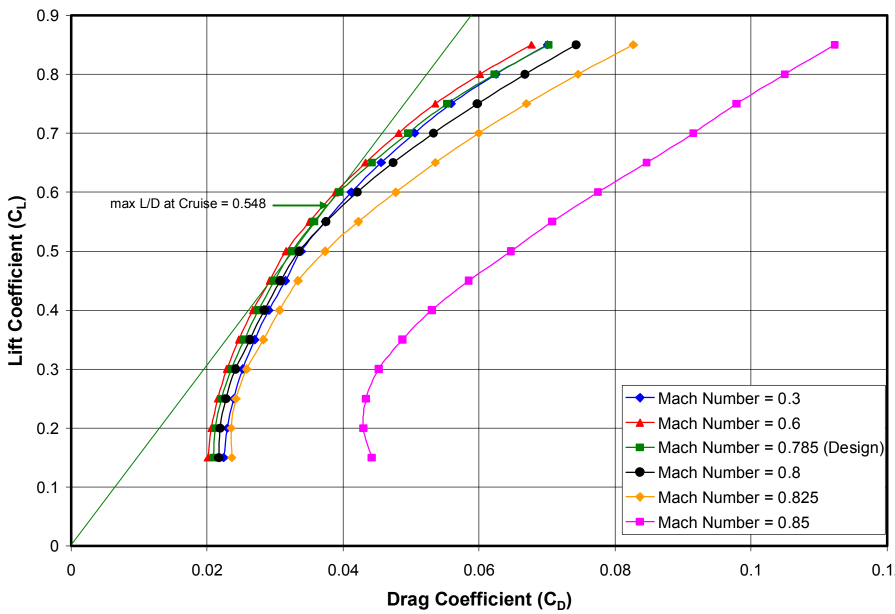


Figure 16: Drag Polar at Cruise Altitude of 40,000 ft. for Different Mach Numbers

Airframe Manufacturer Related Information

The design and manufacturing of the 150 passenger airplane will proceed over a 20 year period. The first five years are allocated for the RDT&E of the airplane. This cost will be $4,718 million and is a set cost no matter how many airplanes are manufactured. The next 15 years will be the production of 800 aircraft. The Airframe manufacturer's cash flow is shown in Figure 17. This amount comprises of the manufacturing costs (airframe, propulsion, and avionics), the RDT&E costs, and the annual income to the manufacturer. The manufacturer demands a 5% down payment on the aircraft, five years before delivery. The cost for manufacturing is $44.8 million per aircraft and is sold with a 12% Return of Investment (ROI) for the manufacturer at $59.2 million. The manufacturer will break even within the twelfth year (141 month) of production. This will be the 326 unit sold out of 800 units. The sensitivity of how much ROI the manufacturer can receive for different aircraft prices is shown in Figure 18. All prices are in 1996 dollars.

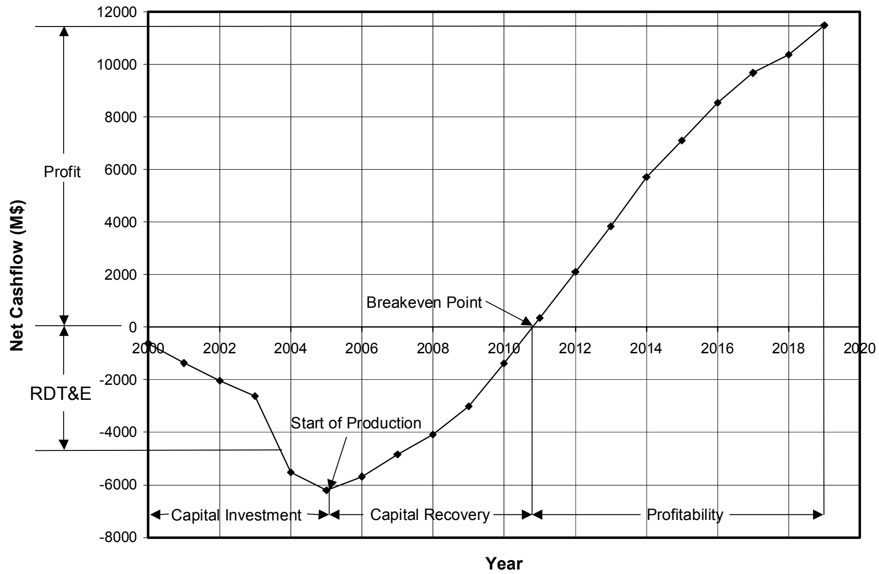


Figure 17: Manufacturer's Cash Flow

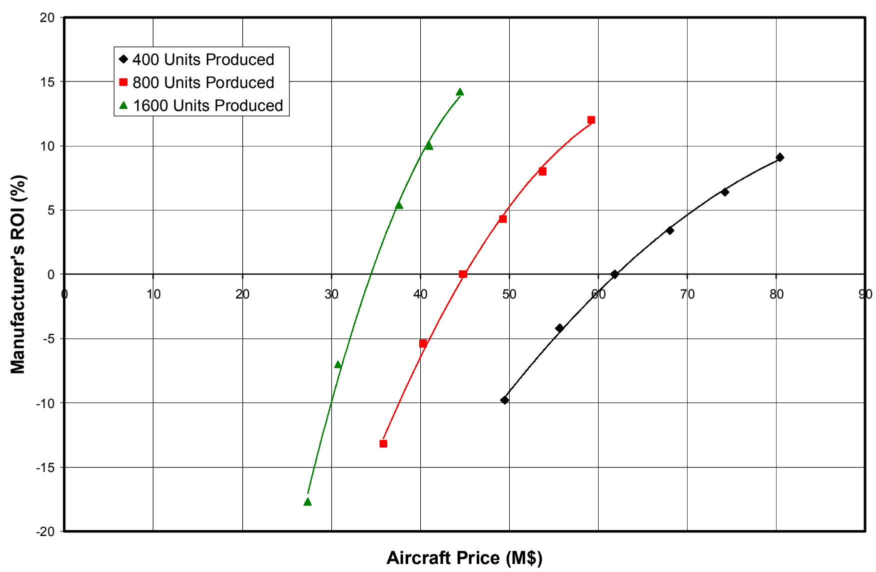


Figure 18: Sensitivity of Manufacturer's ROI as a Function of Aircraft Price for Different Production Quantities

The number of aircraft produced varies from year to year. The program starts off slow, with a production of three aircraft for each month. During the middle segments of production, this number doubles for each month. The production schedule for the 15 years is shown in Table VIII.

Table VIII: Production Schedule

Year	Monthly Rate for Each Year of Program	Number of Units Produced in that Year
1	3	36
2	3	36
3	3	36
4	3	56
5	5	72
6	6	72
7	6	72
8	6	72
9	6	72
10	6	72
11	5	60
12	5	60
13	4	48
14	3	36
15	3	36

The acquisition cost per unit to the manufacturer as a function of the number of units produced is located in Figure 19. The cost to the manufacturer for one unit is over 100 times that to manufacture 800. This is because the RTD&E costs are the same no matter how many units are manufactured and costs for airframe, propulsion, and avionics components are cheaper, the more is produced. It is also because the manufacturer gets better at building aircraft with more practice; the more they build the best, faster, and cheaper it is to make.

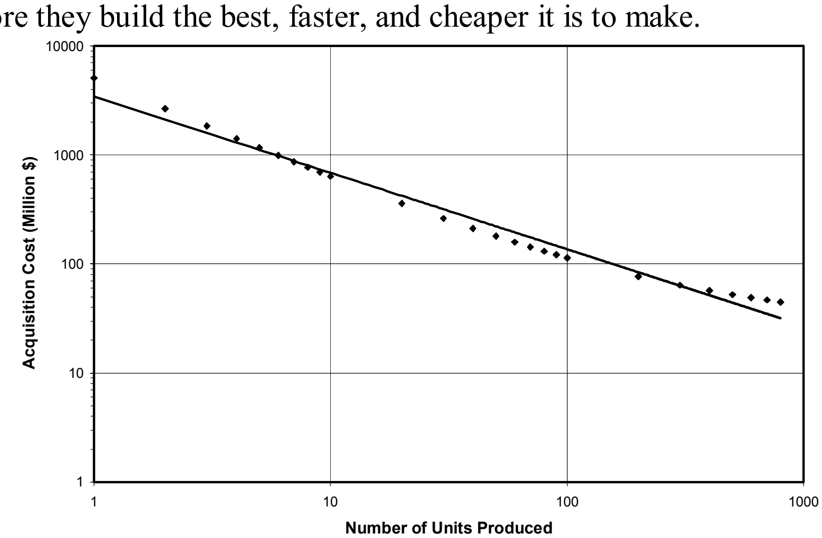
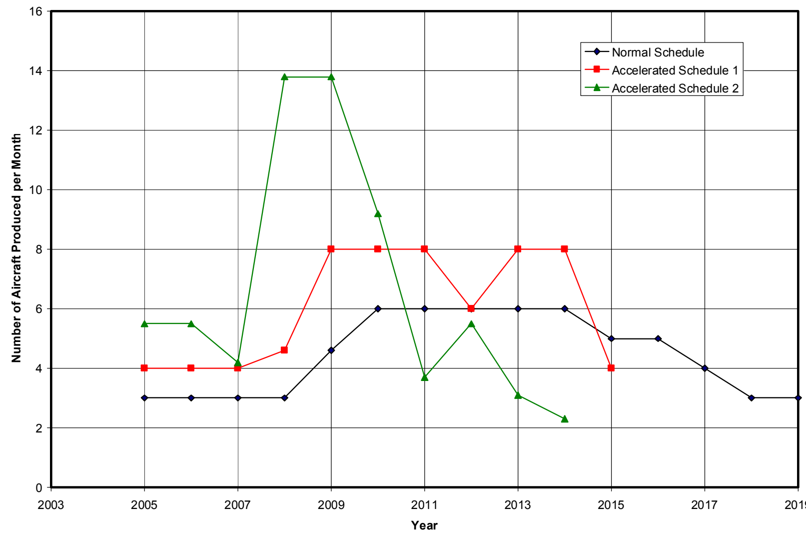


Figure 19: Acquisition Cost as a Function of Units Produced

A short study of the effects of altering the production schedule was performed. Figure 20 shows the normal production schedule for the study and a couple of accelerated schedules. This study included the effects on manufactures cash flow, breakeven unit, and acquisition price with the same number of aircraft being produced overall (800).



	Acquisition Price
Normal Schedule	$59.2 mil
Accel. 1	$55.4 mil
Accel. 2	$52.3 mil

Figure 20: Study on Production Schedule

These changes in production schedule alter the cumulative manufacturer's cash flow as shown in Figure 21. The figure shows that accelerating the production schedule results in a lower minimum cash flow (less maximum loss), but at a higher amount of profit at any time in the process due to the fact that more aircraft are being produced and sold. This as a result changes the acquisition price for the costumer, reducing the price when accelerating the schedule.

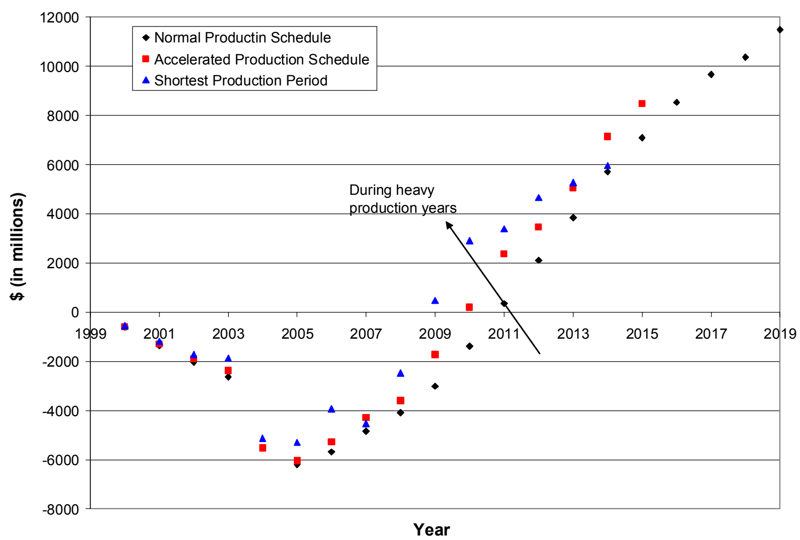


Figure 21: Impact of Production Schedule on Manufacturer's Cash Flow

These alterations also affect the breakeven month and the breakeven aircraft as shown in IX. It is reasonable to conclude that at accelerated production rates, the manufacturer will break even at a sooner time because they are selling a larger number of aircraft even though at a lower price.

Table IX: Effect on Breakeven Moth and Unit

Schedule	Breakeven Month	Breakeven Unit
Normal	141	326
Accelerated 1	130	388
Accelerated (shortest)	118	505

Airline Related Information

Operating Costs for the airline can be broken down into many components. The Direct Operating Costs (DOC) include all costs associated with the operation of the airplane. The Indirect Operating Costs (IOC) are all other costs associated with the operation of the airline and comfort for the passengers. The DOC and IOC breakdown are shown in Figures 22 and Figure 23. The Total Operating Cost (TOC) is both DOC plus IOC and amounts to $15,944/trip.

Direct Operating Costs	$/trip
Flight Crew	1058
Fuel and Oil	1230
Airframe Labor	1205.7
Engine Labor	211.3
Engine Material Cost	500
Depreciation	1643
Financing	1893
Hull Insurance	128
TOTAL	**7860**

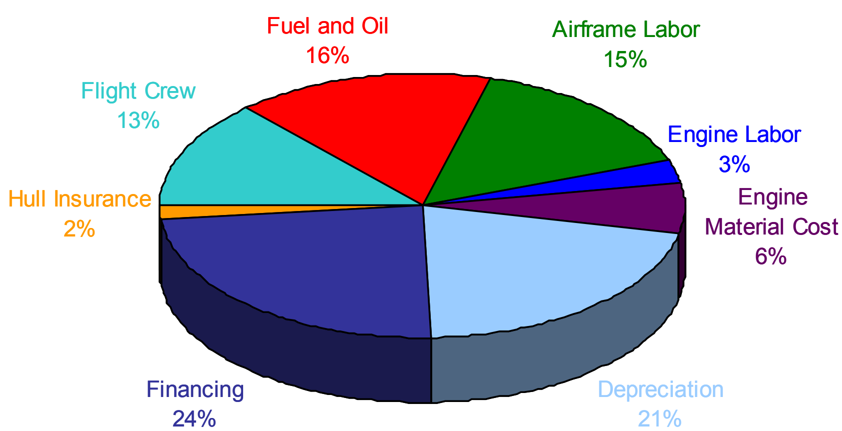


Figure 22: Direct Operating Costs Breakdown

Indirect Operating Costs	$/trip
System Maintenance	193
Local Maintenance	771
Aircraft Servicing	517
Cabin Crew	722
Food and Beveages	512
Passenger Handling	1171
Baggage and Cargo Handling	528
Communiations Public Relations Reservations	2623
General and Administrative	1047
TOTAL	**8084**

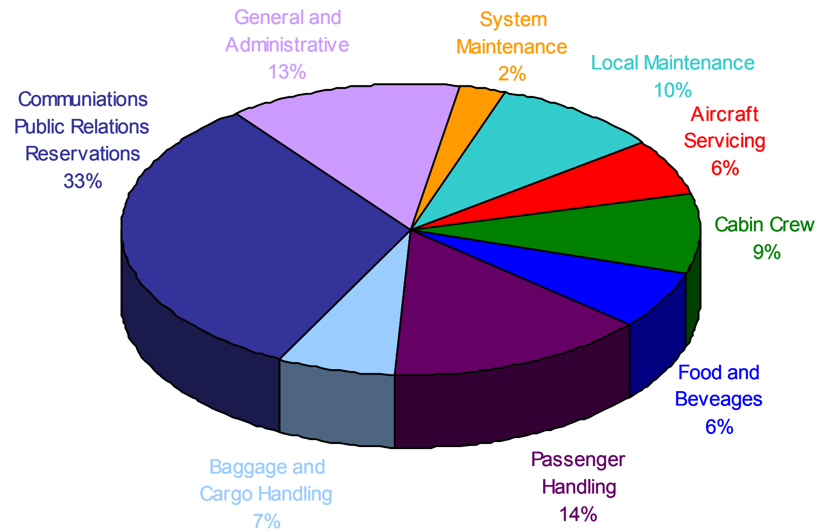


Figure 23: Indirect Operating Costs Breakdown

The acquisition price of the aircraft is $59.209 million. The Airline ROI for the aircraft is 10%. As the acquisition price decreases, the airline ROI increases. This is a linear relationship as shown in Figure 24.

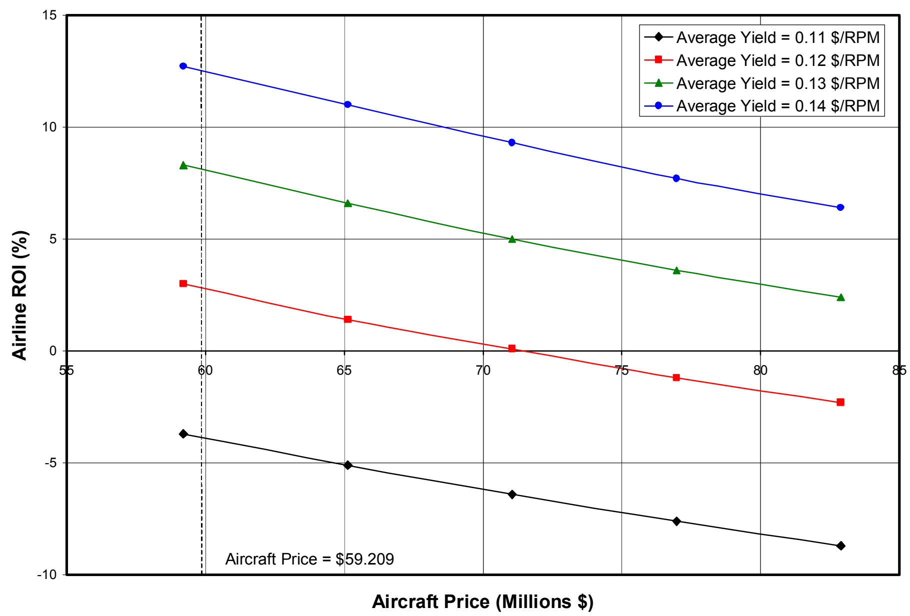


Figure 24: Airline ROI as a Function of Aircraft Price for Different Average Yields

After the initial investment the airline makes by purchasing an aircraft, their ROI for the operation of the vehicle varies over time. In order for the airline to receive an ROI of 10%, they must charge the passenger 0.12$/RPM. The following are terms associated operation ROI:

- The *net income*, or the gross income returned by an investment remains constant over the 20 year period.

- The *operating cost to the airline* is the direct and indirect operating costs associated with the functioning of the airline as an entire system.
- *Interest* accumulates on the loan that the airline must take out for the acquisition of the airplane.
- *Depreciation* is the value the airplane decreases over time, which is at a constant rate.
- The *earnings before tax* are the annual revenue minus the operating costs. In this case, income tax did not show up until 2019.
- The *Net Cash Flow* is a measure of an organization's liquidity that usually consists of net income after taxes plus non-cash charges (as depreciation) against income.
- *Discounted Cash Flow* is the value of future money today.

Table X illustrates how the ROI for the operation of the aircraft varies over time. Plots of how interest, net and discounted cash flow, operating cost, and earnings before tax vary over the years are displayed in Figures 25, 26, and 27, respectively.

Table X: ROI for the Operation of the Aircraft

Year	Annual Revenue	Operating Cost	Interest	Depreciation	Earnings Before Tax	Net Earnings	Net Cash Flow	Discounted Cash Flow
2001	23.856	27.53	4.737	2.664	-3.673	-3.673	-55.481	-55.481
2002	23.856	27.426	4.633	2.664	-3.57	-3.57	3.728	3.623
2003	23.856	27.314	4.521	2.664	-3.458	-3.458	3.728	3.521
2004	23.856	27.193	4.401	2.664	-3.337	-3.337	3.728	3.421
2005	23.856	27.063	4.27	2.664	-3.207	-3.207	3.728	3.325
2006	23.856	26.922	4.129	2.664	-3.066	-3.066	3.728	3.231
2007	23.856	26.77	3.977	2.664	-2.914	-2.914	3.728	3.14
2008	23.856	26.606	3.813	2.664	-2.75	-2.75	3.728	3.052
2009	23.856	26.429	3.636	2.664	-2.572	-2.572	3.728	2.966
2010	23.856	26.237	3.444	2.664	-2.381	-2.381	3.728	2.882
2011	23.856	26.03	3.237	2.664	-2.174	-2.174	3.728	2.801
2012	23.856	25.807	3.014	2.664	-1.95	-1.95	3.728	2.722
2013	23.856	25.565	2.772	2.664	-1.709	-1.709	3.728	2.645
2014	23.856	25.305	2.512	2.664	-1.448	-1.448	3.728	2.571
2015	23.856	25.023	2.23	2.664	-1.167	-1.167	3.728	2.498
2016	23.856	24.719	1.926	2.664	-0.863	-0.863	3.728	2.428
2017	23.856	24.391	1.598	2.664	-0.535	-0.535	3.728	2.359
2018	23.856	24.036	1.243	2.664	-0.18	-0.18	3.728	2.293
2019	23.856	23.653	0.86	2.664	0.203	0.134	3.659	2.187
2020	23.856	23.239	0.447	2.664	0.617	4.315	7.426	4.314
Total	**477.120**	**517.258**	**61.400**	**53.280**	**-40.134**	**-36.505**	**18.980**	**0.498**

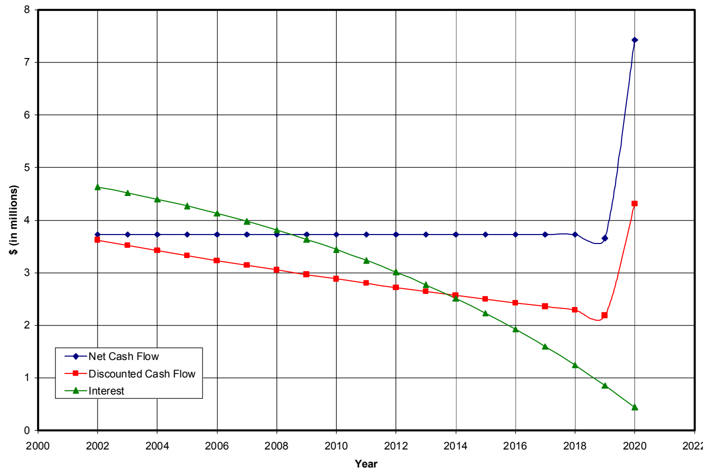


Figure 25: Net Cash Flow, Discounted Cash Flow, and Interest vs. Years

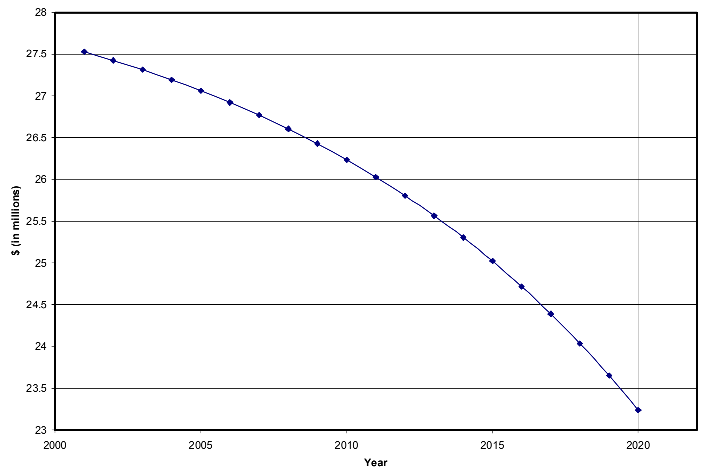


Figure 26: Operating Costs vs. Years

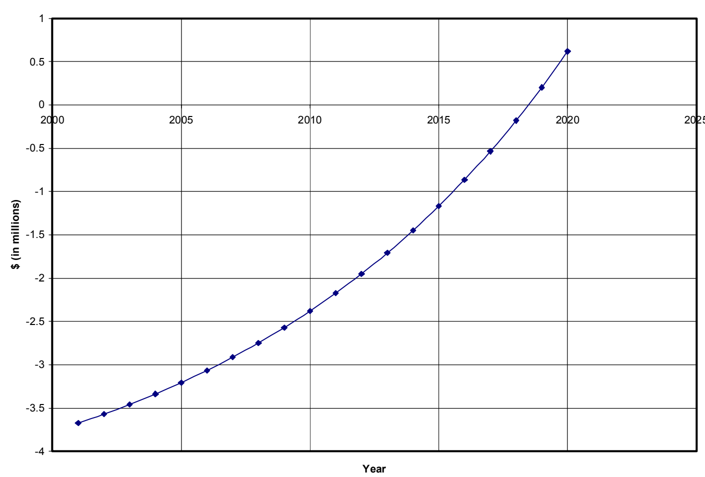


Figure 27: Earnings Before Tax vs. Years

(The economic analysis was performed using the original baseline that was provided at the beginning of the study. This baseline was later changed to perform linear interpolation of aerodynamic data. The difference in responses of interest is minimal, approximately half a percent.)

DESIGN SPACE EXPLORATION

Step 4 of the TIES methodology involves the creation of metamodels for the design parameters using the design variables. Then, with the metamodels, the optimum configuration is calculated using an optimization procedure. There are different methods and computer programs, which can be used for obtaining the metamodels. For the purpose of this report, the metamodels will be created using FLOPS, ALCCA, a statistical software package called JMP, the probabilistic software Crystal Ball, and the spreadsheet program Excel. The following sections describe terms, methods, and the procedure taken for obtaining metamodels describing the design parameters and the design variables listed in Table XI. Also included in this section, are the procedures performed for validating the models and the description of the procedure used for calculating cumulative distribution functions of the design parameter for evaluating the design space.

Table XI: Design Variables and Parameters for Metamodel of System

Design Variable	Design Parameter
Wing Area	Approach speed
Thrust to weight ratio	Landing field length
Wing aspect ratio	Takeoff field length
Wing taper ratio	CO2/ASM
Wing thickness to chord ratio at root	NOx
Wing thickness to chord ratio at tip	Takeoff gross weight
Wing quarter-chord sweep	Acquisition price
HT aspect ratio	RDT&E costs
HT taper ratio	Average required yield per RPM
HT thickness to chord ratio	Total airplane related operating costs
HT area	Direct operating cost plus interest
VT aspect ratio	Wing aerial wt
VT taper ratio	
VT thickness to chord ratio	
VT area	

Design of Experiment (DoE)

In investigating the parameters that affect the quality or performance of a product or process, the analysis of variance and regression techniques are utilized to determine the sources of the differences without making changes to the process [21]. However, the results from these techniques can sometimes be misleading to the efforts on optimizing the desired product or process because a few of the contributing elements may be overlooked or the desired end product is not reproducible when used according to the traditional approach of changing one variable at a time. Furthermore, the couplings effects between the parameters are also tend to be neglected when following the traditional methodology.

These weaknesses or inaccuracies in assessing the contributing parameters lead toward a new improved approach. This is when DoE techniques come into play. "The (statistical) design of experiments (DoE) is an efficient procedure for planning experiments so that the data obtained can be analyzed to yield valid and objective conclusions"[22]. "DoE techniques offer structured approach to change many factor settings within a process at once and observe the data collectively for improvements or degradations", which will "yield not only a significance test of the factor levels but also gives a prediction model for the response" [21]. In addition to that, the use of DoE also offers the reduction in the variability of the results that is of great interest in achieving a robust design [21].

The main objectives of DoE are to gain the maximum amount of knowledge with a minimum expenditure of experimental efforts and hence reduce the total engineering or process cycle time [23]. The experiments can be investigated with regard to all possible combinations of a set of inputs factor (full factorial) or with a subset of all combinations (fractional factorial) [21]. On top of that, the DoE is also used effectively in regression modeling [24].

The method is usually presented as an orthogonal array, which size is depending on the number of factors (also called the control variables) that are being considered and their factor levels. 'Orthogonal' means that all the trial conditions are balanced (the levels of all factors and the combinations of all factors appear in equal number) and the effects of each control variable is not mixed or confounded with each other. This means that the effect of each factor can be separated from that of others as it is assumed initially that all the factor columns are not interacting with each other.

The general DoE array is depicted in Table XII. This example represents an experiment with 8 (A-H) variables, 2 (A-B) resulting parameters, and n number of cases. As depicted in Table XII, two levels are set for each variable, namely 1 or 0. In this specific case, a 1 is portrayed as an 'on' setting and a 0 represents an 'off' setting.

Table XII: General DoE Array

		Control Variables								**Results**	
		X_A	X_B	X_C	X_D	X_E	X_F	X_G	X_H	Y_A	Y_B
Case Number	1	1	1	1	1	1	1	1	1	Y_{A1}	Y_{B1}
	2	1	1	0	0	1	1	0	0	Y_{A2}	Y_{B2}
	3	0	0	1	1	0	0	1	1	Y_{A3}	Y_{B3}
	…	0/1	0/1	0/1	0/1	0/1	0/1	0/1	0/1	$Y_{A\ldots}$	$Y_{B\ldots}$
	n-2	0	1	0	1	0	1	0	1	Y_{An-2}	Y_{Bn-2}
	n-1	1	0	1	0	1	0	1	0	Y_{An-1}	Y_{Bn-1}
	n	0	0	0	0	0	0	0	0	Y_{An}	Y_{Bn}

As been mentioned earlier, the size of the orthogonal array will depend on the numbers of the design variables under consideration. After selecting the control variables that need to be considered, a standard orthogonal array will be chosen based on the amount of the variables and their levels.

A general symbol for an orthogonal array, as first conceived by Euler, is given by [21]:
$L_N (L^M)$,

where:

N: number of trial conditions
L: number of factor levels
M: number of factors

With regards to the design problem at hand, there are 15 design parameters that have to be considered and assessed to see their contribution in achieving the design goals. If a traditional approach of changing one variable at a time is to be utilized, the contribution of each of the 15 variables may not be thoroughly investigated since the effects from a few dominant parameters will overshadow the effects from the less dominant ones. The process also will consume more time as there are many combinations of trials that might need to be done until the optimized condition occurred. The output of the traditional approach will be an optimized condition of factor level combination, which is not of primary objective here since this step of the design project is more interested in finding the relationship between the variables and the desired design characteristics in order to have good understanding of the system.

On the other hand, by utilizing the DoE techniques, each and every contribution from these 15 variables can be investigated rather efficiently. The use of an orthogonal array, which in its primary principle that the trial conditions are designed in such a way that the effects of the parameters are not mixed and confounded with each other, will help to determine the dominant factors that contribute towards the design characteristics that are desired. Furthermore, the approach offers a better structured trial conditions that can allow good investigation on each of the design variables contribution towards the design characteristics of interest, with a minimum time and effort. Instead of just an optimized combination output, the DoE results sets of output data. These sets of output response data information could then be further used in constructing a regressed relationship equation between the variables and the responses that provides a mean of gaining knowledge about the system.

Regression Analysis

Regression analysis in general is a method of developing the best estimate of relationship between dependent variables and the independent variables [22]. This method tries to establish a ‘fitted equation’ that could explain the behavioral pattern of the data set in relation to its independent variables or contributing parameters.

A measure of how well the equation predicts the relationship between the response and its contributing factors is the coefficient of determination (R^2). The R^2 value “has an interpretation as a fraction of the raw variation in y accounted for using the fitted equation” [25], where ‘y’ here corresponds to the actual value of the response. In other words, the value tells how close the prediction equation captures the behavioral relationship pattern between the independent and dependent variables.

The value for R^2 is computed using the equation 4 [25].

$$R^2 = \frac{\sum (y_i - \bar{y})^2 - \sum (y_i - \hat{y}_i)^2}{\sum (y_i - \bar{y})^2} \qquad \text{Eqn. (4)}$$

where: y_i is the actual *i*th value of the response
$\bar{y}$ is the sample mean
$\hat{y}_i$ is the predicted *i*th value from the fitted equation

As a reference, consider an R^2 of 0.9. This value indicates that 90% of the variability in the data is accounted by the model or the fitted equation. Depending on the experiment, accuracy required, and trueness of the data a 'good' R^2 can be defined.

The difference between the actual response value and the predicted value for each data point is called the residual (e). The residual values describe the error in the fit of the model at each pair data points (actual and predicted). The smaller the value of the residual means the better the fit of the prediction equation at that particular data point.

The value for the residual for the *i*th point is given by equation 5 [25].

$$e_i = y_i - \hat{y}_i \qquad \text{Eqn. (5)}$$

where y_i is the actual value of response at *i*th data point
$\hat{y}_i$ is the predicted value of response at *i*th data point

Response Surface Equations

Response surface equations (RSEs) are equations that serve as the 'metamodels' of the system in predicting the relationship between the contributing variables and responses. In order to obtain the RSEs, the Response Surface Methodology (RSM) is used. The RSM is utilized "to gain a better understanding of the overall response system" [23] and is modeled "based on the DoE methodology" [23].

RSMs also act as the link between the DoE and the regression analysis, where this methodology provides "a multivariate regression technique developed to model the response of a complex system using a simplified equation" for which the regression data is gained from the DoE techniques [23]. The data results from the DoE analysis are "analyzed by using the regression analysis techniques to determine the output response surface as a function of the input variables" [21]. As briefly mentioned before, the regression analysis is a method to fit an equation in establishing the relationship between the inputs and the outputs or the responses. With regards to the design problem at hand, the relationship will be between one dependent variable (design characteristics of interest) and multiple independent variables of the selected design parameters. This is an obvious multiple linear regression case.

The responses from the DoE with each different factor level combinations are modeled by a 'fitted equation' using the least squares method. This equation usually takes the form of a second-order quadratic equation after higher order terms are removed from the Taylor expansion. The general form of the equation is given in equation 5 [23].

$$R = b_0 + \sum_{i=1}^{k} b_i k_i + \sum_{i=1}^{k} b_{ii} k_i^2 + \sum_{i=1}^{k-1} \sum_{j=i+1}^{k} b_{ij} k_i k_j \qquad \text{Eqn. (6)}$$

where: b_i are the regression coefficients for the first-degree terms

b_{ii} are the coefficients for the pure quadratic terms

b_{ij} are the coefficients for the cross-product terms

$k_{i,j}$ are the design variables

$k_i k_j$ represent the interactions between design variables

With the help of computer program such as JMP, the RSEs can be obtained from the software without the normal hands-on mathematical manipulation of the least square regression method.

Creation of Response Surface Equations

As a preliminary step, one must identify the design variables and the metrics for which the RSEs are desired. With these set, a screening test can be performed to reduce the number of design variables to be studied. This is done in order to only have variables that significantly influence the outcome metrics. With the final variables (including study ranges) and metrics identified, a DoE suitable for the model at hand must be created. It is necessary to have a full understanding of the model and a good understanding of the variables affecting the outcome in order to create the correct DoE. The DoE is created using JMP by selecting the 'Response Surface Design' tab in the main DoE window. The number of variables desired to study is entered and then the user must select what kind of DoE to use. When all the desired options are selected, a table with the DoE opens. The table is copied to excel to convert the 1s, -1s, and 0s to real numbers to linearly match the ranges with 1 being the high limit and -1 being the low limit. The real numbers are saved into a table, which is used to create input files for FLOPS. A script can be written to speed this process as well as to run all the input files thought FLOPS. Another script can be used to extract the data (metrics) from the output files. The data then needs to be copied to JMP into columns dedicated to the design metrics.

The initial model then is created by selecting the design variables and selecting 'Response Surface'. Other options are available that need to be taken in consideration depending on the study. This process fits the model and a window opens up with the responses for each metric analyzed. Each metric can be predicted by selecting the 'Prediction Formula' option for each fitted metric. Then the error of the FLOPS output and the RSEs predicted value can be calculated in a new column for each metric. With all these done, the goodness of the model can be observed.

There are five good means of evaluation to see whether the wellness fit of the RSE to the actual condition. They are the plot of predicted values against the actual values, the residual plot, the error distribution plot, the value of the coefficient of determination (R^2) and the confirmation test. The plot of actual responses against the predicted responses (whole model test) from the fitted RSE can show a good indication whether that predicted equation gives the right relationship between the variables and the responses. The equation is a bad interpretation of the relationship if the actual data points deviate far from the perfect fit line. In addition to that, the 95% confidence line may be added to the plot such that a good prediction line will have the confidence lines wrap tightly around it. The residual plot is the plot of error term with respect to each pair of data points (actual and predicted responses for each inputs set). A good fit line will have a random 'gunshots' residual plot without any visible or obvious pattern of residual values trend. In addition to that, a good measurement of a fit line is that the residual value is less than 1% of the data value, with small absolute range of the plot to the magnitude of the response. The third evaluation of a fit is the error distribution. A good fit line should be normally distributed with a zero mean and a standard deviation of less than one. Any error distribution that is far deviate from a normal distribution indicates inaccurate fitted equation. Another means for evaluating a fit is the coefficient of determination (R^2), which indicates how well the equation predicts the relationship between the response and its contributing factors. The value indicates the amount of the variability in the data is accounted by the model or the fitted equation. A perfect fit will have a R^2 of one and acceptable range for certification of a good fit would be around 0.99 and above. The final test for "goodness" of a fit is a confirmation test is done by taking random points within the variable range apart from those considered while doing the regression analysis and see whether the fitted equation corresponds well to the actual responses of these cases. A good fitted equation will derive small residual values between the actual and predicted responses. To get these random points, FLOPS needs to be run again with the converted random numbers to real numbers and then the error is calculated.

In the case one or more of these methods for evaluating the goodness of fit fail, four procedures can be considered. Namely, these are the exclusion of cases used to fit the model, the addition of higher order terms to the fitted model, the transformation of a variable, and the selection of a new set of ranges for the design variables. The exclusion of points can be done by selecting the points whose residual is higher that most other cases. There is a maximum of about 3% of cases that can be excluded and still obtain an acceptable fit. To check for the need of higher order terms, the influence of each design variable is checked. If needed, combination of the variables that largely influence the result should be used to create higher order terms and refit the model. The third possibility is the transformation of metrics. For example, instead of using a metric as outputted by FLOPS, it is sometimes useful to use the natural log of it to fit the model, or another transformation that might improve the accuracy of the model and reduce the residual error and error distribution. This can easily be done by refitting the model using the transformed metric instead of the regular metric. A final, and least desired, procedure for improving the goodness of the model is to establish different ranges and repeat the entire process of running FLOPS and fitting the model.

After performing all the goodness tests and improving the goodness using the four described methods above, the prediction formulas of the final fitted model can be added to the JMP sheet in the corresponding columns and by double clicking in the corresponding columns the contribution of each variable and each interaction can be observed. These are the final RSEs of the metrics.

DoE Used to Describe the 150 Passenger Aircraft Parameters

For the design task in hand, with the 15 variables need to be considered, there are three proposed good optional DoE types that can be used, which are the Full Factorial, Central Composite Design and the D-Optimal Design [23]. Since the orthogonal designs are of great importance to ensure that the effects of each variable are not mixed and not confounded with each other, the D-Optimal Design is not a good choice of DoE for this project. The Full Factorial, although it will provide a more comprehensive knowledge about the system responses, is subjected to a large amount of trials and will consumed a lot of time and effort. Therefore, the Central Composite Design (a type of fractional factorial DoE) is chosen as the DoE type to be used in assessing the system, as the number of trials needed to be run is very much reduced from that of the Full Factorial, but at the expense of decreasing the orthogonal effect of the process and reducing the amount information gained.

The Central Composite Design (CCD) is a type of DoE that includes the investigation on every end-point level and the center points of the interested design space. In addition to that, the responses at the 'star points' are also included. The 'star' or the axial points are added to the trials combination to provide additional information about the system response. These additional points can be fixed at any location on the design space, even can be stretched out to the outside of the interested 'design space box'. For this project, the axial points are located on the face of the 'box' as the information gained from that responses will be more appropriate in assessing the relationship within the 'box', as intended in this project. This type of CCD is called the 'face-centered CCD' and is depicted in Figure 28 [26].

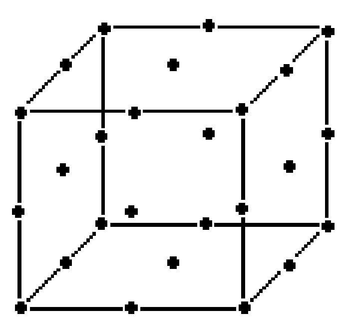


Figure 28: Face-Centered Central Composite Design

The CCD is an "efficient test approach to determine the coefficients of a second-degree polynomial" since it also includes the "additional levels of variables between the end-point levels" [21]. This criterion is very much of great preference to the team as the RSE is intended to be in the second-order quadratic equation. Furthermore, the CCD can be made as a uniform precision design, which requires the variance of the response at the origin and that at a unit distance from the origin to be equal, by using a proper number of center points [21]. In this case, for the CCD utilized in the project, all the center points are being considered and thus making the regression analysis has the edge of a uniform precision design, which is essential since “it gives more protection against bias in the regression coefficients because of the presence of third-degree and higher terms in the true surface) than does the orthogonal design” [21]. Thus, the choice to use a CCD type of DoE is well justified.

For the purpose of this study, more specifically a 15 variable Oliver Bandte CCD with resolution IV fractional factorial design will be used. The reason is that JMP can only create an 8 variable RSE and the custom design created by Dr. Bandte can deal with up to 16 variables.

Creation of RSEs of the Metrics for the 150 Passenger Aircraft

The DoE needed for this study was a 15 variable handmade design created by Dr. Oliver Bandte, as previously mentioned. A total of 287 cases are included in this specific design. After opening the design, the table was copied to a excel spreadsheet that converts the 1s, -1s, and 0s to real numbers depending on the ranges listed in Table I. The created table file (doe.table) was used along a script to create 287 FLOPS input files. Then a script to run FLOPS for each created input file was modified for the correct purpose and run. This script produced 287 FLOPS output files. To extract the metrics of each output file, another script was modified correcting which metrics to extract and was run. This process created two files, one containing the performance metrics and another one containing the economic metrics.

The files were modified and the data was placed in the JMP file containing the DoE. At this point, the JMP document contained the values (1s, -1s, and 0s) for the design variables and the metrics of importance for each case. Then the model was fitted selecting the 15 variables and the 12 responses. The variables were selected under the ‘Response Surface’ option and set as the ‘Model Effect’. The responses were set as the ‘Role Variables’. Also, the ‘Center Polynomial’ option was unselected. To finish the set-up, the model was run.

The “goodness” of the fit was then evaluated. From the resulting analysis, the actual vs. predicted and residual plots were observed. These did not show a nearly perfect fit as desired. Before any conclusions, the predicted formulae were saved and the percent error for each case was calculated using equation 7 below,

$$error = \frac{predictedValue - actualvalue}{actualvalue} * 100 \qquad \text{Eqn. (7)}$$

where the predicted value is the calculated value from the RSE and the actual value is the value calculated by FLOPS. The error distribution for each metric was plotted and the group noted that the distribution of error was not as desired for all of the metrics, especially for NOx, CO2/ASM, and take-off field length. To obtain valid RSEs, the mean of the error must be around zero and the standard deviation must be close to 1 or less. The next evaluation was the R^2 check. All the fits were more than 99% correct, but as previously stated, this does not mean that the RSEs are valid for the study. The final test to observe the validity of the RSEs created was to run some random cases in FLOPS and observe the error distribution using the current

RSEs. This was performed in a similar manner as the regular cases, except that instead of generating the real numbers with 1s, -1s and 0s, the real numbers were generated using any random number between 1 and -1 for each single variable for each of the 287 cases. These cases were analyzed and the output was entered into JMP. It was found that the error distribution beyond acceptable limits.

From the five tests performed for each one of the metrics, it was concluded at this point that the model was not accurate. To get a more accurate model, NOx was transformed to LN NOx, some cases that were believed to be producing biased or incorrect responses were excluded, and higher order effects were included.

The third order effects included were considered by observing the individual effects of the variables in each of the responses, and also by observing the contribution of interactions of the variables to the responses. All the new interactions were included in a new fitted model for which some random cases had to be added in order to observe their effect. From this new fitted model the higher order interactions that influenced the responses were chosen.

Table XIII lists the higher order interactions that were concluded to be influencing the responses and the excluded cases believed to be causing biased errors.

Table XIII: Higher Order Interactions and Excluded Cases

Higher Order Interactions	Excluded Cases
AR^3	45
SW^3	46
TWR^3	61
$TOC(1)^3$	62
$TOC(3)^3$	109
SW^2 TOC(1)	125
SW^2 TOC(3)	126
AR^2 TOC(1)	257
AR^2 TOC(3)	258
AR^2 SW	261
SW^2 AR	262

With these higher order interactions, excluded cases, and previous conclusion of using the natural log of NOx a new model was fitted in the same manner as before. For confirmation and validating the RSEs, the same five tests were performed for each metric as previously done.

The summary of fit of each one of the metrics studied is displayed in Appendix B – Goodness of Fit for Metrics. Each figure contains four quadrants. The first one is the actual versus predicted plot, the second one is the residual plot, the third quadrant contains the error distribution of the actual minus the predicted, and the fourth quadrant summarized the R^2 value of the fit. All of the metrics show a good fit.

Appendix B – Goodness of Fit for Metrics also contains the error distributions for the random cases studied in this project. As expected, the error in random cases is larger than that for the DoE cases. The diagram in the appendix shows that there is a maximum error of about 3 percent for the random cases. All the metrics, except for NOx and Wing Aerial Weight have standard deviations below 1, meaning the error is normally distributed. NOx has a standard deviation of 1.37 and Wing Aerial Weight has a standard deviation of 1.17. Both are higher than one, but still since they have a very small maximum error (about 4 percent), the fits are considered good.

From the observations of the tests performed to evaluate the goodness of the fits, it is suitable to conclude that the created RSEs represent a good model of the problem at hand. These RSEs can predict, within the specified ranges, the metrics to a high level of confidence. Appendix C – Design Space RSE Coefficients contains all the coefficients of the RSEs of the metrics here studied.

Figure 29, 'Prediction Profiles', shows the sensitivity of the responses to the design variables. The left column represents all the responses, and the bottom row represents the design variables. It is clearly shown that the wing area (SW) highly influences most of the responses, mainly the approach speed, the landing field length, the take off field length, and the wing aerial weight. The figure indicates that as the wing area increase, these four decrease in magnitude. The reason is that a larger wing area produces more lift, which means that the aircraft can fly at lower speeds and still maintain control, that the aircraft needs less runway to takeoff, and less runway for landing. The other two metrics noticeably affect by a change in wing are RDT&E costs and acquisition price. For these two, an increase in wing area indicates an increase in costs and price, due to the fact that a larger wing area means more weight. Thrust to weight ratio seems to only influence the economic metrics. The prediction profile indicates that a higher thrust to weight ratio increases all the economic metrics. The reason is that a higher thrust to weight ratio requires a bigger engine (for this study), which as a result increases the weight of the aircraft, and all the economic metrics are based on weight. The final design parameter that heavily influences the metrics is aspect ration. An increase in aspect ratio indicates a decrease in landing and taking off field length, due to the fact that more lift is being created. Aspect ratio also heavily influences the emissions of carbon dioxide. The reason behind this is that a higher aspect ratio creates more lift and less drag, thus reducing the amount of fuel burned by the engine throughout the flight. All the other changes in design variables do not seem to highly influence the metrics within the ranges being studied. This does not mean that the variables are not important, but just that variations of these variables within the established ranges do not alter the outcome of the metrics.

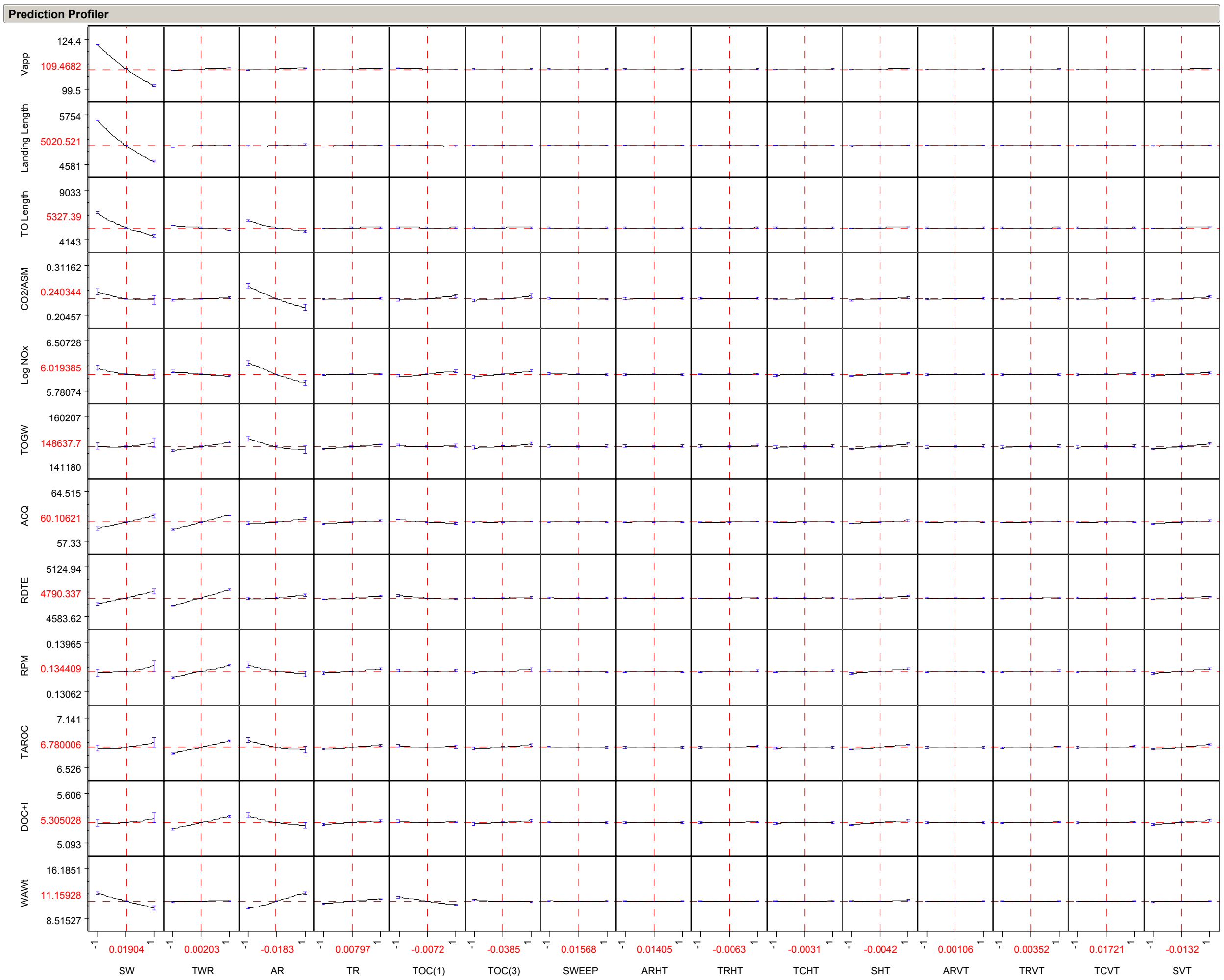


Figure 29: Prediction Profiles

DETERMINE SYSTEM FEASIBILITY AND VIABILITY

Step 5 in the TIES method is to determine if the conventional airplane configuration will qualify as a feasible and viable solution. Contour plots (carpet plots) to observe the design space available based on the constraints were created using the RSEs. A Monte Carlo simulation was also used to create a Cumulative Distribution Function (CDF) to determine the probability for success.

Optimized Baseline

The design variables were optimized using the desirability function in JMP. For an optimal solution, all of the metric responses determined from the first step 1 need to be minimized. The metrics for the optimized baseline vary from that of the original baseline as listed in Table XIV. The Takeoff Field Length (TOFL) was drastically reduced by almost 17 percent, whereas the

Landing Field Length was only reduced by 7%. The economics of the system only reduced slightly. This is the configuration that will determine if the system is feasible and viable.

Table XIV: Comparison of the Baseline and Optimal Metrics

Parameter	**Baseline**	**Optimized**	**Units**	**% Change**
Performance				
Approach Speed (Vapp)	106.8	99.9	knots	6.46
Landing Field Length (LdgFL)	4897	4599	ft	6.08
Takeoff Field Length (TOFL)	5367	4458	ft	16.94
CO2/ASM (CO2)	0.24605	0.25372	lb/ASM	3.12
NOx/ASM (NOx)	456	385	lb	15.57
Takeoff Gross Weight (TOGW)	148,219	144,694	lbf	2.38
Economics				
Acquisition Price (Acq $)	59.259	59.240	M$	0.032
Research, Development, Testing & Evaluation Costs (RDT&E)	4,721.8	4,714.82	M$	0.15
Average Required Yield per Revenue Passenger Mile ($/RPM)	0.134	0.132	$	1.49
Total Airplane Related Operating Costs (TAROC)	6.752	6.646	¢/ASM	1.48
Direct Operating Cost plus Interest (DOC+I)	5.279	5.191	¢/ASM	1.57
Miscellaneous				
Wing Aerial Weight (WAWt)	10.48	9.97	lb/ft^2	4.87

By optimizing the baseline, a new airplane geometry was created. These new design variables from FLOPS are listed in Table XV.

Table XV: Design Variable Baseline and Optimal Values

Design Variable	Description	Baseline	Optimal	Units
SW	Wing area	1310	1500	ft^2
TWR	Thrust to weight ratio	0.3098	0.398	~
AR	Wing aspect ratio	8.78	9.81	~
TR	Wing taper ratio	0.25	0.2	~
TOC (1)	Wing thickness-to-chord ratio at root	0.13	0.14	~
TOC (3)	Wing thickness-to-chord ratio at tip	0.13	0.1	~
SWEEP	Wing quarter-chord sweep	20.0	30.0	deg
ARHT	HT aspect ratio	5.67	7.5	~
TRHT	HT taper ratio	0.281	0.237	~
TCHT	HT thickness-to-chord ratio	0.09	0.06	~
SHT	HT area	201	150	ft^2
ARVT	VT aspect ratio	1.24	0.9	~
TRVT	VT taper ratio	0.386	0.27	~
TCVT	VT thickness-to-chord ratio	0.09	0.06	~
SVT	VT area	153	100	ft^2

Feasible Space Exploration

With the RSEs set, JMP has the option of producing contour plots for observing the design space available. Two sets of goals were established for this study. One of the established goals is for the year 2007 and the other one is for the year 2022. The first one, requires a 25 percent reduction in emissions and DOC+I. Figure 30 shows the design space available for the year 2007 with the 25 percent reductions. Figure 31 contains the contour plot for the year 2022. Both of these plots show that there is not feasible space with the current design. In order to meet these constraints, the requirements would have to be relaxed or if that is not possible technology would be implemented. If the requirements were to be relaxed, the minimum values would be 0.21 lb/ASM of CO2/ASM, 300 lb of NOx (5.7 in a natural log scale), and 5.15 cents/ASM for DOC+I. If the constraints are not meet, then heavy penalties would be given to the airlines, and even worse less aircraft would be sold since the aircraft would not meet the requirements specified by law.

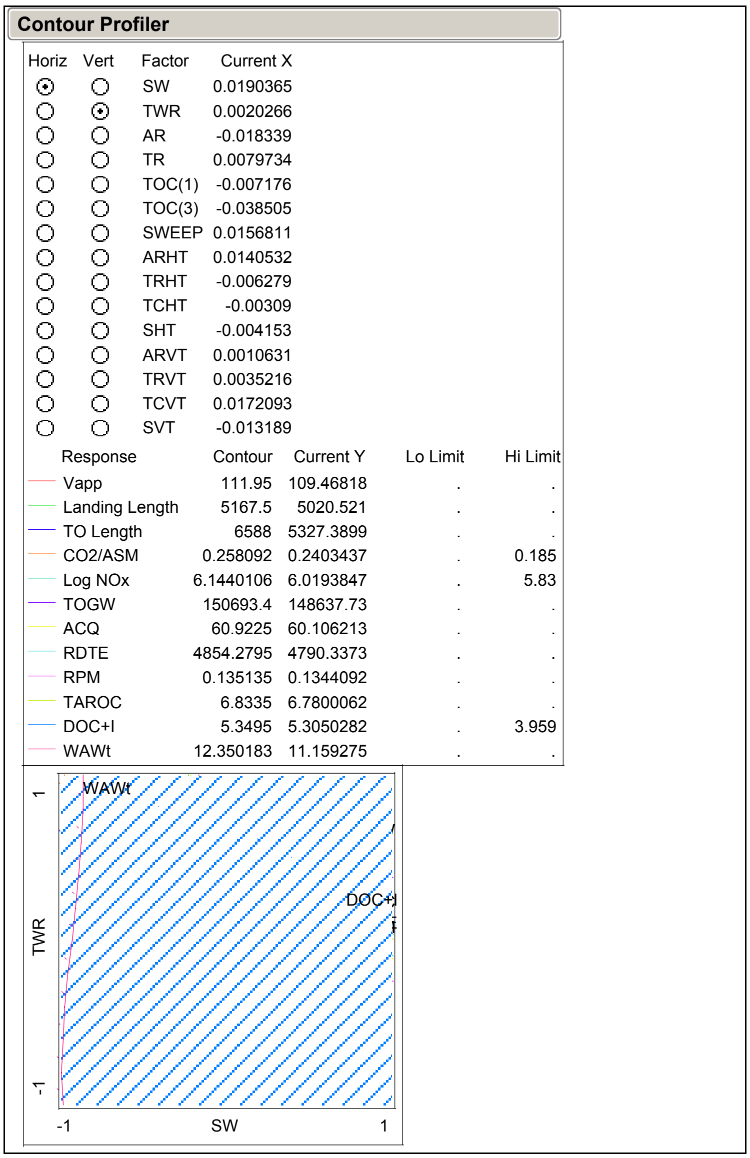
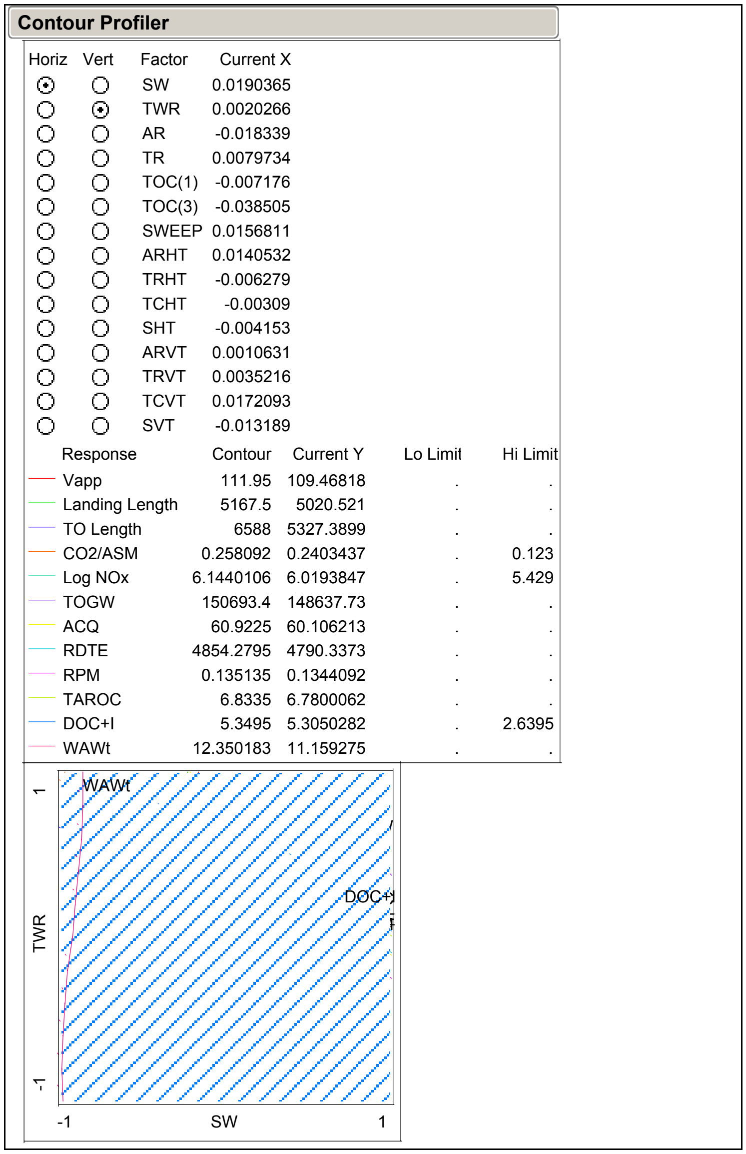


Figure 30: Contour Plot for Constraints for 2007


Contour Profiler

Horiz	Vert	Factor	Current X
⦿	○	SW	0.0190365
○	⦿	TWR	0.0020266
○	○	AR	-0.018339
○	○	TR	0.0079734
○	○	TOC(1)	-0.007176
○	○	TOC(3)	-0.038505
○	○	SWEEP	0.0156811
○	○	ARHT	0.0140532
○	○	TRHT	-0.006279
○	○	TCHT	-0.00309
○	○	SHT	-0.004153
○	○	ARVT	0.0010631
○	○	TRVT	0.0035216
○	○	TCVT	0.0172093
○	○	SVT	-0.013189

Response	Contour	Current Y	Lo Limit	Hi Limit
Vapp	111.95	109.46818	.	.
Landing Length	5167.5	5020.521	.	.
TO Length	6588	5327.3899	.	.
CO2/ASM	0.258092	0.2403437	.	0.123
Log NOx	6.1440106	6.0193847	.	5.429
TOGW	150693.4	148637.73	.	.
ACQ	60.9225	60.106213	.	.
RDTE	4854.2795	4790.3373	.	.
RPM	0.135135	0.1344092	.	.
TAROC	6.8335	6.7800062	.	.
DOC+I	5.3495	5.3050282	.	2.6395
WAWt	12.350183	11.159275	.	.

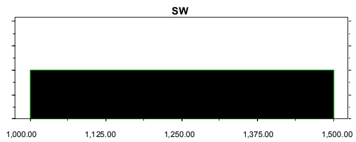
Figure 31: Contour Plot for Constraints for 2022

Feasibility

With the RSEs obtained from JMP, a Monte Carlo Simulation is performed on each one in order to observe the probability of achieving a specific value for the metrics based on the established ranges. To do this, the Crystal Ball add-in package is used in Excel. A feasible system can be determined by looking at the CDF created with the Monte Carlo Simulation.

The design variables are given a uniform distribution between the ranges for the simulation. Table XVI, lists the ranges and shows the uniform distribution for the simulation. An error term, with the previously established mean and standard deviation was added to the responses.

Table XVI: Variables Distribution and Ranges for Monte Carlo Analysis

<table>
<tr>
<td>Assumption: SW
Uniform distribution
Minimum: 1,000
Maximum: 1,500

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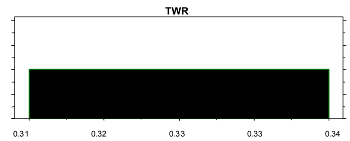
<td>Assumption: TWR
Uniform Distribution
Minimum: 0.31
Maximum: 0.34

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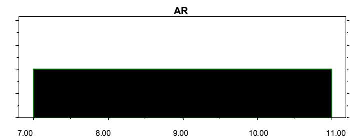
<td>Assumption: AR
Uniform distribution
Minimum: 7
Maximum: 11

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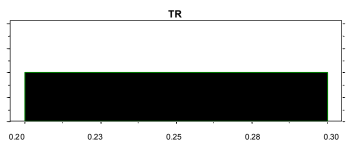
</tr>
<tr>
<td>Assumptions: TR
Uniform distribution
Minimum: 0.20
Maximum: 0.30

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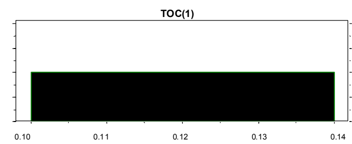
<td>Assumptions: TOC(1)
Uniform distribution
Minimum: 0.10
Maximum: 0.14

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<td>Assumptions: TOC(3)
Uniform distribution
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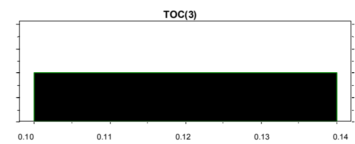
Maximum: 0.14

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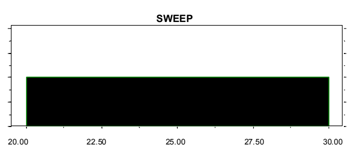
<td>Assumptions: SWEEP
Uniform distribution
Minimum: 20
Maximum: 30

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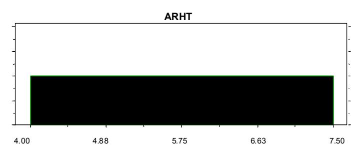
<td>Assumptions: ARHT
Uniform distribution
Minimum: 4.0
Maximum: 7.5

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Uniform distribution
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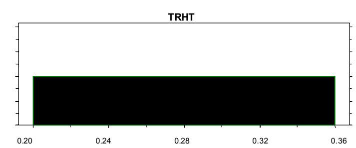
Maximum: 0.36

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<td>Assumptions: TCHT
Uniform distribution
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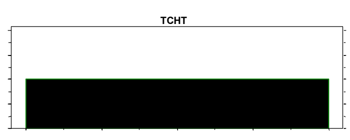
Maximum: 0.12

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Uniform distribution
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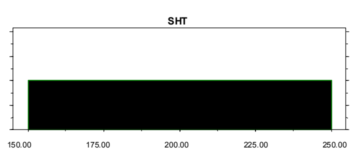
Maximum: 250

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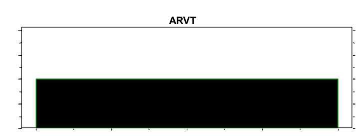
<td>Assumptions: ARVT
Uniform distribution
Minimum: 0.9
Maximum: 1.6

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</tr>
<tr>
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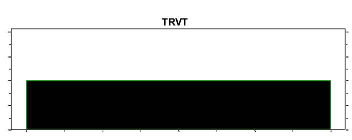
Maximum: 0.50

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<td>Assumptions: TCVT
Uniform distribution
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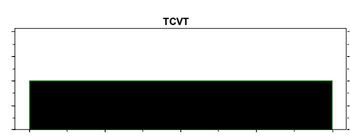
Maximum: 0.12

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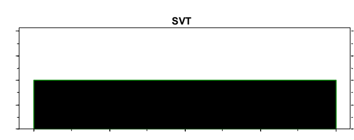
<td>Assumptions: SVT
Uniform distribution
Minimum: 100
Maximum: 200

</td>
</tr>
</table>

With all these values established and entered into the Crystal Ball macro, the simulations were run for a total of 10,000 cases. The CDFs represent the percent of certainty for attaining a specified value for each metric. The CDF including the error term was used to account for the small variability within the model. The probability that a target can be met is determined where the CDF intersects the target value. For example, the CDF and PFD for the Takeoff Field

Length (TOFL) are shown in Figure 32. The target for the TOFL is less than 7,000 feet, which corresponds to a probability of 97%.

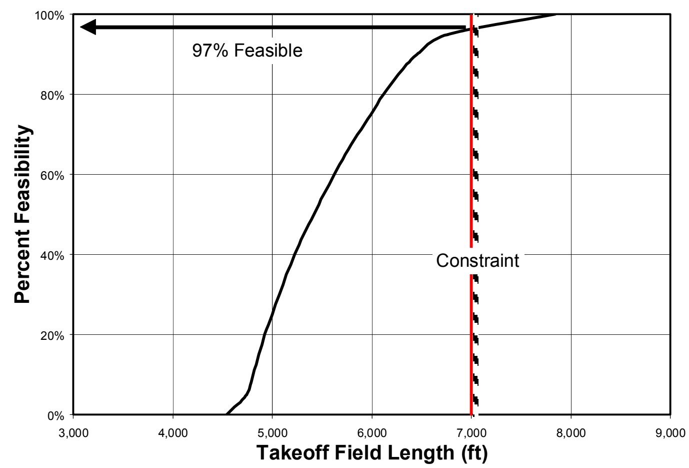


Figure 32: Feasibility Study of Takeoff Field Length

The only parameters that can be 100% met are the approach velocity, the landing field length, and the takeoff gross weight, as shown in the CDFs in Figures 33, 34, and 35, respectively. The other parameters have a zero percent (or very small) probability, as shown in Figures 36-38. This means that with the technology of 1997, the airplane will not be able to meet stringent emissions regulations for 2007 and 2022, as well have a reduction in the operation cost.

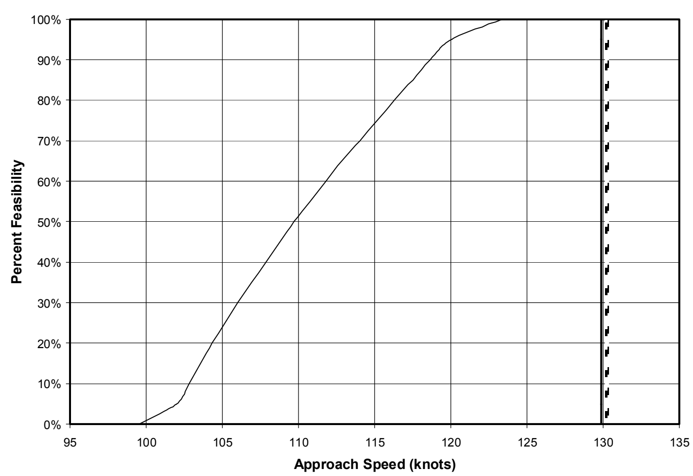


Figure 33: Feasibility Study of Approach Velocity

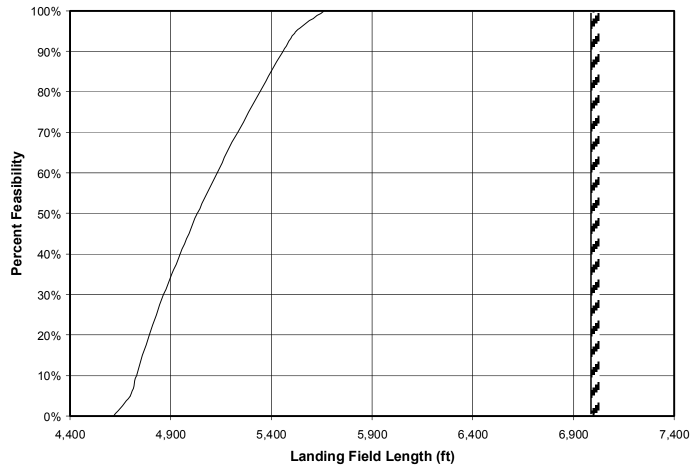


Figure 34: Feasibility Study of Landing Field Length

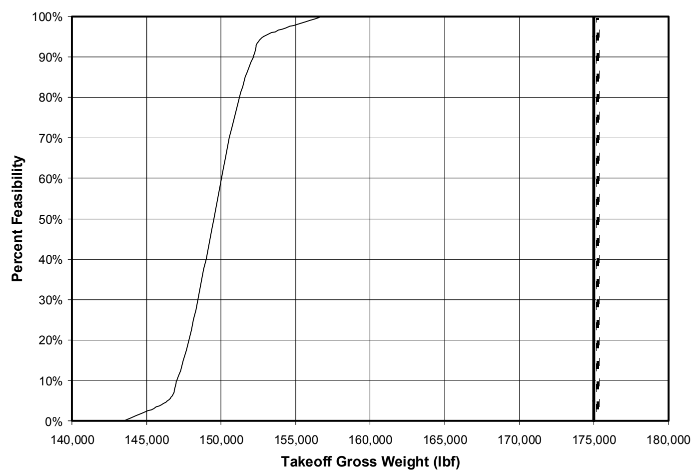


Figure 35: Feasibility Study of Takeoff Gross Weight

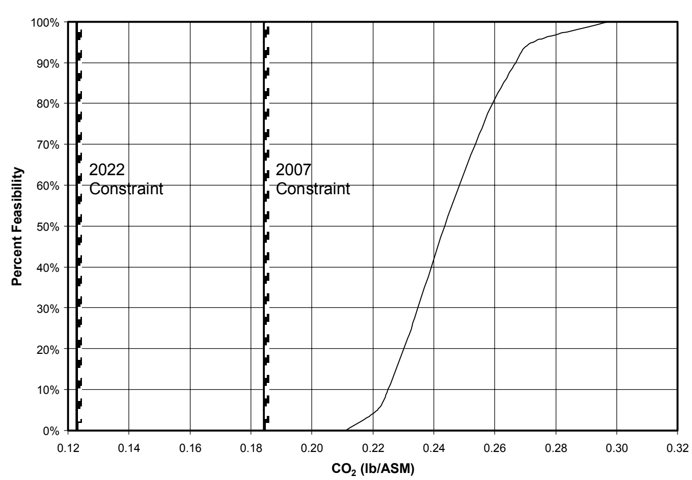


Figure 36: Feasibility Study for Carbon Dioxide Emissions

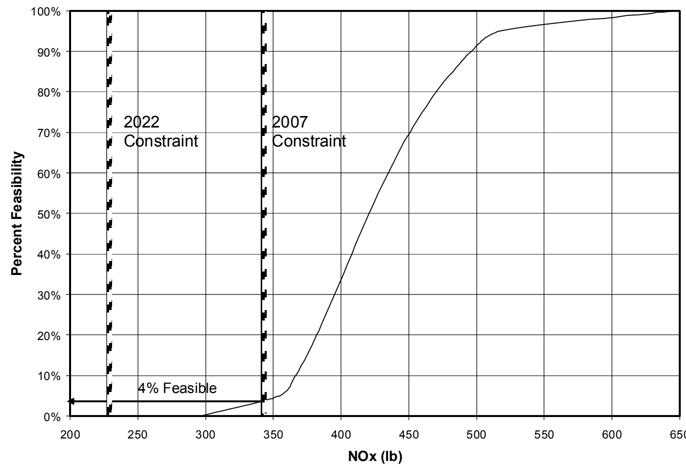


Figure 37: NOx Emissions Feasibility CDF

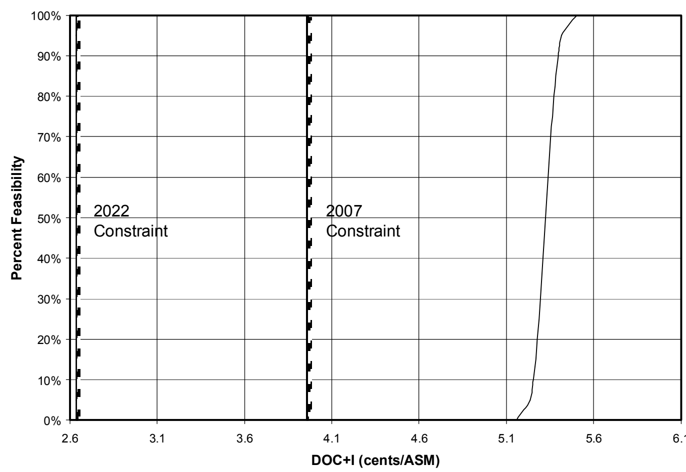


Figure 38: Feasibility Study for DOC+I

A CDF for Acquisition Price, Revenue per passenger mile, RDT&E, TAROC, and wing aerial weight have been omitted because each of these parameters are qualitatively constrained to be minimized. Table XVII lists the percent feasibility of the parameters.

Table XVII: Percent Feasibility of Optimized Configuration

Parameter	Constraint	% Feasibility
Performance		
Approach Speed (Vapp)	< 130	100%
Landing Field Length (LdgFL)	< 7000	100%
Takeoff Field Length (TOFL)	<7000	97%
CO2/ASM (CO2)	-25% for 2007 -50% for 2022	0% for 2007 0% for 2022
NOx/ASM (NOx)	-25% for 2007 -50% for 2022	4% for 2007 0% for 2022
Takeoff Gross Weight (TOGW)	<175,000	100%
Economics		
Acquisition Price (Acq $)	Minimize	No Constraint
Research, Development, Testing & Evaluation Costs (RDT&E)	Minimize	No Constraint
Average Required Yield per Revenue Passenger Mile ($/RPM)	Minimize	No Constraint
Total Airplane Related Operating Costs (TAROC)	Minimize	No Constraint
Direct Operating Cost plus Interest (DOC+I)	-25% for 2007 -50% for 2022	0% for 2007 0% for 2022
Miscellaneous		
Wing Aerial Weight (WAWt)	Minimize	No Constraint

Since not all of the constraints could be met with this airplane configuration, additional options must be considered. There are four options: change the ranges and run the time consuming analysis again, alter the baseline design configuration, relax the constraints, or infuse new technologies. Since the primary focus of this study is to evaluate new technologies to introduce a feasible design space, the next step (that will be presented in the next deliverable), introduces new technologies and then determines the impact each technology makes on the system.

Viability

The economic viability is determined by assuming operational scenarios that will affect the economics of the operation of the airplane. Since the future of economy, or the economic uncertainty, of the United States is unknown, a Monte Carlo Simulation can model how well the designed system will survive in different economic crises. There are five different operational scenarios that were looked at when determining the viability of the optimized baseline airplane configuration:

1. *Isolation*: The U.S. is isolated from the world where no international travel is allowed. This has little impact on the economic mission, utilization, and load factor of the 150-passenger vehicle since the market was determined to be domestic flights within the U.S. Since there will be no international flights, the load factors will decline on this type of aircraft for those passengers that must fly to a city that has international connections. Also, if the U.S. is in isolation, the economy will most likely be hurt. This will cause less coach passengers to travel, so the load factor will decrease more than the first class load factor.

2. *No International Oil Available*: The U.S. must produce its own oil and thus fuel, this would drastically increase the fuel cost and resulting in lower coach and first class load factors.
3. *Reduced Production*: The number of aircraft sold is reduced because a competitor released a superior product, causing a reduction in the quantity of aircraft produced. This results in a loss for the manufacturer's return on investment.
4. *Labor Unions Dissolve*: Labor unions are abolished within the U.S. and the manufacturing capability is lost, affecting the learning curves.
5. *Airline Re-regulation*: The government imposes new pricing regulations to airlines and places fixed prices on certain city pairs, which affects the airline's return on investment as well as coach and first class load factors.

Economic Variables

By studying the operational scenarios, the economic variables that are affected were determined. These include the utilization of the airplane, the production quantity, coach and first class loading factors, airline and manufacturing ROIs, fuel cost, the manufacturing learning curves, and the economic stage length. Ranges for each of these variables were determined based on the impact the operational scenarios would have. A summary of the baseline values and the ranges determined is listed in Table XVIII.

Table XVIII: Economic Variables and Ranges

Name	ALCCA Variable Name	Baseline Value	Min. Limit	Max. Limit	Units
Utilization	U	3900	3500	4300	Hrs.
Production Quantity	NV	800	640	1040	units
Coach Load Factor	CLF	0.71	0.55	0.8	%
First Class Load Factor	FLF	0.71	0.55	0.8	%
Airline Return on Investment	RTRTNA	10	7	13	%
Manufacturer Return on Investment	RTRTN	12	8	15	%
Fuel Cost	COFL	0.7	0.63	2	$/gal
Manufacturer's Learning Curve	LEARN1	81.5	79.5	83.5	%
	LEARN2	85.0	83.0	87.0	%
	LEARNA1	81.5	79.5	83.5	%
	LEARNA2	85.0	83.0	87.0	%
	LEARNAS1	76.0	74.0	78.0	%
	LEARNAS2	79.0	77.0	81.0	%
	LEARNFE1	82.0	80.0	84.0	%
	LEARNFE2	85.0	83.0	87.0	%
Economic Range	SL	1000	800	1200	nm

Utilization is the amount of block time, in hours, which the aircraft can be operated. This includes the daily operational availability, the mean time to repair (MTTR), and the mean time between failures (MTBF). A ten percent increase and decrease was used for the ranges of utilization. Isolation, having no international oil, and airline re-regulation will affect the amount the airplane needs to be used because people will travel less.

The Production quantity is the number of operational vehicles demanded, including one flight test vehicle. This could happen when a competitor releases an aircraft that is superior. More airlines will buy the competitor's aircraft and thus the production quantity will be reduced. The minimum range was a reduction of 20% from 800 aircraft produced. An upper limit was an increase by 30%.

The coach and first class load factors are the percentage of passengers that will occupy the airplane compared to the total capacity. The baselines for each of these factors are 71%. In the possibility of isolation, no international oil available, or airline re-regulation less passengers will be willing to travel. To determine the effects of reduced load factors, a minimal range for both coach and first class was a reduction of about 20%. To look at the other end of the spectrum, and upper limit with an increase of about nine percent was used.

The Return on investment for both the airline and manufacturer could be disturbed with economic uncertainty. The airline baseline ROI is 10%. A range of plus and minus 3% was used to determine the effect of airline re-regulation. The manufacturer ROI would be greatly affected in the case of a reduced production quantity. To model this effect, a decrease of four percent from 12% was used as a lower limit.

In the case where no international oil is available, fuel cost will be greatly affected. The U.S. will be forced to produce its own fuel of U.S. oil reserves. The baseline cost of fuel is $0.7 per gallon. With a crisis, an increase in fuel cost could be up to $2 per gallon.

In the case where labor unions are dissolved in the U.S., the manufacturer's learning curves would be impacted. A range of plus and minus two percent was used for each of the following learning curves:

LEARN1: Airframe Learning Curve Factor for first lot
LEARN2: Airframe Learning Curve Factor for second lot
LEARNA1: Avionics Learning Curve Factor for first lot
LEARNA2: Avionics Learning Curve Factor for second lot
LEARNAS1: Assembly Learning Curve Factor for first lot
LEARNAS2: Assembly Learning Curve Factor for second lot
LEARNFE1: Fixed Eq. Learning Curve Factor for first lot
LEARNFE2: Fixed Eq. Learning Curve Factor for second lot

If a labor union is dissolved, a labor union will not be enforcing manufacturing quality and workers will take a longer time to become good at what they do.

The economic range is the average trip length in nautical miles. If the U.S. becomes isolated from the world, the range of a 150-passenger airplane would not be significantly impacted because the market is aimed at domestic U.S. flights only.

Response Surface Equation for Economic Metrics

The variables mentioned above will affect the economic metrics determined in the first step of the TIES process. These are airplane acquisition price, RDT&E costs to the manufacturer, average required yield per revenue passenger mile ($/RPM), the total airplane related operating costs (TAROC), and the direct operating costs plus interest (DOC+I). With each of the variables tabulated into a 16 variable Doe, an RSE was created for the five response metrics. There were no higher order effects used in this RSE and all points were included for the fit. The goodness tests used to determine the "goodness" of the RSE for each metric are displayed in Appendix D. All of the actual versus predicted plots were very accurate. The residual plots, minus the RDT&E, resembled a gun shot, which represents a good fit. The RDT&E did not have a residual because the value varied only by thousandths of a million dollars between the different responses for the DOE matrix. All of the errors displayed an error of less than 0.2% with a standard deviation of under 0.2, which is very acceptable. All the R^2 values resembled a "good" fit. The final test was a random generation of cases within the ranges to evaluate the accuracy of the RSE. The results are located in Appendix D. All of the errors are under plus and minus one percent error, which verifies a good RSE model. The coefficients for the RSE are listed in E – Economic RSE Coefficients.

The Prediction Profiles shown in Figure 39 displays the sensitivity of the response to the design variables. This shows that the coach load factor, fuel cost and stage length have the most effect on the yield per RPM. The acquisition price is obviously influenced by the production number and the amount of ROI for the manufacturer. The RDT&E costs are directly related to the production number. Both the TAROC and the DOC+I are most influenced by the Utilization, ROI for the manufacturer, fuel cost, and stage length.

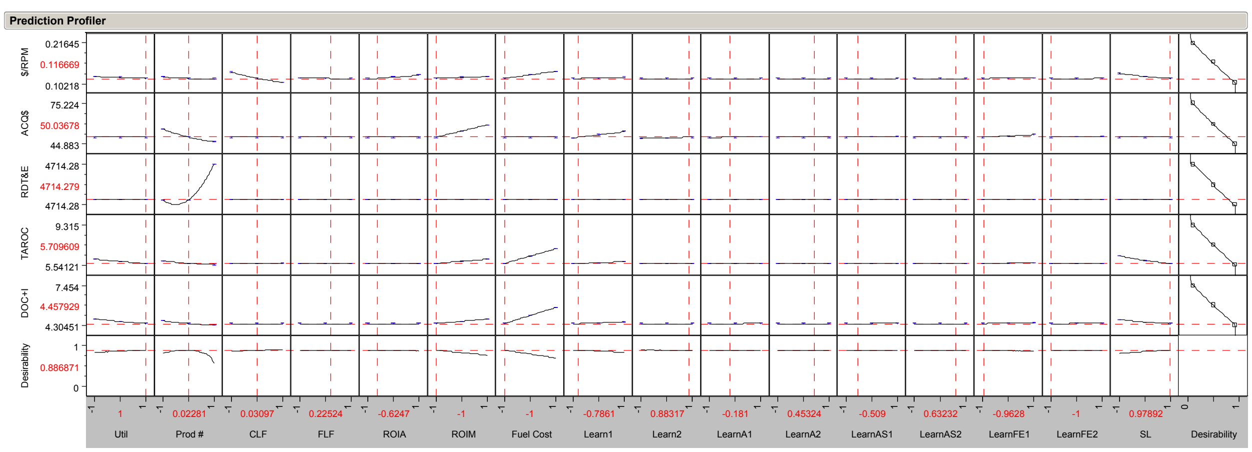


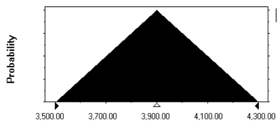
Figure 39: Economic Prediction Profiles

<u>Viability Study</u>

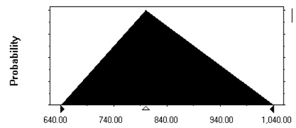
The viability study was preformed in a similar manner as the feasibility study. A Monte Carlo simulation was conducted to create CDFs to determine the probability of meeting the economic requirements. A triangular distribution was used for each of the variables with the apex of the triangle at the baseline value. This allows for a minimum and maximum value to be declared ,as apposed to positive and negative infinity for a normal distribution. The distribution shapes for each of the metrics are in Table XIX.

Table XIX: Economic Variables Distribution and Ranges for Monte Carlo Analysis

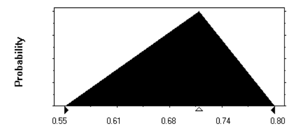
Assumption: Utilization
Triangular Distribution:
Minimum: 3500
Maximum: 4300
Apex: 3900



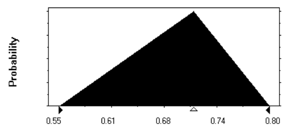
Assumption: Production #
Triangular Distribution:
Minimum: 640
Maximum: 1040
Apex: 800



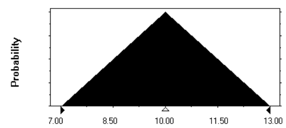
Assumption: Coach Load Factor
Triangular Distribution:
Minimum: 0.55
Maximum: 0.80
Apex: 0.71



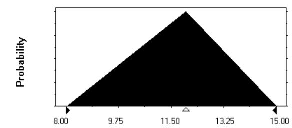
Assumption: First Class Load Factor
Triangular Distribution:
Minimum: 0.55
Maximum: 0.80
Apex: 0.71



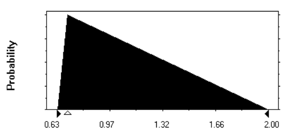
Assumption: Airline ROI
Triangular Distribution:
Minimum: 7
Maximum: 10
Apex: 13



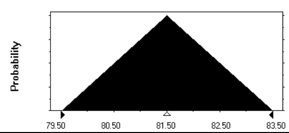
Assumption: Manufacturer ROI
Triangular Distribution:
Minimum: 8
Maximum: 15
Apex: 12



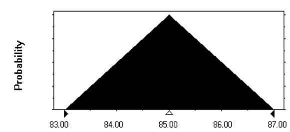
Assumption: Fuel Cost
Triangular Distribution:
Minimum: 0.63
Maximum: 2.00
Apex: 0.73



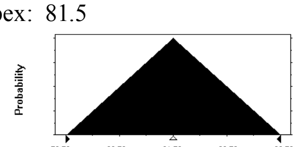
Assumption: Learn1
Triangular Distribution:
Minimum: 79.5
Maximum: 83.5
Apex: 81.5



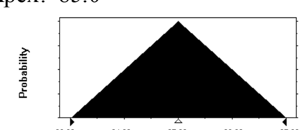
Assumption: Learn2
Triangular Distribution:
Minimum: 83.0
Maximum: 87.0
Apex: 85.0



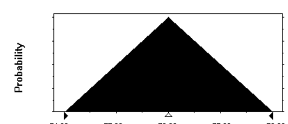
Assumption: LearnA1
Triangular Distribution:
Minimum: 79.5
Maximum: 83.5
Apex: 81.5



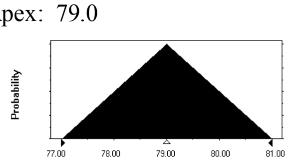
Assumption: LearnA2
Triangular Distribution:
Minimum: 83.0
Maximum: 87.0
Apex: 85.0



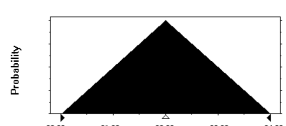
Assumption: LearnAS1
Triangular Distribution:
Minimum: 74.0
Maximum: 78.0
Apex: 76.0



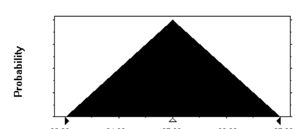
Assumption: LearnAS2
Triangular Distribution:
Minimum: 77.0
Maximum: 81.0
Apex: 79.0



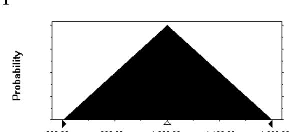
Assumption: LearnFE1
Triangular Distribution:
Minimum: 80.0
Maximum: 84.0
Apex: 82.0



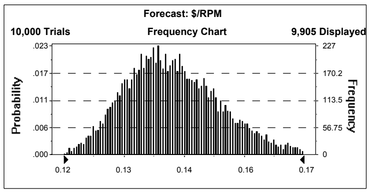
Assumption: LearnFE2
Triangular Distribution:
Minimum: 83.0
Maximum: 87.0
Apex: 85.0



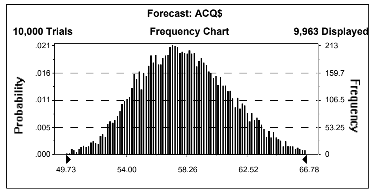
Assumption: Stage Length
Triangular Distribution:
Minimum: 800
Maximum: 1200
Apex: 1000



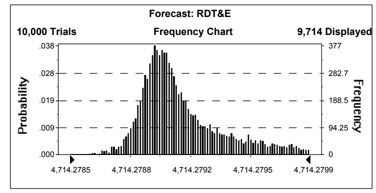
The Probability Density Functions (PDF) from the Monte Carlo simulation are all displayed in Figure 40. They illustrate the frequency of values within the 10,000 runs and the probability distribution at which there is 100% certainty.



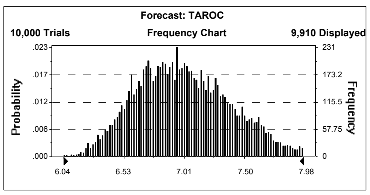
$/RPM PDF



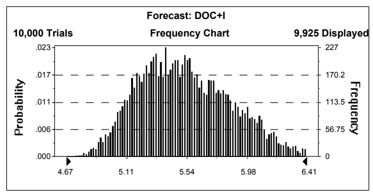
Acquisition Price PDF



RDT&E PDF



TAROC PDF



DOC+I PDF

Figure 40: Probability Density Functions for Economic Data

The Cumulative Distribution Function for DOC+I is displayed in Figure 41. The CDFs for Revenue Passenger Mile, Acquisition Price, and TAROC were omitted since there is no quantitative constraint, only the desire to be minimize. The cost per revenue passenger mile and the DOC+I are not viable for either 2007 or 2022.

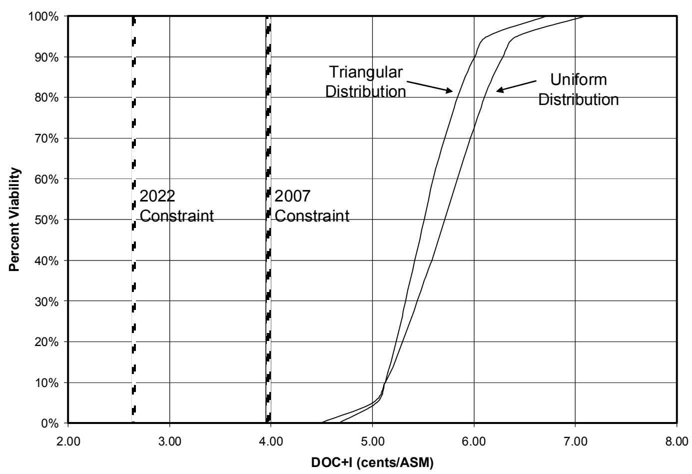


Figure 41: Viability Study of DOC+I

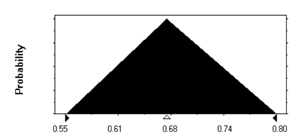
<u>Viability Study of Economic Uncertainty</u>

A study was completed on the five operational scenarios mentioned earlier to determine the viability of the system under economic crises. This simulation was done in the same manner as before, using a Monte Carlo simulation to develop CDFs. The shape functions for each of the metrics were a triangular distribution where the apex changed depending on the scenario.

Changing the apex provided results of the extreme cases, which could be representative of economic uncertainty.

In the case of U.S. isolation for the world, the 150 passenger aircraft would only slightly be impacted. The only shape functions that were varied were both the coach and first class load factors. The coach load factor would be impacted more than first class. If the U.S. were in isolation, the U.S. economy would most likely be affected. People traveling in the coach would be less inclined to travel. The apex for the coach load factor was reduced to 0.63 instead of 0.71 to account for this affect. The first class load factor would also be reduced only because there would be no travel overseas. Those traveling coach are less affected by economic hardships and would still be willing to travel, so the apex was shifted to 0.67 from 0.71 to account for this scenario. The new shape functions are in Table XX.

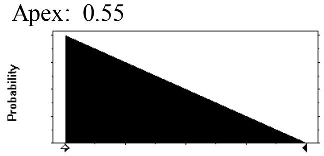
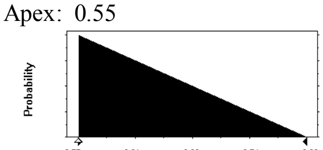
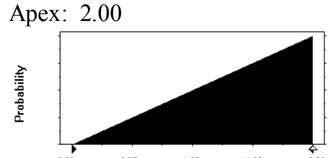
Table XX: U.S. Isolation Scenario Shape Functions

Assumption: Coach Load Factor	**Assumption: First Class Load Factor**
Triangular Distribution: Minimum: 0.55 Maximum: 0.80 Apex: 0.67 	Triangular Distribution: Minimum: 0.55 Maximum: 0.80 Apex: 0.63 

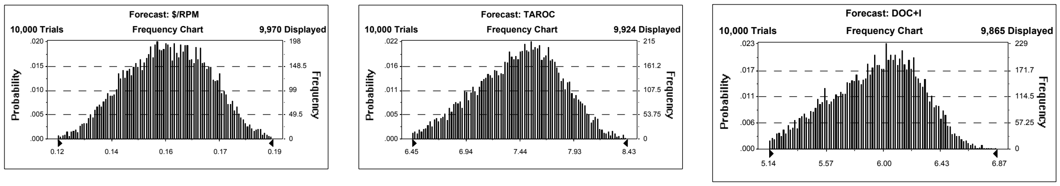
The only metric that was changed in the case of U.S. isolation was the $/RPM. No PDFs nor CDFs are illustrated here since $/RPM is desired to be minimized with no quantitative constraint.

In the scenario where no international oil is available, the fuel cost, and coach and first class load factors, would all be impacted. The shape functions used to describe this case were triangular distributions with the apex for the load factors reduced to the minimum of 0.55 to demonstrate the extreme case and the fuel cost set to 2.0 instead of 0.7 as displayed in Table XXI.

Table XXI: No International Scenario Shape Functions

Assumption: Coach Load Factor	**Assumption: First Class Load Factor**	**Assumption: Fuel Cost**
Triangular Distribution: Minimum: 0.55 Maximum: 0.80 Apex: 0.55 	Triangular Distribution: Minimum: 0.55 Maximum: 0.80 Apex: 0.55 	Triangular Distribution: Minimum: 0.63 Maximum: 2.00 Apex: 2.00 

The metrics affected by no international oil are the $/RPM, TAROC, and the direct operating cost. The PDFs for these three metrics are displayed in Figure 42. The CDFs for DOC+I is shown in Figure 43. With no international oil, the constraints have a lower probability of being met. The $/RPM, Acquisition Price, and TAROC were again omitted since the constraint is to be minimized.



$/RPM PDF **TAROC PDF** **DOC+I PDF**

Figure 42: Probability Density Functions for No International Oil

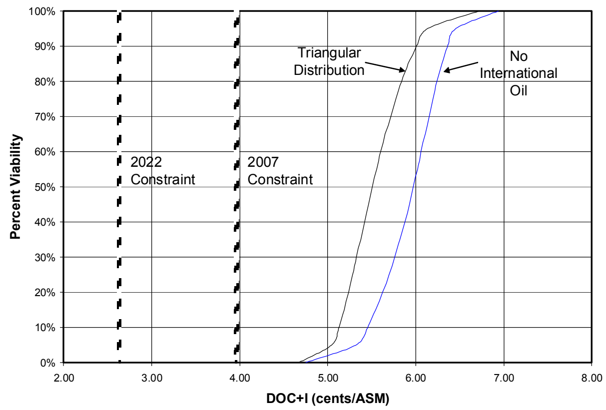
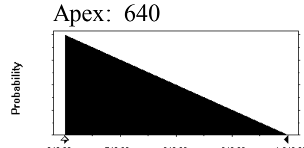
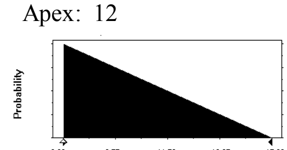
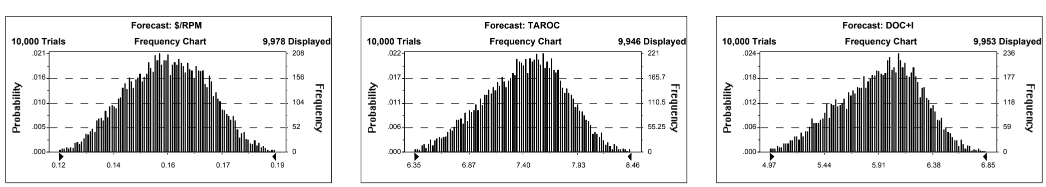


Figure 43: Viability Study for DOC+I with No International Oil

If the number of aircraft produced would be decreased, the manufacturer's return on investment would reduce. To simulate this scenario, the apex for the production number and manufacturer's ROI was set to the minimum as is listed in Table XXII. With a reduced production quantity, the $/RPM, TAROC, and DOC+I are changed. The PDFs for these metrics are displayed in Figure 44. The CDF for DOC+I is shown in Figure 45. With a reduced number of aircraft produced, there is a lower probability of meeting the constraints.

Table XXII: Reduced Aircraft Production Scenario Shape Functions

Assumption: Production #	**Assumption: Manufacturer ROI**
Triangular Distribution: Minimum: 640 Maximum: 1040 Apex: 640	Triangular Distribution: Minimum: 8 Maximum: 15 Apex: 12
	



$/RPM PDF **TAROC PDF** **DOC+I PDF**

Figure 44: Probability Density Function with Reduced Production Quantity

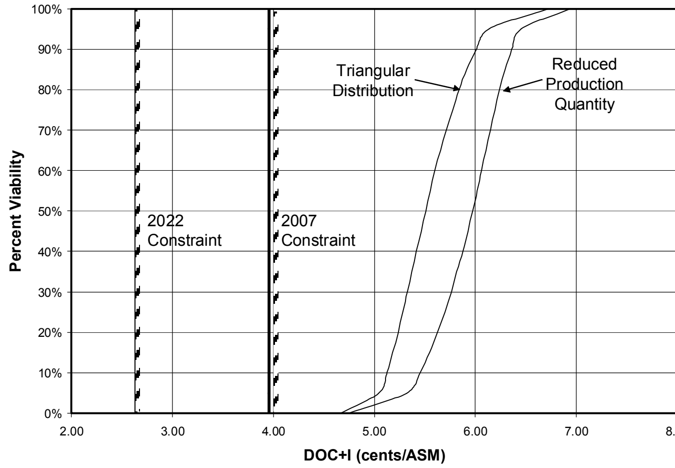
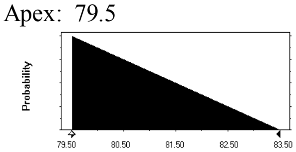
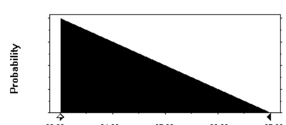
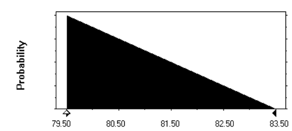
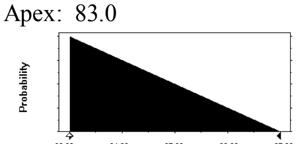
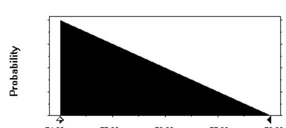
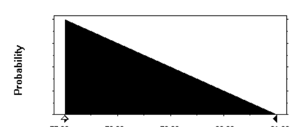
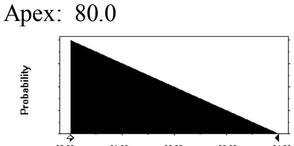
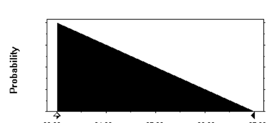


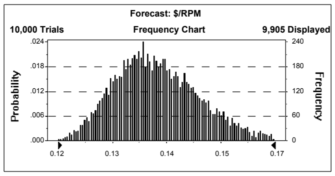
Figure 45: Viability Study for DOC+I with a Reduced Production Quantity

If labor unions would be abolished in the U.S., all of the manufacturer's learning curves would be reduced. The shape functions capture this scenario by placing the apex at all of the learning curve minimums located in Table XXIII.

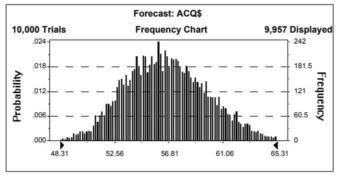
Table XXIII: Labor Unions Abolished Scenario Shape Functions

Assumption: Learn1 Triangular Distribution: Minimum: 79.5 Maximum: 83.5 Apex: 79.5 	**Assumption: Learn2** Triangular Distribution: Minimum: 83.0 Maximum: 87.0 Apex: 83.0 	**Assumption: LearnA1** Triangular Distribution: Minimum: 79.5 Maximum: 83.5 Apex: 79.5 
Assumption: LearnA2 Triangular Distribution: Minimum: 83.0 Maximum: 87.0 Apex: 83.0 	**Assumption: LearnAS1** Triangular Distribution: Minimum: 74.0 Maximum: 78.0 Apex: 74.0 	**Assumption: LearnAS2** Triangular Distribution: Minimum: 77.0 Maximum: 81.0 Apex: 77.0 
Assumption: LearnFE1 Triangular Distribution: Minimum: 80.0 Maximum: 84.0 Apex: 80.0 	**Assumption: LearnFE2** Triangular Distribution: Minimum: 83.0 Maximum: 87.0 Apex: 83.0 	

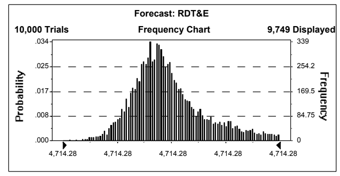
All of the metrics are affected if labor unions were to be abolished in the U.S. The new PDFs are located in Figure 46. The CDF for DOC+I is in Figure 47. This graph shows that by reducing the learning curves, the probability of meeting the constraints are increased. The remaining economic metrics again have no CDFs since they have no quantitative constraint.



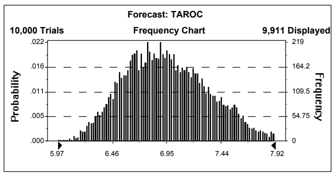
$/RPM PDF



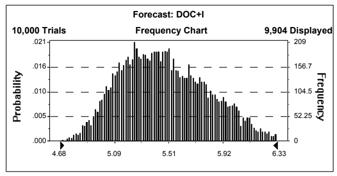
Acquisition Price PDF



RDT&E PDF



TAROC PDF



DOC+I PDF

Figure 46: Probability Density Functions if Labor Unions Abolished in the U.S.

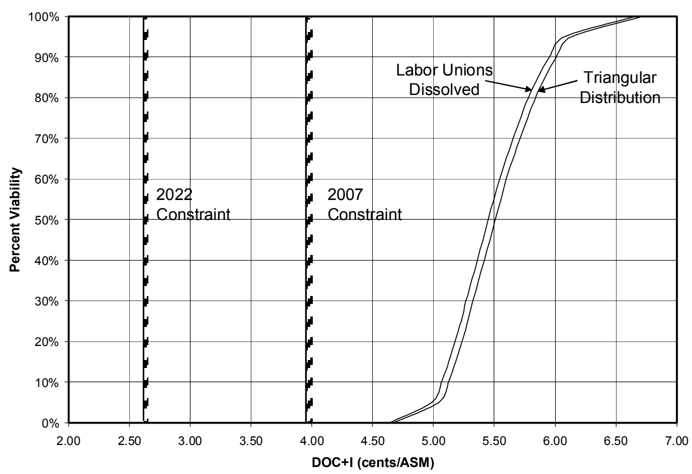
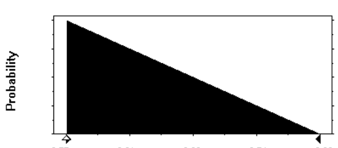
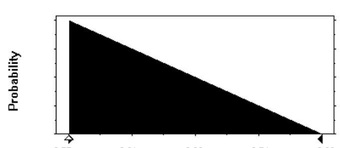
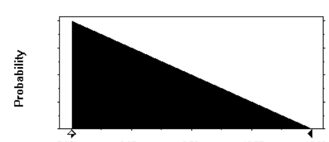


Figure 47: Viability Study for DOC+I with Labor Unions Abolished in the U.S.

In the scenario with airline re-regulation, the variables that are reduced are the airline ROI and the load factors. For each of these variables, the apex was set to the minimum to illustrate the extreme affect. These new shape functions were put in Table XXIV.

Table XXIV: Airline Re-Regulation Scenario Shape Functions

Assumption: Coach Load Factor	**Assumption: First Class Load Factor**	**Assumption: Airline ROI**
Triangular Distribution: Minimum: 0.55 Maximum: 0.80 Apex: 0.55 	Triangular Distribution: Minimum: 0.55 Maximum: 0.80 Apex: 0.55 	Triangular Distribution: Minimum: 7 Maximum: 10 Apex: 13 

The $/RPM is the only metric affected by airline re-regulation. The PDF for $/RPM is displayed in Figure 48. No CDF are displayed for this $/RPM since it is not constrained by a target value.

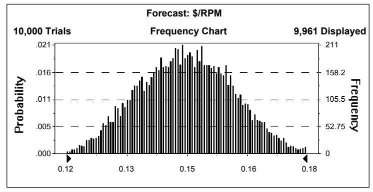


Figure 48: Probability Density Function for Airline Re-Regulation

TECHNOLOGY ALTERNATIVES SPECIFICATION

The CDF plots resulting from the previous step indicate that there is not a high probability of meeting all of the design requirements. Therefore, in order to improve the success probability of the design, new technologies to help the design in achieving the target goals must be considered and identified. However, care must be taken such that these chosen technologies must be expected to mature or ready for implementation on the design before the time the design is expected to enter into service.

The classification of the development process or the maturity level of a given technology is measured by a 1-9 scale called the 'Technology Readiness Level' (TRL). The general definition of TRL by the National Aeronautics and Space Administration (NASA) is listed in Table XXV [27].

Table XXV: Technology Readiness Level Definition

TRL Level	Level Definition
9	Actual system "flight proven" on operational flight.
8	Actual system completed and "flight qualified" through test and demonstration.
7	System prototype demonstrated in flight environment.
6	System/subsystem model or prototype demonstrated/validated in a relevant environment.
5	Component and/or breadboard verification in a relevant environment.
4	Component and/or breadboard test in laboratory environment.
3	Analytical and experimental critical function or characteristic proof-of-concept.
2	Technology concept and/or application formulated (candidate selected).
1	Basic principles observed and reported.

Based on the current Technology Readiness Level (TRL), the impact on the design by implementing the particular technology can be investigated and estimated.

Technology Identification

For a subsonic transport aircraft, there are some technologies under development that might be of great interest for the design to increase the aircraft's feasibility and economic viability. These technologies are listed in Table XXVI as given in [16].

Table XXVI: Subsonic Alternative Technologies

ID #	Technology Description	Current TRL	TRL=9 Date
T1	Adaptive Performance Optimization (APO)	9	2000
T2	Stitched RFI Composite on Tail Skin	4	2006
T3	Stitched RFI Composite on Tail Structure	4	2006
T4	Stitched RFI Composite on Wing Skin	4	2006
T5	Stitched RFI Composite on Wing Structure	4	2006
T6	Airframe Methods	4	2007
T7	Fire Suppression	3	2007
T8	Low Cost Composite Manufacturing on Tail Structure	2	2009
T9	Low Cost Composite Manufacturing on Wing Structure	2	2009
T10	Propulsion System Health Management	2	2009
T11	Smart Nacelle – Propulsion-Airframe Integration (PAI)	3	2009
T12	Emerging Alloy Tech & Forming on Tail Skin	3	2010
T13	Emerging Alloy Tech & Forming on Tail Structure	3	2010
T14	Emerging Alloy Tech & Forming on Wing Skin	3	2010
T15	Emerging Alloy Tech & Forming on Wing Structure	3	2010
T16	Superplastic Forming on Fuselage Skin	2	2011
T17	Superplastic Forming on Tail Skin	2	2011
T18	Superplastic Forming on Wing Skin	2	2011
T19	Russian Aluminum Lithium Fuselage Skin	4	2011
T20	Adaptive Engine Control System (ADECS)	4	2011
T21	Revolutionary Metallic Materials Systems on Fuselage Structure	2	2013
T22	Revolutionary Metallic Materials Systems on Landing Gear	2	2013
T23	Revolutionary Metallic Materials Systems on Tail Structure	2	2013
T24	Revolutionary Metallic Materials Systems on Wing Structure	2	2013
T25	Composite Fuselage Shell (Fuselage Skin)	2	2013
T26	Living Aircraft	2	2013
T27	Active Load Alleviation on Tail	4	2013
T28	Active Load Alleviation on Wing	4	2013
T29	Antenna Systems	2	2014
T30	Adaptive Wing Shaping	3	2014
T31	Biologically Inspired Material Systems on Fuselage Structure	1	2015
T32	Biologically Inspired Material Systems on Tail Structure	1	2015
T33	Biologically Inspired Material Systems on Wing Structure	1	2015
T34	BIOSANT on Fuselage Structure	1	2015
T35	BIOSANT on Tail Structure	1	2015
T36	BIOSANT on Wing Structure	1	2015

A more thoroughly discussion on each of the technology alternatives is presented as follows:

T1: Adaptive Performance Optimization (APO)

The adaptive performance optimization method or approach is basically an automatic control adjustments system to obtain minimum drag, which "exploits existing redundant control-effector capabilities by providing for automatic reconfiguration of control surface deflections to achieve a minimum-drag trim condition" [28]. The basic implementation configuration of the system is depicted in Figure 49 [28]. The utilization of this technology requires the use of actuators on each of the control surfaces, which are connected to the center APO analysis system that will control the smooth, long-period excitation of the redundant control surfaces [28].

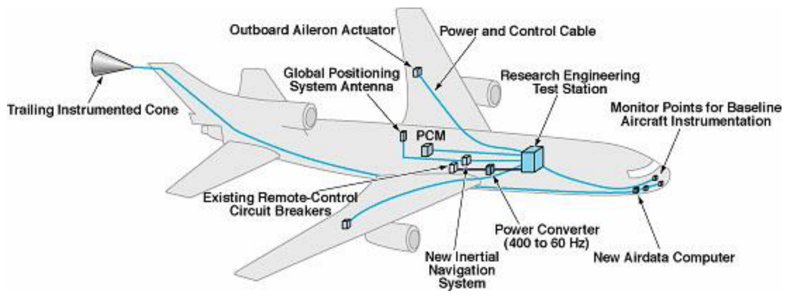


Figure 49: Modified Transport Aircraft With APO Implementation

The concept behind the development of this technology is based on the knowledge that the design of an aircraft is usually made through compromising the performance of the design in the various mission flight conditions. The end output design may be shaped up to optimize the performance in only one or two most important mission segments and thus the design will fare lower in the other flight conditions. Enabling the configuration of the aircraft (control surfaces) to change during flight as to suit the operation segments better will increase the aircraft performance, which results in the reduction of drag forces subjected during flight [29].

By implementing this technology, the redundant, variable geometry of an aircraft can be optimized to reduce the drag during flight operation, which in turn will reduce the fuel consumption of the installed engine [28]. This criterion will reduce the operating cost for the airlines and the operational emission level of the aircraft.

The development of this technology is already completed by NASA, through the Dryden Flight Research Center in California, where the APO system has been tested on a modified L-1011 aircraft. The test has been a success and the results show a reduction of drag forces acting on the aircraft [28]. Thus, the TRL level of 9 given for this technology is very much adequate in showing its readiness availability to be applied.

T2, T3, T4, T5: Stitched Resin-Film-Infusion (RFI) Composite

The current practice of manufacturing composite aircraft structures is by the lamination process, which lacks the confidence of the industry for wider implementation since the cost is high and the structures have low damage tolerance. The stitched resin-film-infusion (RFI) composite is a type of textile composites where the manufacturing process involves the stitching of the composite materials and the resin infusion process and this method will prevent delamination (separation of layers) to allow for full-span composite structures. This manufacturing process will reduce the cost as compared to that of the current lamination process and the structures also have higher damage tolerance barriers [30].

The stitched RFI process in more details includes the stitching of carbon fabric (pre-cut pieces of material) performs at a closely spaced through-the-thickness as to provide the essential reinforcement for damage tolerance, which is then infused with resin film after being molded with the outer mold line (OML) tool that shape the outside surface of the structure [30]. The sequence of the full process is shown in Figure 50 [30].

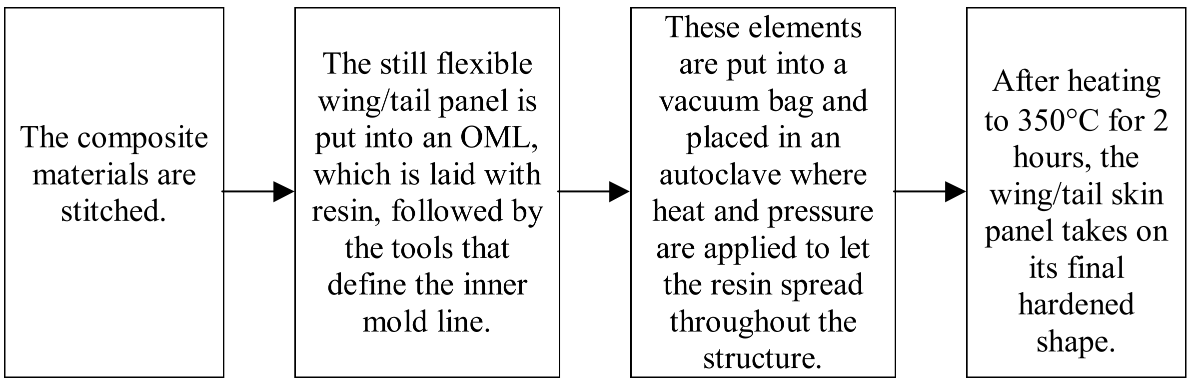


Figure 50: The Stitched RFI Process

The stitched RFI composite structure for the wing and tail is preferred because the composite has a lower weight than the commonly used aluminum alloys with comparable strength. The cost for composites also is very much lower than the metallic materials, which will reduce the production costs and subsequently the operating costs to airlines [30]. In addition to that, this new stitched RFI composite has a high strength and the process enables “the various elements of wing skin, stiffeners, ribs, and spars to be incorporated into an integral structure that would eliminate thousands of mechanical fasteners” [30].

NASA in a partnership with the Boeing Company has developed this technology. The demonstration of the performance of a 12-ft long ‘wing stub box’ at the NASA Langley Research Center in July 1995 has been a success [30]. However, to build a real full-scale wing/tail structure will require an advanced stitching machine, which is still under the development by The Boeing Company [30]. Therefore, the TRL level of 4 is adequate since only an experimental model has being developed and tested in the laboratory environment.

T6: Airframe Methods

The airframe methods technology is aimed to “reduce the design cycle time by delivering integrated design methodologies and new aerodynamic concepts” [31]. “The future new aircraft designs require the ability to define, early in the design cycle, an optimized airframe structure,” which can be achieved through the use of computerized methods for structural analysis and design optimization [32]. “These concepts and tools will enable revolutionary aircraft designs and faster design cycles while reducing aircraft operating costs, environmental impacts and aircraft development risks" [31].

Among the airframe method tools that are being developed are [33]:

- Integrated Computational and Experimental Fluid Dynamics.
- Tools for Rapid Design of Multipoint Wing (including the effects of PAI and yield technology).
- Analysis Tools for Cost Effective Implementation of Advanced Low-Noise, High-Lift System Concepts and Yield.

The development of these methods will enable the reduction in the design cycle time, which will also reduce the production costs, and the creation of an optimized airframe design that will reduce the drag forces subjected to the aircraft during flight and the emission level [33]. The reduction of drag forces also relates to the reduction of the fuel consumption by the engine. These benefits are due to the fact that the methods will enable improvements on the airframe design as to suit the operational condition better and thus increase the performance.

Currently, NASA is developing these methods, which have achieved validated progress demonstrations of improvements in the aircraft operating costs and design cycle time [31]. One of the successful demonstrated tools is the pressure-sensitive-paint system for use in wind tunnel research to improve the methods of designing a cruise wing configuration, by which the results of pressure data obtained aligned very well with the results from conventional computational-fluid-dynamics tools [31]. The TRL level given for this technology is 4 and it is justified since only experimental results from a laboratory environment has been achieved at this point.

T7: Fire Suppression

Fires and explosions are the major threat in the safety of the aircraft's operation. The fire suppression system on an aircraft is to restrain fires that may break out in an engine. For the past decades, the practice of fire suppression system for aircraft has utilized the halon 1301 (CF_3B_r) as the fire suppressant agent, which was banned from production as of January 1, 1994 by the 1992 Copenhagen Amendments to the 1987 Montreal Protocol on Substances That Deplete the Ozone Layer due to its high ozone-depleting potential (ODP) [34].

The technology search in the fire suppression system mainly involves the development of a new fire suppressant agent that would be of low mass and volume with comparable high fire suppression efficiency performance to that of halon 1301 [34]. In addition to that, the new chemicals must also perform well with regard to the ozone-depletion potential (ODP), global warming potential (GWP), atmospheric lifetime, re-ignition quenching, residue level, electrical conductivity, corrosity to metals, polymenic material compatibility, stability under long-term storage, toxicity of the chemical and its combustion and decomposition products, speed of dispersion, and safety and occupational health requirements [34].

Currently, the largest development effort is done by the US Department of Defense (DoD) through the Next Generation Fire Suppression Technology Program (NGP) [34]. The European

Community is also doing research through the FIREDETEX project, but in a smaller scale compared to NGP [35]. The NGP program has resulted new fire suppression concepts, such as the solid propellant gas generator (SPGG), and also a few potential alternatives to replace the halon 1303 as the fire suppressant, which have been successfully verified in concept through laboratory experiments [34]. The current TRL level assigned for this technology is 3 and this is a fair indication of the technology development since the new concepts and alternatives have been proven conceptually.

T8, T9: Low Cost Composite Manufacturing

The current manufacturing process of composite structures through lamination process is subjected to a high manufacturing cost. Thus, in order to widen up the usage of the composites on aircraft structures, new low cost composite manufacturing processes must be developed. The composite materials are preferred for aircraft structures because of the lighter weight and comparable strength to metallic materials.

The technologies under consideration are basically the "design and analysis of manufacturing processes that will improve the performance and reduce fabrication cost of composite materials" [36]. These will include the utilization of "innovative composite design technologies, materials and manufacturing processes" [37].

Among the processes that are being developed in lowering the cost of composite manufacturing are [36]:

- Development of science-based process simulation models
- Use of embedded sensors to monitor the process, to verify the process simulation models and for health monitoring
- Composite and matrix resin characterization
- Novel composite processing method
- Coupled thermal/structural analyses to minimize fabrication induced stresses
- Design for manufacture with composite parts
- Design of functionally graded and multifunctional composites

The modeling capability will enable the development of a more cost-effective, automated composite structures manufacturing. Obviously, the advantage of this technology will be the reduction of the production costs, and by allowing this to happen, an increase use of composite structures on aircraft design will be able to be adopted. The use of composite structures will consequently reduce the weight of the aircraft. Among the desirable process will be a 2-D braiding technique associated with a low cost that will enable the creation of textile composites with fibers placed in any direction [38].

The development of these technologies is still in the early phase, where various academic institutions like Cranfield University [39] and Virginia Tech [36], commercial companies such as Boeing and also the various government agencies are still developing the concepts of the manufacturing process and tools without any full scale experiments being done yet. One of the potential manufacturing process tools that have been developed is the "RFI Process Modeling for

Large Transport Aircraft Composite Wing Structures" by the Virginia Tech Center for High Performance Manufacturing, in which the development of a 3-D comprehensive simulation model of the RFI composite manufacturing process is done and verified [36]. The model has been adopted by the Boeing Company, which uses the simulation model in developing "the cure cycle that resulted in complete resin infiltration and cure of a 42 foot long aircraft wing section" [36]. The TRL level for this technology is given as 2 and it is a fair indication since the concepts are still in the verification stage and need to be proven successful.

T10: Propulsion System Health Management

The propulsion system health management technology is referring to a "smart self-diagnostic and prognostic propulsion system", which will utilize "advanced smart sensors integrated with on-board engine models and failure detection algorithms that will identify the direct cause for a current or impending problem, allowing for timely maintenance action to be taken" [40]. In other words, the management system will enable early detection of the propulsion system problem to permit prevention steps be taken before the total failure. The objectives of this technology are "to develop and validate propulsion system health monitoring technologies designed to prevent engine malfunctions from occurring in flight, and to mitigate detrimental effects in the event an in-flight malfunction does occur" [41]. The propulsion health management system functions are listed in Table XXVII [40].

Table XXVII: Propulsion Health Management System Functions

System	Functions
Engine Instrumentation	EPR Fuel Flow EGT Rotor Speeds Oil Temperature Oil Pressure Engine Vibration Cycle Counts
Health Monitoring Algorithm	Gas Path Analysis Trend Monitoring Signal Processing Neural Networks Expert Systems Statistical Analysis
Anomalies & Degradations	Sensor and Actuator Failures Increased Tip Clearance Blade Fouling Blade Leading Edge Blunting FOD Bearing Anomalies Blade Outs Seal Wear Lubrication System Anomalies

The advantages from this technology are the reduction in maintenance time and costs and the reduction of fuel consumption that will reduce operating costs for airlines, plus the extending on-wing life and increase the operational safety [40].

The development of this technology is still under the concept stage where experimental and development efforts are being done by NASA through collaborations with industry and academia [40]. The work done currently involve in the concept development of the "Automated On-Line Health Management and Data Analysis System" which in theory will enable online health monitoring of the propulsion sub-systems and "information monitoring from many sources over local/wide area networks" [42]. The given TRL level for this technology is 2 and this is justified with the current technology development, which is still in the concept generation and evaluation process.

T11: Smart Nacelle –PAI

The propulsion-airframe integration (PAI) technology involves the "determination of optimum nacelle placement and optimum shaping to both the nacelle and airframe to minimize drag" [43]. This method of integration is intended to be achieved through the use of advanced computational and experimental methods [43]. The simulation of PAI program is depicted in Figure 51 [43].

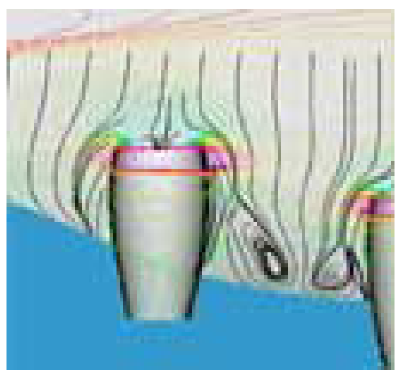


Figure 51: Propulsion-Airframe Integration

The development of this technology also includes several advanced subsystems designs such as [44]:

- Validated, rapid turnaround design tools
- Active flow control
- Active shape control

The advantages of this technology to the operation of the aircraft are the lower drag due to the propulsion system integration with the airframe, which will improve the aircraft performance and efficiency, plus the reduction in the fuel consumption and emissions levels [43].

NASA has pursued the development of this technology through the Ultra Efficient Engine Technology (UEET) program. Currently, some of the concepts developed for the smart propulsion-airframe integration methods have been fully developed but validity through experimental sense has yet to be done. One of the methods developed under this program is the "highly efficient flow sensing and control system to eliminate adverse propulsion inlet/boundary layer interactions in advanced PAI concepts" that helps to manage inlet flow fields [44]. The TRL level of 3 is therefore adequate to indicate the current development phase of this technology.

T12, T13, T14, T15: Emerging Alloy Technology and Forming

The alloy technology that results in higher strength, higher operating temperature, lower manufacturing and production costs and lighter weight material is always a benefit to the aerospace industry. New alloys such as titanium alloy are being investigated for structural application in the aerospace industry [38]. Apart from that, in much general basis, research has been done to result in better concepts of alloy materials for various uses in the industry. The current most potential emerging alloy technologies for aircraft structures is the 'shape memory' alloy.

"Shape Memory Alloys (SMA's) are novel materials, which have the ability to return to a predetermined shape when heated. When an SMA is cold, or below its transformation temperature, it has a very low yield strength and can be deformed quite easily into any new shape that it will retain. However, when the material is heated above its transformation temperature it undergoes a change in crystal structure, which causes it to return to its original shape. If the SMA encounters any resistance during this transformation, it can generate extremely large forces" [45]. "The 'shape-memory' phenomenon relies on the existence of two stable metallurgical phases and a reversible, temperature-dependent transformation between a high-temperature, high strength austenitic structure and a relatively weaker, highly twinned martensite" [46]. This shape memory phenomenon is depicted in Figure 52 [46].

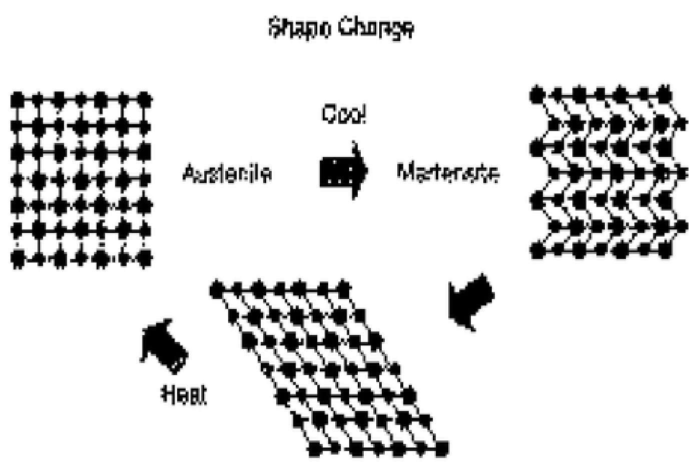


Figure 52: The Shape-Memory Phenomenon

This alloy technology will enable the tail/wing structure to change shapes during flight as to obtain an optimal shape for various flight conditions. In addition to that, the use of this alloy material will eliminate the use of hinge devices that are driven by hydraulic systems [47]. The benefits for using this alloy technology are that there is a lighter structure weight and also a reduction in drag forces acting on the aircraft. A reduction in drag will reduce the fuel consumption and therefore, the operating costs of the aircraft. The weight of the structure will reduce due to the fact that hydraulic systems that currently used to control the actuators for the control surfaces will be eliminated [47].

The development of this technology is currently done by various commercial companies in the alloy and materials business such as the Advanced Metal Components Inc. of California [46], TiNi Alloy Company [45], and others. Currently, a few shape-memory alloys have been created such as the Tinel or Nitinol, which "contains equal proportions of titanium and nickel, along with a small amount of an undisclosed third element" [46]. However, these alloys have yet to be tested for aircraft structures implementation.

In implementing the new alloys on aircraft structures, they have to be compatible with the forming processes that are being utilized in the industry. Among the new forming technologies that have been utilized in the aerospace industry are listed in Table XXVIII.

Table XXVIII: Forming Technologies in Aerospace Industry

Forming Technology	Description	Status
1. Spray Forming	"This technology uses very small, atomized droplets of metallic alloys to produce components that in many cases are stronger and tougher than the traditionally produced parts" [48]. This technique is found to reduce the cost and a more reliable forming method. [48]	Currently used in producing the aircraft engine parts from nickel and aluminum superalloys and is being developed for bigger utilization for aircraft structures [48].
2. Guerin Forming or Rubber Pad Forming.	"This method involves high pressure forming and utilizes a rubber pad inside a chamber to apply pressure on metal blanks over tools. The pressure on the blanks forms them around the tools" [49]. This technique has been found to reduce the cycle time, cost, and also has a high reliability [49].	Currently used for aluminum sheetmetal forming by Boeing Company and McDonnell-Douglas Company [49].
3. CAD-Driven Laser Forming.	The process involves "the method of layered manufacturing, where complex-shaped components are built upon layer without the need of expensive tooling or operator intervention" [50]. This forming technology is found to reduce the cost by reducing the cycle time, materials used and inventory [16].	Currently, this method is under final implementation stage through the Dual Use Science and Technology (DU S&T) program by Naval Air Systems Command, Boeing and Northrup Grumman, for commercial aircraft manufacturing application and expected to be ready by the year 2003 [16].

The TRL level given for the emerging alloys technology and forming is 3, which is a fair indication of the development level especially in the alloy technology development.

T16, T17, T18: Superplastic Forming (SPF)

Superplasticity is "the ability of a material to exhibit extreme tensile deformation (usually greater than 1000% elongation) prior to failure" [51]. This criterion of material is very desirable in the design of an aircraft. Superplastic forming (SPF) process is defined as a "metal forming process that takes advantage of the high extendibility of certain materials in order to form components whose shapes might be otherwise very difficult to obtain" [52].

"During the SPF process, the superplastic material is heated to the SPF temperature within a sealed die. Pressure is then applied, forcing the material to take the shape of the die pattern. The flow stress of the material during deformation increases rapidly with increasing strain rate. Thus, the ability to deform the material uniformly requires precise control of strain rate and strain rate sensitivity. Additional parameters requiring careful control include temperature, forming pressure, and stress." [53].

The SPF process enables the formation of unique, complex shapes and also the fabrication of components from a single piece of material, which is one of the reasons for the increase in its application [51]. In addition to that, this forming process also reduces the weight and the manufacturing costs since the process eliminates parts and subsequent processing, as well as reducing the design cycle time [51].

The development of the SPF process is done by various research institutes and commercial companies such as Lawrence Livermore National Laboratory [51], Boeing Company, McDonnell Douglas Aerospace (MDA) Company and others [53]. Since the SPF forming process has been used in manufacturing of a few aircraft structures before, the concept of the process is already known. However, there is still no experimental effort in forming the aircraft skin using the SPF method to prove whether the concept will work for this application. Thus, the current assigned TRL level of 2 for this technology is adequate.

T19: Russian Aluminum Lithium Fuselage Skin

The advancement in the aluminum-lithium alloys, which high development work has been done by Russia, is of great interest to the industry. This type of material is preferred to the conventional aerospace materials because of the higher strength and lighter weight criteria [54]. However, the use of this alloy has been limited due to the high manufacturing cost associated with the forming process of the material.

Research has been done to develop new Al-Li alloys that can be easily formed and still maintain the same attractive criteria of the strength and weight advantages. "Research and development efforts in Russia and the United States have focused on advanced Al-Li alloys for aerospace applications where reduced structural weight is a critical goal" [55]. The Al-Li Alloy 1441, one of the latest of this alloy series, is currently used for fuselage applications on the Russian Be-103 amphibious aircraft [55]. This Al-Li alloy is “cold-rollable and has several attributes that make it attractive for fuselage skin applications” [55]. The advantages of this Russian Al-Li alloy are the better mechanical properties and strength with lower density than the conventional aluminum fuselage skin alloy, and the potential increase in the life of the fuselage structure with decreased structural weight [55].

The development of this Al-Li alloy technology for the fuselage skin application has been done by NASA in collaboration with the All-Russia Institute of Aviation Materials (VIAM), Moscow, Russia [55]. Under this development program, a few new alloy series has been successfully developed and tested in laboratory experiments, such as the Aluminum-Cuprum-Lithium alloys (1450,1460), Aluminum-Magnesium-Lithium alloys (1420,1424) and the Aluminum-Cuprum-Magnesium-Lithium alloys (1440,1441) [55]. Thus, the current TRL level of 4 is the right indication of the development phase for this technology development.

T20: Adaptive Engine Control System

The adaptive engine control system (ADECS) is the technology that will enable the system to reduce the engine temperature (and pressure) while holding the engine thrust constant [56]. This technology will permit the control of engine condition as to change accordingly to suit the flight environment or condition. This function can be done by utilizing an automated control system, which includes a sensor system that can predict the fuel consumption of the engine, engine power output, and emissions level [57]. The benefits from this technology are the extension of the engine life, the increase in thrust production by the engine and also the reduction in fuel consumption and emissions level [56].

The development work on this technology is currently done by NASA, in collaboration with Pratt & Whitney Company and also by various academia institutions [56]. To date, the technology concept has been successfully demonstrated by using the F-15 Highly Integrated Digital Electronic Control (HIDEC) aircraft [56]. The TRL given for this technology is 4, which indicates that the technology has been verified as successful in the laboratory environment testing and since the demonstration of this technology is by implementation on a modified F-15 aircraft, which is totally different with the commercial transport aircraft, this level of TRL may be taken as adequate reflection on the technology development.

T21, T22, T23, T24: Revolutionary Metallic Materials Systems

Metallic materials have been used for aerospace applications for a long time. In recent years, technology development of the metallic materials are being pursued in establishing new revolutionary concepts of this materials for increased performance capability, especially in producing lighter weight structures with comparable existing strength and increase in the durability of the structure. The main goal of this technology is “to replace the discrete conventional materials/structures with continuous functionally-graded materials/structures in applications where extreme environment attenuation is critical” [58]. An example of this is the low-carbon steel material, which is anticipated to be utilized for high impact structures and corrosion resistance purposes [38].

In much general scope, this objective has leads to the research on new metallic materials on bio-inspired product form, which includes the development processes of [58]:

- synthesize of new metallic material product forms, such as porous and direct deposited metals
- development of processing methods and establishment of processing-structure-property correlations
- development of synergistic materials/structural methodology using physical models to link structural functions to material properties
- definition of extreme environment combinations and associated system functional gradients

Some of the new revolutionary metallic materials characteristics are nanostructured, functionalized, self-healing, and self-assembling [58]. The benefits from using this metallic material technology are the reduction of the structural weight, reducing the maintenance and manufacturing costs, and the increased life of the structures.

The work in developing this technology is being done by NASA, where concepts of the revolutionary metallic materials are being generated and have yet to be proven feasible through experimental efforts [58]. Thus, the TRL level of 2 is indicative of the current development phase for this technology.

T25: Composite Fuselage Shell (Fuselage Skin)

A composite fuselage shell technology is preferred to the current aluminum technology mainly because of its much lighter weight with comparable strength [59]. "The composite sandwich structures offer potential weight reduction by decreasing the number of frames by increasing the fuselage frame spacing" [60].

The composite fuselage shell will be basically made of similar structures of the current aluminum applications but with stiffened and curved sandwich composites at interfaces with internal structure members such as airframe stringers or flanges and areas of high stress concentration [60]. With the fuselage skin also made of composites, there is a possibility of mechanical fastener reductions [32]. The advantage of this technology will mainly decrease the fuselage weight.

The development on this technology is currently pursued by EU community through the FUBACOMP program [32], and also NASA [59]. The concept of the composite fuselage shell and skin has been generated. Currently experiments and testing are being done to see the strength and applicability of the composite structure concept in aircraft fuselage application and has yet to produce validation of the concept. Thus, the TRL level of 2 is appropriate to measure the development of this technology.

T26: Living Aircraft

Living aircraft technology refers to an aircraft that can adapt efficiently to various mission functions in any given environment. The design of a living aircraft will utilize integrated technologies such as the morphing technology, adaptive control of lifting surfaces and propulsion system, shape memory metallic materials technology, and several others [61]. The main objective of this technology is to enable the aircraft to mimic the nature function for any mission or flying environment [38].

The living aircraft is expected to have shape-changing structures beyond just the wing, such as changing engine inlets to optimize air flows in different speeds or the contraction of the fuselage as fuel being burned [61]. The development of this technology basically revolves around the research to "develop and mature smart component technologies for advanced airframe systems, which are done in four key areas of computational materials, advanced piezoelectric materials, fiber optic sensing devices and integrated composite structures"[62]. The ability of the aircraft to adapt to different flight mission will give main advantages of lower drag forces, high utilization, and lower structural weight.

The development on this technology is currently done by DARPA, NASA, and The Boeing Company [61, 62]. The concepts for this technology generated and evaluated without any experimental verification as yet. Thus, the TRL level of 2 is a good reflection on the development level.

T27, T28: Active Load Alleviation

The flutter effect in flight is commonly caused by the structural-mode response of the lifting surfaces of an aircraft in correspond to the induced unsteady pressures application to the lifting surfaces due to turbulent and separated flows during flight. This effect is called 'buffeting' and the factor is called the 'buffet' [63].

The active load alleviation technology is aimed to reduce this effect, which will cause fatigue damage to the aircraft structures. The technology development is focused on implementing an active control system to the lifting surfaces as to reduce the buffet response and the consequent structural dynamic response to the structures. The advantage of utilizing this technology will reduce the cost of redesigning processes and support cost since the fatigue damage can be avoided or reduced [63].

The development on this technology has been pursued by the collaborative efforts from The Boeing Company, the Air Force Research Laboratory and NASA [30]. One of the successful developments of the active load alleviation system concepts is the active control using 'smart' materials (piezoelectric actuators) that is distributed over the structure, which has been tested successfully on the vertical tail of F/A-18 aircraft with a reduction in the buffet response [63]. The current TRL level for this technology is given as 4 and it is adequate to the corresponding development of this technology.

T29: Antenna Systems

Antenna system is a compulsory system to be installed in all commercial airplanes as required by the Federal Aviation Administration (FAA) regulations. This system, as much as its importance for the communication operations, is making the aircraft subjected to more drag since the antenna is mounted on the airframe [64].

The development of technology in the antenna system is focused on eliminating the mounted antenna structure or equipment on the external aircraft surface as to reduce the drag forces. This motive has spawned researches on making the aircraft skin to operate as an antenna instead of having another structure on the aircraft for the antenna system [65].

The advantages of this technology is clearly the reduction of the drag forces subjected to the aircraft during flight, a much wider communication range and also a reduction in the equipment weight since the complex antenna equipments are being replaced by a thin 'patch' of sensors embedded in the aircraft skin [65]. A comparison between a mounted antenna and the new 'smart skin' antenna is depicted in Figure 53 [65].

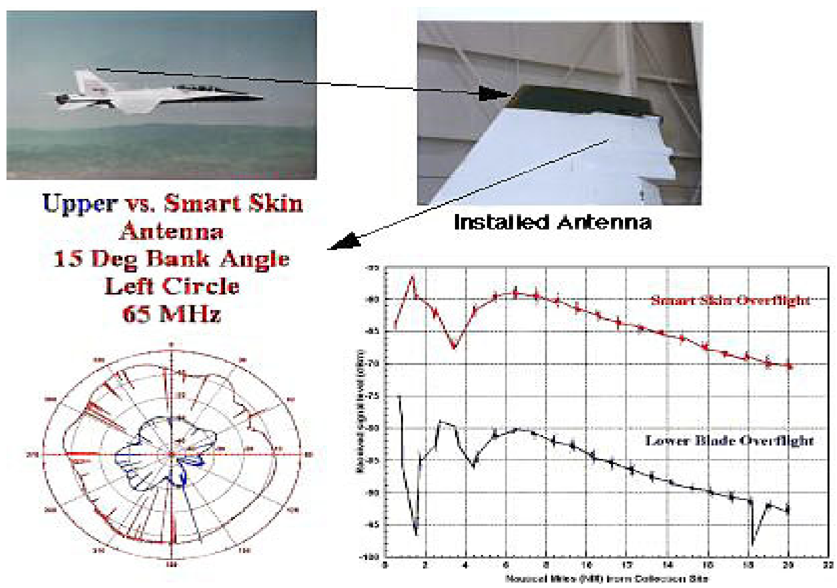


Figure 53: Comparison Between Upper Antenna and Smart Skin Antenna

The research on the development of this technology is being done collaboratively by NASA, the Air Force, Northrop-Grunman Corporation and TRW´s Avionics Systems Division [61]. The smart skin antenna has been tested successfully on an F-18 SRA aircraft where the antenna system is embedded physically and electronically into the right vertical stabilizer surface [61]. With this success, the TRL given for this technology, which is 2, may be increased to TRL=3.

T30: Adaptive Wing Shaping

Adaptive wing technology corresponds to wings whose shape can be altered during flight. In further detailed description, the adaptive wing has the ability to vary its shape parameters such as the camber, wing twist, and thickness in order to achieve an optimized wing shape for the different flight conditions [66]. “The ideal use of an adaptive strategy allows the wing to vary its geometric parameters in flight during encounters in situation of changing flow conditions such as wind speed or direction” [67].

The main governing principle of the technology is to improve the efficiency of the airfoil in off-design flight regimes [67]. The development of this technology has now become feasible with the “development of sensors and actuators using the smart materials that potentially can reduce the complexity and weight” [66]. In order to achieve this, development of the variable-camber control of the wing, which has the “ability to actively modify airfoil camber, spanwise camber distribution, and wing sweep while maintaining a smooth continuous airfoil surface” is being pursued [68]. “The features of the mission adaptive wing will include cruise camber control to maximize vehicle efficiency during straight and level flight, maneuver camber control, maneuver load control, and maneuver enhancement and gust alleviation” [68].

The advantages of this technology are the increased aerodynamic efficiency of the wing, which will increase lift force generation and reduce drag forces subjected to the aircraft, and a better control and maneuverability of the aircraft that reduce the dependency on the tail control surfaces [67].

Currently, the development work on this technology is being pursued by NASA and the technology concept has been proven positively through wind tunnels experiments of the adaptive wing tunnel models [67]. Thus, the current TRL level for this technology, which is given as 3, is fairly adequate.

T31, T32, T33: Biologically Inspired Material Systems

Biologically inspired materials are materials that have the ability to self-repair when damaged and are able to self-assemble the structures back to a near-perfect final shape [69]. The technology development on this material will involve “a greater understanding of mechanical properties associated with biological materials whose primary function is to sense environmental changes and respond by generating forces or being modified by an applied force” [70]. The knowledge of this characteristic will enable the findings of new materials that can “mimic the extraordinary structural and self-repairing properties of biological substances such as bone or sea shells” [71]. These materials, when applied for aerospace structure applications, are expected to have the ability to sense the damage conditions on its structure and take steps to repair the damage [71].

Steps have been taken in developing this technology and the refinement of “necessary instrumentation required characterizing these biological properties at multiple scales and using this knowledge to provide hierarchical design approaches required to the engineering devices capable of sensing and actuating at all scales for realization of new material systems” [70]. Advantages associated with this technology will be the reduced maintenance costs and increase in the life of the structure. This material will also help in reducing the weight of the aircraft by eliminating the required redundancy in structural strength of the aircraft airframe.

The development on this technology has been done by NASA in collaboration with various academia institutions [69]. Currently, the technology is still in the concept development stage and thus the current TRL level of 1 is indicative of the current development stage.

T34, T35, T36: BIOSANT

BIOSANT is the abbreviated form of BIOlogically-inspired SmArt NanoTechnology. The nanotechnology is corresponding to the "thorough three-dimensional structural control of materials, processes and devices at the atomic scale", which enables the manipulation of the molecular structures for technical purposes [72].

The development of this technology has focused on several aspects, which are the atomically precise control of matter, the development of molecular machines and also the programmable matter [73]. In the aerospace aspect of the technology, this BIOSANT material is preferable to be integrated from its molecular components level into the larger atomically precise aircraft systems in order to produce a structure that can respond when being stimulated, i.e. to reform back to its original shape after being damaged by an external factor or to change shape during flight as to better suit the flight condition [74].

The advantages of this technology will be much higher tensile strength, lighter weight, smart and active structures, a reduction in cost as structures can be developed precisely through biological molecular machines, and reduced drag forces on the aircraft as much smoother aerodynamically shaping process is possible [72].

Currently, the research on this technology has been done by NASA, which is still in its earliest stage of concept formulation since the development in the nanotechnology materials itself is still in its early stage [73]. To date, "substantial progress has been made towards the construction of molecular computers, which will enable polymeric molecules, notably proteins, DNA, and RNA, be automatically synthesized from precise specifications" [72]. One of the potential molecules in the aerospace application is the carbon nanotubes [73]. The TRL given for this technology is 1 and that appropriately implies that current level of this technology development.

Technology Compatibility

After all the useful technology alternatives have been clearly identified, the compatibility characteristics of each technology against each other must be investigated. This is to ensure that the set of technology selections to be implemented on the design will not have negative effects on each other performance and the technologies are able to co-exist on the design. The original full compatibility technology matrix provided by [16] is found to provide no flaw in depicting the compatibility relationship between the technologies. Therefore, from the compatibility matrix, incompatible pairs of technologies can be identified and the discussion on each of the incompatibility relationships is summarized in Table XXIX.

With this information, the technology compatibility matrix (TCM) can be constructed for each year. The TCM is based on the compatibility rules and includes the technologies that have reached the TRL=9 data for the TCM of that year. The TCMs for the year 2007 and 2016 are shown in Table VI and Table VII, respectively. The TCM for the other years are included in Appendix F. Since the TCM is a symmetrical matrix and thus, only half of the matrix is populated with the relationship signs, where 1 indicates compatible relationship and 0 means in incompatible combination.

Table XXIX: Incompatible Technologies

Incompatible Technology Pairs	Discussion
T2, T12, T17	These technologies are not compatible with each other because each technology corresponds to different materials and manufacturing methods to be utilized for the tail skin.
T3, T8, T13, T23, T32, T35	These technologies are not compatible with each other because each technology corresponds to different materials and manufacturing methods to be utilized for the tail structure.
T4, T14, T18	These technologies are not compatible with each other because each technology corresponds to different materials and manufacturing methods to be utilized for the wing skin.
T5, T9, T15, T24, T33, T36	These technologies are not compatible with each other because each technology corresponds to different materials and manufacturing methods to be utilized for the wing structure.
T16, T19, T25	These technologies are not compatible with each other because T19 corresponds to the Al-Li Alloy materials and T25 corresponds to the composite materials, both for the fuselage skin, and these two types of materials do not possess a superplasticity criterion that is a requirement for superplastic forming process.
T21, T31, T34	These technologies are not compatible with each other because each technology corresponds to different materials to be utilized for the fuselage structure.

The year 2007 is chosen because this is the first year where a collective set of technology alternatives can be grouped out as they reached their TRL=9 date (with the exception of the Adaptive Performance Optimization, which is already at TRL=9). In 2016 all of the alternative technologies will be all at their TRL=9 level. By examining the impact of technologies in 2016, it can be determined if by adding technologies, a feasible design space can be achieved. It can be seen in Table XXX that all the technology alternatives that have reached TRL=9 date by the year 2007 are compatible with each other. This means that each of technology can be selected to be implemented on the design.

Table XXX: Technology Compatibility Matrix for Year 2007

	T1	T2	T3	T4	T5	T6
TRL=9 Date	2000	2006	2006	2006	2006	2007
T1		1	1	1	1	1
T2			1	1	1	1
T3				1	1	1
T4					1	1
T5						1
T6						

On the other hand, the technology compatibility matrix for the year 2016 in Table I is shown to be consisted of several incompatible pairs of technologies. Care must be taken to not choosing the incompatible pairs of technologies for implementation on the design.

Table XXXI: Technology Compatibility Matrix for Year 2016

	T1	T2	T3	T4	T5	T6	T7	T8	T9	T10	T11	T12	T13	T14	T15	T16	T17	T18	T19	T20	T21	T22	T23	T24	T25	T26	T27	T28	T29	T30	T31	T32	T33	T34	T35	T36
TRL=9 Date	2000	2006	2006	2006	2006	2007	2007	2009	2009	2009	2009	2010	2010	2010	2010	2011	2011	2011	2011	2011	2013	2013	2013	2013	2013	2013	2013	2013	2014	2014	2015	2015	2015	2015	2015	2015
T1		1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
T2			1	1	1	1	1	1	1	1	1	0	1	1	1	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
T3				1	1	1	1	0	1	1	1	1	0	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1	1	1	0	1	1	0	1
T4					1	1	1	1	1	1	1	1	1	0	1	1	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
T5						1	1	1	0	1	1	1	1	1	0	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1	1	1	0	1	1	0
T6							1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
T7								1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
T8									1	1	1	1	0	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1	1	1	0	1	1	0	1
T9										1	1	1	1	1	0	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1	1	1	0	1	1	0
T10											1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
T11												1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
T12													1	1	1	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
T13														1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1	1	1	0	1	1	0	1
T14															1	1	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
T15																1	1	1	1	1	1	1	1	0	1	1	1	1	1	1	1	1	0	1	1	0
T16																	1	1	0	1	1	1	1	1	0	1	1	1	1	1	1	1	1	1	1	1
T17																		1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
T18																			1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
T19																				1	1	1	1	1	0	1	1	1	1	1	1	1	1	1	1	1
T20																					1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
T21																						1	1	1	1	1	1	1	1	1	0	1	1	0	1	1
T22																							1	1	1	1	1	1	1	1	1	1	1	1	1	1
T23																								1	1	1	1	1	1	1	1	0	1	1	0	1
T24																									1	1	1	1	1	1	1	1	0	1	1	0
T25																										1	1	1	1	1	1	1	1	1	1	1
T26																											1	1	1	1	1	1	1	1	1	1
T27																												1	1	1	1	1	1	1	1	1
T28																													1	1	1	1	1	1	1	1
T29																														1	1	1	1	1	1	1
T30																															1	1	1	1	1	1
T31																																1	1	0	1	1
T32																																	1	1	0	1
T33																																		1	1	0
T34																																			1	1
T35																																				1
T36																																				

Technology Impact

The identification process of each technology has given an insight on which criteria of the design will be impacted by the utilization of that particular technology. In order to generate estimated impact of these technologies, the impact of each technology has to be quantified, either to the advantage of the system or to the degradation of the system performance, before selection of which technologies to be implemented on the aircraft is made. In making this estimation, these technologies are assumed to be matured technologies, meaning that the use of the technologies have been widely accepted and verified through extensive applications in commercial fields. This situation will correspond to the TRL=9 in the technology development phase, with additional validated impact proofs in commercial applications. Immature technologies, on the other hand, corresponds to technologies that are either still under the development phase or new technologies that never been applied extensively in commercial applications.

It should be noted that the impacts of the technology, which are assumed in the design process, are based on the expected or the desired performance of the technology to the design. These impacts are only applicable if and only if the technology is fully matured. Thus, by making the assumption that these technologies are all matured by the anticipated TRL=9 year, the impact on the design is considered based on the fact that the technology has been proven in many applications, which reduces the risk and also the research costs to develop the technology. On top of all, the technology is assumed to be ready by its anticipated TRL=9 date although there is always a possibility that the TRL=9 date will be later than the date expected. For example, with the current TRL of 4, the stitched RFI composite technology may be anticipated to achieve the readiness level of 9 by the year 2006. However, it may takes more time to be matured and thus, by the year 2006, the technology may not be as ready as anticipated. This situation will jeopardize the impact that has been input into the design probability predictions for the given sets of the technology applications (for year 2007 and above) since the costs of researches and the impact advantages of the technology applications that have been assumed for a matured technology level will be degraded. However, in making the assumptions for the design, each technologies is taken to be at their TRL=9 level for their respective anticipated year and their advantages on the design are fully applied.

The impact of these technologies to the design has been provided in the original Technology Impact Matrix (TIM) in reference [16], which is included in the Appendix G. However, the values given are corresponding only to the main advantages of each technology to the design. A more extensive prediction should be made, especially in capturing the negative side of the technology to the design and also the inclusion of the design economic parameters impact. From the discussion in the technology identification process, these impacts can be predicted and are summarized in Table XXXII.

Table XXXII: Technology Impact on the Design

Technology Impact	Anticipated Impact	Related Technology
Wing Weight (skin or structure)	Weight Reduction	T4, T5, T9, T14, T15, T18, T24, T28, T33, T36
Fuselage Weight (skin or structure)	Weight Reduction	T16, T19, T21, T25, T31, T34
Horizontal Tail Weight (skin or structure)	Weight Reduction	T2, T3, T8, T12, T13, T17, T23, T27, T32, T35
Vertical Tail Weight (skin or structure)	Weight Reduction	T2, T3, T8, T12, T13, T17, T23, T27, T32, T35
Induced Drag Coefficient (C_{Di})	Drag Reduction	T1, T11, T26, T29, T30
Zero-Lift Drag Coefficient (C_{D0})	Drag Reduction	T6, T11, T29, T30
Landing Gear Weight	Weight Reduction	T22
Avionics Weight	Weight Increment	T1, T10, T26, T27, T28, T30
	Weight Reduction	T29
Hydraulics Weight	Weight Increment	T30
	Weight Reduction	T26
Furnishings & Equipment Weight	Weight Reduction	T7
Vertical Tail Area	Area Reduction	T30
Horizontal Tail Area	Area Reduction	T30
Engine Weight	Weight Increment	T10, T20
Fuel Consumption	Fuel Consumed Reduction	T1, T6, T10, T11, T20, T26, T29, T30
RDT&E Costs	Cost Reduction	T6, T11
	Cost Increment	T1, T2, T3, T4, T5, T7, T8, T9, T10, T12, T13, T14, T15, T16, T17, T18, T19, T20, T21, T22, T23, T24, T25, T26, T27, T28, T29, T30, T31, T32, T33, T34, T35, T36
O&S Costs	Cost Reduction	T1, T6, T10, T11, T12, T13, T14, T15, T16, T17, T18, T19, T20, T21, T22, T23, T24, T27, T28, T29, T30, T31, T32, T33, T34, T35, T36
	Cost Increment	T2, T3, T4, T5, T7, T8, T9, T25, T26
Production Costs	Cost Increment	T1, T2, T3, T4, T5, T7, T8, T9, T10, T12, T13, T14, T15, T16, T17, T18, T19, T21, T22, T23, T24, T25, T26, T27, T28, T29, T30, T31, T32, T33, T34, T35, T36
Utilization	Utilization Level Increment	T10, T12, T13, T14, T15, T16, T17, T18, T19, T20, T21, T22, T23, T24, T26, T27, T28, T30, T31, T32, T33, T34, T35, T36
	Utilization Level Reduction	T2, T3, T4, T5, T8, T9, T25

With these additional predicted impacts of the technologies, the original technology impact matrix (TIM) can be modified to include these data. A more thorough discussion on how these impacts are quantified in the TIM is presented in the Appendix H. The modified TIM is shown in Table XXXIII. It should be noted that a negative sign in the matrix is referring to the degradation of the values for the corresponding technology impact with the implementation of the respective technology, and vice versa for a positive sign. The blank space will refer to no impact relationship between the technology and the impact criteria.

Table XXXIII: Modified Technology Impact Matrix

	FRWI	FRFU	FRHT	FRVT	FCDI	FCDO	FRLGM	WAVONC	WHYD	WFURN	SVT	SHT	WENG	FACT	AKRDTE	AKOANDS	AKPRICE	U	SW	TWR
T1					-0.040			0.005								-0.025	0.005			
T2			-0.030	-0.030		-0.005									0.025	0.005	0.005	-0.010		
T3			-0.130	-0.130												0.005	0.005	-0.010		
T4	-0.030					-0.005										0.010	0.010	-0.020		
T5	-0.130															0.010	0.010	-0.020		
T6						-0.020									-0.015	-0.020				
T7										-0.020					0.001	0.010	0.001			
T8			-0.200	-0.200											0.030	0.005	-0.010	-0.020		
T9	-0.200															0.010	-0.020	-0.030		
T10								0.005					0.025		0.010	-0.030	0.010	0.030		
T11					-0.010	-0.010									-0.020	-0.020				
T12			-0.020	-0.020											0.030	-0.010	0.002	0.010		
T13			-0.080	-0.080												-0.010	0.004	0.010		
T14	-0.020															-0.010	0.008	0.020		
T15	-0.080															-0.010	0.010	0.020		
T16		-0.070													0.030	-0.010	0.020	0.010		
T17			-0.030	-0.030												-0.010	0.005	0.020		
T18	-0.030															-0.010	0.010	0.010		
T19		-0.070													0.010	-0.020	0.030	0.010		
T20													0.025	-0.170	0.005	-0.020	0.005	0.020		
T21		-0.110													0.035	-0.010	0.030	0.020		
T22							-0.210									-0.010	0.002	0.020		
T23			-0.150	-0.150												-0.005	0.005	0.010		
T24	-0.150															-0.010	0.015	0.020		
T25		-0.070													0.020	0.020	0.025	-0.040		
T26					-0.030			0.020	-0.500						0.030	-0.005	0.030	0.015		
T27			-0.050	-0.050				0.005								-0.005	0.010	0.010		
T28	-0.050							0.005							0.015	-0.005	0.010	0.010		
T29						-0.010		-0.450							0.001	-0.010	0.001			
T30					-0.091	-0.091		0.010			-0.150	-0.150			0.030	-0.020	0.025	0.010		
T31		-0.180													0.050	-0.010	0.035	0.010		
T32			-0.350	-0.350												-0.005	0.015	0.010		
T33	-0.300															-0.010	0.025	0.010		
T34		-0.180													0.050	-0.010	0.035	0.020		
T35			-0.300	-0.300												-0.005	0.015	0.020		
T36	-0.300															-0.010	0.025	0.020		

TECHNOLOGY ALTERNATIVES ASSESSMENT

The results from Step 5 have shown that with the current technology level the optimized 150 passenger aircraft configuration does not satisfy all the constraints for the performance metrics. In dealing with this situation, new technologies will be infused into the design. The technologies identified in Step 6 will be assessed as to see how the infusion of these technologies to the design will affect the performance of the design. The impacts, either benefits or degradations, will be predicted using a deterministic approach rather than a probabilistic approach due to the time constraint. The main objective in this step is to assess the technology impacts on the design.

Technology Impact Factor

The influence of the technology infusion to the design is difficult to be evaluated directly. Thus, the impact is translated into 'k-factors', which can be quantitatively evaluated in a modeling and simulation environment [3]. These 'k-factors' correspond to the impact subjected by each of the technologies, which are quantified by using 'k-vectors' that are assigned with values derived from the generated Technology Impact Matrix (TIM) in the previous step. The minimum and maximum values of a particular k-factor correspond to the case when all the technologies are utilized into the design. These k-factors are then mapped to the input of FLOPS/ALCCA to obtain usable values to run the analysis codes. The corresponding values are tabulated in Table

XXXIV. Appendix I, contain the three scripts used for creating the DoE input files, the script for running flops, and a last script used to get the metrics from the FLOPS output files.

Table XXXIV: Technology Impact Factors with Specified Ranges

	Tech. Impact Vector	Variable	Namelist	Optimized Baseline	Dimensionalized		Non-Dimensionalized	
					MIN	MAX	MIN	MAX
1	Wing Weight (skin or structure)	FRWI	WTIN	1	0.65	1.15	0.65	1.15
2	Fuselage Weight (skin or structure)	FRFU	WTIN	1	0.75	1	0.75	1
3	Horizontal Tail Wgt. (skin or structure)	FRHT	WTIN	1	0.6	1	0.6	1
4	Vertical Tail Wgt. (skin or structure)	FRVT	WTIN	1	0.6	1	0.6	1
5	Cdi	FCDI	MISSIN	1	0.8	1	0.8	1
6	Cdo	FCDO	MISSIN	1	0.8	1	0.8	1
7	Landing Gear Wgt.	FRLGM	WTIN	1	0.75	1	0.75	1
8	Avionics Wgt.	WAVON	WTIN	1	0.5	1.05	0.5	1.05
9	Hydraulics Wgt.	WHYD	WTIN	1	0.5	1.05	0.5	1.05
10	Furnishing and Equip. Wgt.	WFURN	WTIN	1	0.9	1.05	0.9	1.05
11	VT Area	SVT	WTIN	117.65	100	200	-1	1
12	HT Area	SHT	WTIN	176.47	150	250	-1	1
13	Engine Wgt.	WENG	WTIN	6466	3556.3	6789.3	0.55	1.05
14	Fuel Consumption	FACT	MISSIN	1	0.8	1.01	0.8	1.01
15	RDT&E Costs	AKRDTE	IWGT	0	-0.2	0.2	-20%	20%
16	O&S Costs	AKOAND	IWGT	0	-0.2	0.2	-20%	20%
17	Production Cost	AKPRICE	IWGT	0	-0.2	0.2	-20%	20%
18	Utilization	U	COPER	3900	3120	4680	-20%	20%
19	Wing Area	SW	CONFIN	1500	1000	1500	-1	1
20	Thrust-to-Weight ratio	TWR	CONFIN	0.3098	0.3098	0.3400	-1	1

K-Factors Response Surface Equations

Based on the resultant ranges of the k-factors as mapped to the analysis codes' inputs, the corresponding response surface equations for each of the k-factors can be generated. The process of creating these equations will be of similar procedures as before. In a brief description, the creation of the equations start by inputting the non-dimensional values of the k-factors ranges into the analysis codes by means of the design of experiments table set-up for the k-factors. The data results from the analysis codes (FLOPS and ALCCA) are then extracted and input into the statistical software package, JMP, where the data is manipulated to create corresponding response surface equations by means of least squares method. The resultant response surface equations for the system level metrics with the k-factors as input variables will take the similar form of the second order quadratic equation, which is shown in equation 8.

$$R = b_0 + \sum_{i=1} b_i k_i + \sum_{i=1} b_{ii} k_i^2 + \sum_{i=1} \sum_{j=i+1} b_{ij} k_i k_j \qquad \text{Eqn. (8)}$$

where, R is a given system metric

b_i represents regression coefficients for linear terms

b_{ii} represents quadratic coefficients

b_{ij} represents cross-product coefficients

k_i represents "k" vector elements

k_{ii} denotes interactions between two "k" vector elements

In assessing the impact of a given technology to the design, the technology 'k-vector' is mapped to the response surface equation. The impact values, which are quantified by the approximation done in the TIM, are being inputted into the equation to get the overall quantified prediction impact on the design parameters. These values will be the values for the corresponding k_i or k_j in the equation. Assuming that for a given system level metric, with two k-factors subjected to the impact of infusion of one technology, the corresponding response surface equation for the k-factors will be as shown in equation 9 [17].

$$R = b_0 + b_1 k_1 + b_2 k_2 + b_{11} k_1^2 + b_{22} k_2^2 + b_{12} k_1 \qquad \text{Eqn. (9)}$$

From the TIM, the technology has been estimated to reduce k_1 value by (-50%) and has no impact on the k_2 factor. Thus, these predicted k-vector values are mapped to the response surface equation by substituting the vector value into the corresponding k-factor value. Thus, equation 2 will results as shown in equation 10. This is how the technology k-vectors are mapped to the response surface equations [3].

$$R = b_0 + b_1(-50\%) + b_2(0\%) + b_{11}(-50\%)^2 + b_{22}(0\%)^2 + b_{12}(-50\%)(0\%) \qquad \text{Eqn. (10)}$$

The corresponding response surface equations for the system level metrics are created in JMP. The coefficients of the response surface equations generated are listed in Appendix J. The accuracy of the response surface equations can then being investigated through the examination of the corresponding R^2 value, whole model test, and residual plot of the RSE of a given metric. Table XXXV list the R^2 values, the maximum and minimum errors of the distributions, the standard deviation of the error distribution, and the mean of the error distribution. The tests for the goodness of fit and error distributions for the random cases are displayed in Appendix K. All of the tests pass, verifying a good RSE. As should be predicted, the error in random cases is larger than the original cases investigated in creating the equations. The maximum error for most cases is less than 1.5%, except for the $/RPM and the NOx cases that correspond to about 3% of maximum error. The value for the standard deviation is below 1 for all cases except again for the $/RPM and NOx cases, which have the values of 1.44 and 1.18, respectively. Although the standard deviation values for these cases are above than 1, the corresponding maximum error values are small. Thus, all the equations can be considered to be good fits.

Table XXXV: Summary of FIT for Responses

Metric	Minimum Error (%)	Maximum Error (%)	Standard Deviation of Error Distribution	Mean of Error Distribution	R^2 Value
Approach Speed	-0.036	0.048	0.0131412	0.0000015	0.999998
Landing FL	-0.036	0.043	0.0152698	0.0000000	0.999997
TOFL	-0.313	0.232	0.0991517	-0.000003	0.999975
CO2/ASM	-0.281	0.208	0.0780068	0.0000196	0.999980
NOx	-0.984	0.626	0.2364763	0.0003171	0.999864
TOGW	-0.079	0.06	0.0225849	0.0000013	0.999991
Acquisition $	-0.172	0.127	0.0511374	0.0000065	0.999995
RDT&E	-0.111	0.073	0.0308667	-0.000004	0.999998
$/RPM	-1.404	1.469	0.4461861	0.0013586	0.999437
TAROC	-0.427	0.440	0.1374065	-0.000003	0.999969
DOC+I	-0.518	0.547	0.1644542	0.000022	0.999961
WAWt	-0.269	0.313	0.0972956	-0.000028	0.999992

Impacts of the K-Factors

The prediction profiles for the metrics as a function of the k-factors, at the baseline k-factor values, are shown in Figure 54. These profiles show the sensitivity of the metrics to the changes of the k-factors.

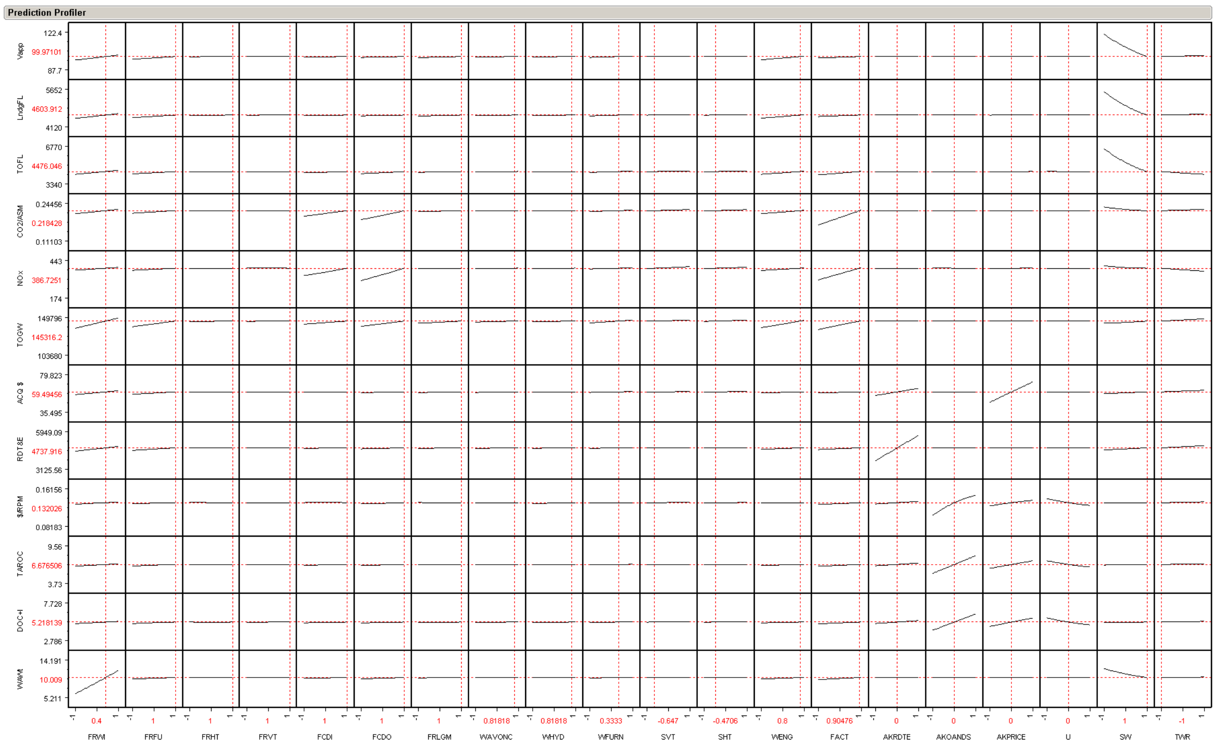


Figure 54: Prediction Profiles of the Metrics Against The K-Factors (baseline values)

From the prediction profiles, relationship between the k-factors to the performance and economic metrics can be defined. It can be seen that there are at least 12 k-factors that have influences on different sets of the metrics, which are the wing weight (FRWI), fuselage weight (FRFU), induced drag coefficient (FCDI), parasite drag coefficient (FCDO), the engine weight (WENG), fuel consumption (FACT), RDT&E costs (AKRDTE), O&S costs (AKOANDS), production costs (AKPRICE), utilization level (U), wing area (SW) and the thrust-to-weight ratio (TWR). Apart from the mentioned factors, the others seem to have either a very small impact or no impact at all on the interested metrics.

The wing weight has an influence on almost all the performance metrics. The relationship follows that the reduction of the wing weight will reduce the corresponding values for all the metrics. Similar argument can be said about the influence of the fuselage weight but to a much smaller magnitude compared to the influence of the wing weight.

Both of the drag coefficients, induced drag and the parasite drag, have significant impact on the CO_2 and NOx emission levels and a small influence on the takeoff gross weight. The reduction of both the drag coefficients will decrease the emission levels and also the takeoff gross weight.

Similarly, the impact of reducing the fuel consumption will also produce the same impacts but to a much greater magnitude.

The engine weight is found to have significant effect only on the takeoff gross weight, where the reduction of the engine weight will reduce the total gross weight. On the other hand, the RDT&E costs changes will have a significant impact on the acquisition price and obviously, the RDT&E costs itself. It follows that the reduction in the RDT&E costs will reduce the magnitude of the two metrics.

The O&S costs and the production costs are found to have similar impact on three economic metrics, which are the required yield per RPM, the total aircraft required operating costs, and also the direct operating costs. The two factors have a directly proportional relationship with these metrics, with the former having a bigger magnitude of impact. In addition to that, the latter factor has an additional significant impact on the acquisition cost in the same relationship manner.

The utilization level and the wing area have indirect proportional relationships with the metrics. The utilization level can be seen to have significant impact on economic metrics such as the required yield per RPM, the total airplane operating costs, and the direct operating costs plus interest. The higher the utilization level is, the lower the amount of the impacted metrics. The wing area (SW) factor can be seen to have a great impact on four of the metrics, which are the approach velocity, landing field length, takeoff field length and the wing aerial weight. It follows that for each of the metrics, the increasing value of the wing area, the lower the corresponding values for the metrics will be. As for the thrust-to-weight ratio, it is shown that it has small influence on different performance metrics. The obvious impact from this factor is the takeoff field length, where a directly proportional relationship exists.

Feasibility and Viability with K-Factors

By observing the minimum and maximum values of the metrics from the prediction profile, the target value for DOC+I for the year 2022 can never be achieved, regardless of what the combinations of technologies being infused into the design. The other metrics have shown that with the right combinations of the technologies, the target values can be obtained. The performance metrics of the approach speed, landing field length, takeoff field length, and takeoff gross weight have been shown that regardless of the settings of the technology impact factors, the target values for these four metrics would always be achieved. Table XXXVI, lists the k-factor values of the unmodified design, in other words, the optimized baseline values of the k-factors. The values depend on the ranges previously specified in Table XXXVII, and range from -1 to 1, as required for the analysis software JMP.

Table XXXVI: Systems Level Metrics and Future Constraints

Parameter	Baseline	2007 Constraint	2022 Constraint	Units
Performance				
Approach Speed (Vapp)	106.8	130	130	knots
Landing Field Length (LdgFL)	4897	7000	7000	ft
Takeoff Field Length (TOFL)	5367	7000	7000	ft
CO2/ASM (CO2)	0.24605	0.1845	0.1230	lb/ASM
NOx (NOx)	456	342	228	lb
Takeoff Gross Weight (TOGW)	148,219	175,000	175000	lbf
Economics				
Acquisition Price (Acq $)	59.259	Minimize	Minimize	M$
Research, Development, Testing & Evaluation Costs (RDT&E)	4,722	Minimize	Minimize	M$
Average Required Yield per Revenue Passenger Mile ($/RPM)	0.134	Minimize	Minimize	$
Total Airplane Related Operating Costs (TAROC)	6.752	Minimize	Minimize	¢/ASM
Direct Operating Cost plus Interest (DOC+I)	5.279	3.959	2.640	¢/ASM
Miscellaneous				
Wing Aerial Weight (WAWt)	10.48	Minimize	Minimize	lb/ft^2

Table XXXVII: K-Factor Values for Baseline (range of -1 to 1)

K-factor	Value (nondimensionlized)	Dimensionalized Value
Wing Weight (skin or structure)	0.4	1
Fuselage Weight (skin or structure)	1	1
Horizontal Tail Wgt. (skin or structure)	1	1
Vertical Tail Wgt. (skin or structure)	1	1
Cdi	1	1
Cdo	1	1
Landing Gear Wgt.	1	1
Avionics Wgt.	0.81818	1
Hydraulics Wgt.	0.81818	1
Furnishing and Equip. Wgt.	0.33333	1
VT Area	-0.64706	117.6 ft^2
HT Area	-0.47059	176.5ft^2
Engine Wgt.	0.8	6466 lb
Fuel Consumption	0.90476	1
RDT&E Costs	0	0
O&S Costs	0	0
Production Cost	0	0
Utilization	0	3900 hrs
Wing Area	1	1500 ft^2
Thrust-to-Weight ratio	-1	0.3098

Using the optimized baseline values, one obtains the contour plots shown in Figure 55. The first cell contains the values of the k-factors, in this case they must correspond to the baseline values listed in the table above. It also contains the response values for the chosen point under the title “Current Y”. The 5 other cells contain contour plots, which as previously mentioned, show the design is not feasible and viable without the implementation of technologies. In each one of these contour plots, the red dot signifies the baseline value.

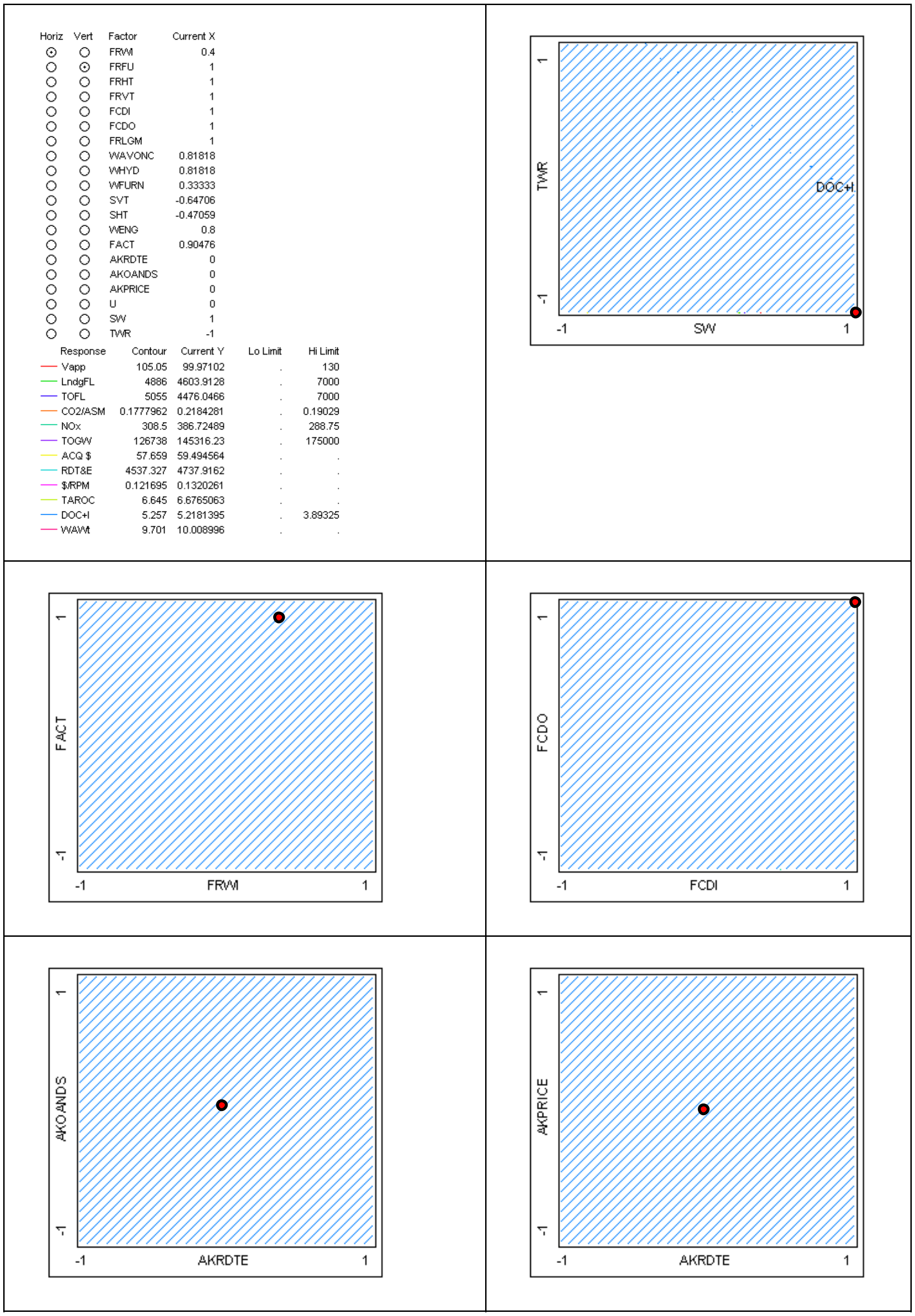


Figure 55: Contour Plots of Optimized Baseline

To analyze the implementation of technologies, one can alter the k-factors until a feasible and viable space is achieved. The three constraints that are not met are those of CO2/ASM, NOx, and DOC+I. In order to create a feasible and viable space, one observes from the prediction profile that that CO2/ASM and NOx are highly influenced by drag coefficients and fuel consumption. DOC+I is highly influenced by operation costs, acquisition price, and utilization. Taken these observations in consideration, one can modify the k-values in the contour plots to obtain a feasible and viable space. Figure 56 shows the new contour plots and k-factor settings. Note that the Wing Area and Thrust to Weight Ratio were kept constant to signify a fixed geometry analyzes and for comparison of similar conditions with the other studies.

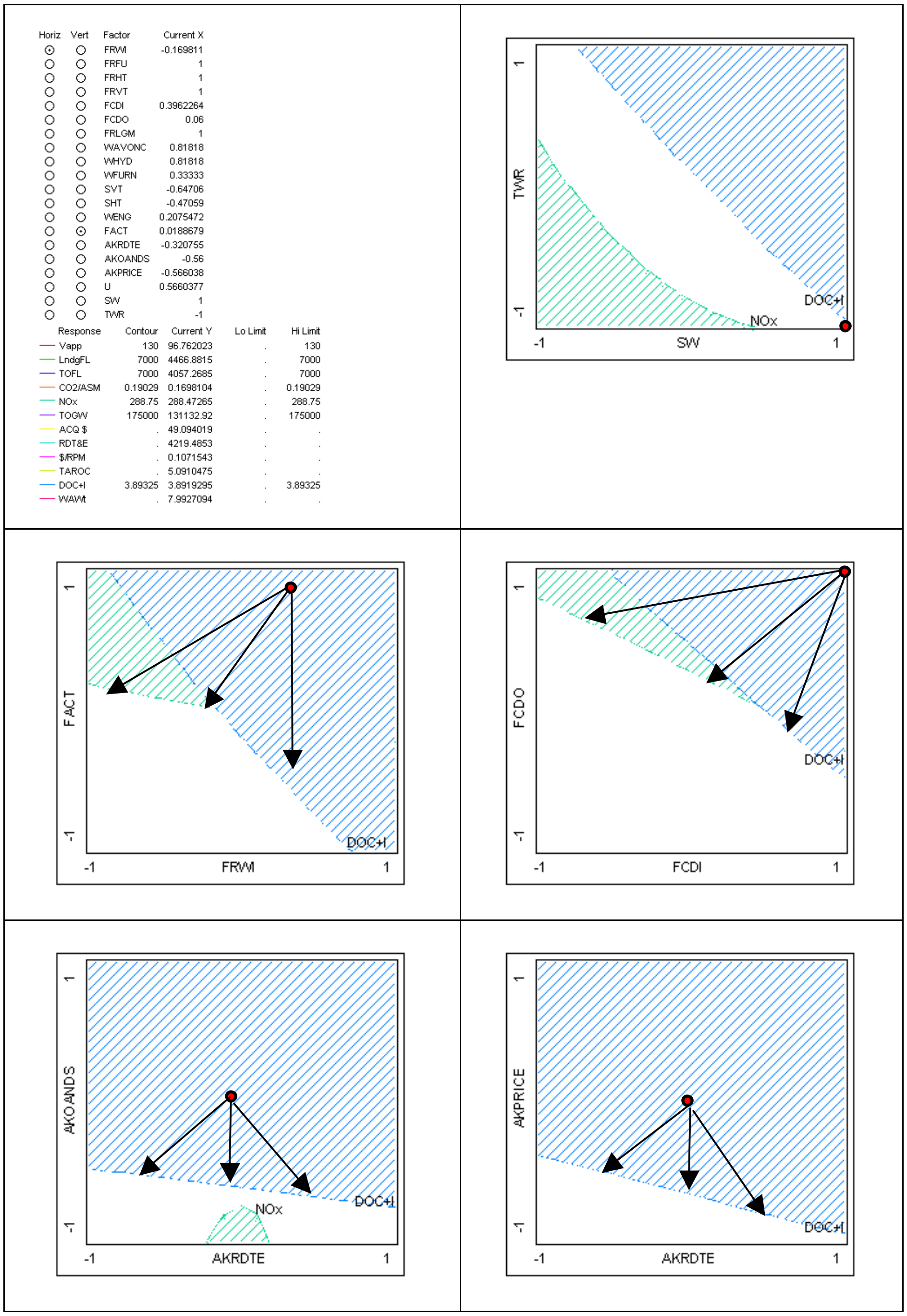


Figure 56: Contour Plots with Modified K-Factors

Based on the knowledge so far regarding the technology impact, the required settings of the impact values to meet the performance and economic metric targets can be derived. The selection of the combination setting is done by including considerations on the easiness and risk factor in achieving the settings set-forth for a particular impact factor. For example, in achieving the target values for the emission levels, few combinations of settings can be derived out, with the two drag coefficients and the fuel consumption factors settings as the main factors. However, to reduce drag is easier than to reduce the fuel consumption, thus the selected combination of the settings should be based on this knowledge accordingly.

The procedure can be repeated again considering only the performance metrics, and again only considering the economic metrics. Figure 57 and 58 shows the results of this investigation.

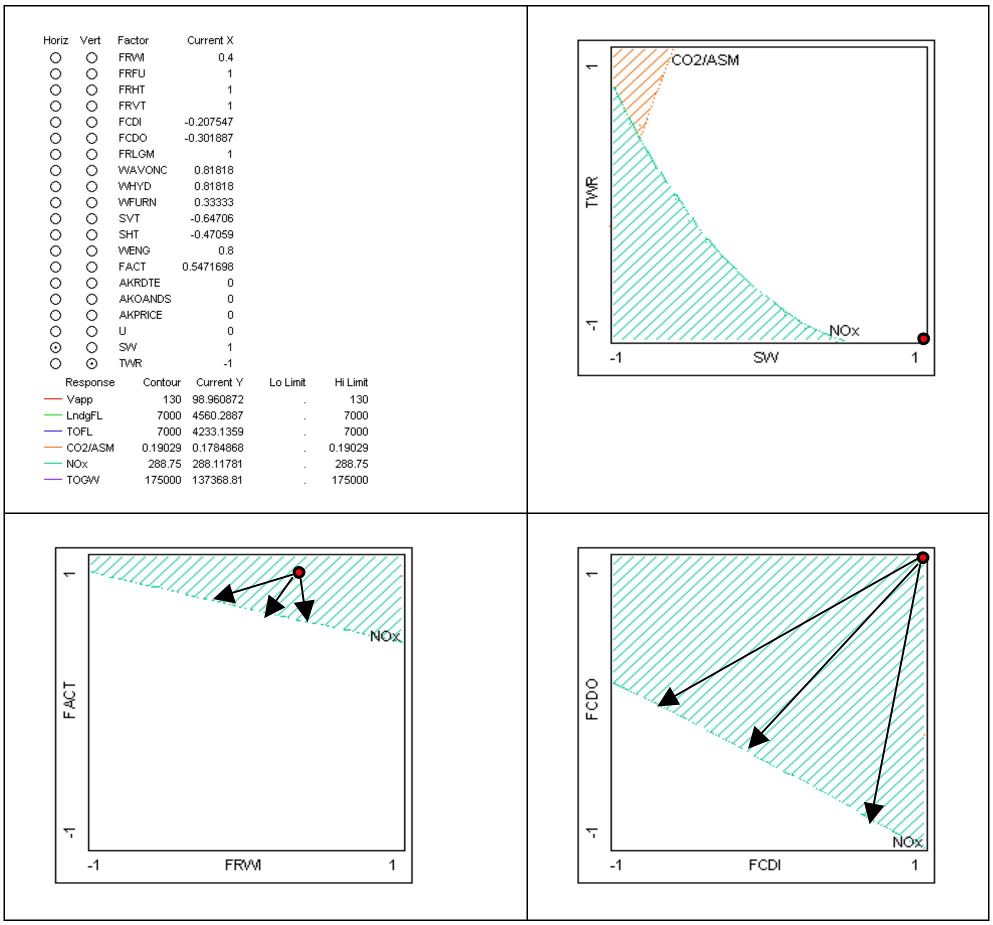


Figure 57: Contour Plots of K-factors for the Performance Metrics

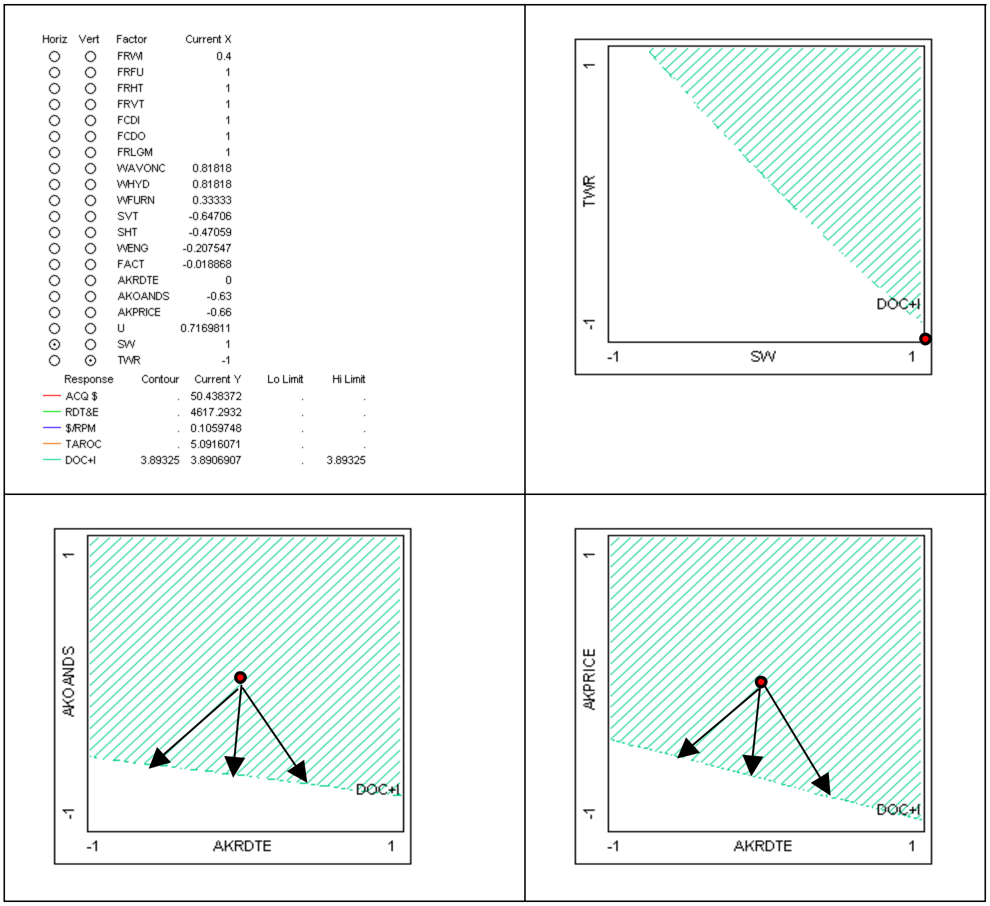


Figure 58: Contour Plots Of K-factors for the Economic Metrics

Table XXXVIII, summarizes the responses for each of the analyses performed for calculating the required impact factors. As shown in the figures and the table below, all the response constraints can be met with the corresponding k-factors listed in Tables XXXIX, XL, and XLI.

Table XXXVIII: Metric Values Based on Contour Plots

Metric	Baseline	Constraint	Performance Metrics	Economic Metrics	All Metrics	Units
Vapp	99.97	130	98.961	N/A	96.76	knots
LndgFL	4604	7000	4560	N/A	4467	ft
TOFL	4476	7000	4233	N/A	4057	ft
CO2/ASM	0.21843	0.19029	0.17849	N/A	0.1698	lb/ASM
NOx	386.72	342	288.12	N/A	288.47	lb
TOGW	145,316	175,000	137,368	N/A	131,133	lbf
Acquisition Price	59.4946	-	N/A	50.4384	49.0940	M$
RDT&E Costs	4737.92	-	N/A	4617.29	4219.49	M$
$/RPM	0.13203	-	N/A	0.1060	0.10715	$
TAROC	6.6765	-	N/A	5.0916	5.0910	¢/ASM
DOC+I	5.2181	3.959	N/A	3.8907	3.89193	¢/ASM
WAWt	10.009	-	N/A	N/A	7.993	lf/ft^2

Table XXXIX: K-Factors for a Feasible Space Based on All the Metrics

K-factor	Baseline Value	All Metrics	Change (%)	Units
Wing Weight (skin or structure)	1	0.858	14.2	-
Fuselage Weight (skin or structure)	1	1	0	-
Horizontal Tail Wgt. (skin or structure)	1	1	0	-
Vertical Tail Wgt. (skin or structure)	1	1	0	-
Cdi	1	0.94	6	-
Cdo	1	0.906	9.4	-
Landing Gear Wgt.	1	1	0	-
Avionics Wgt.	1	1	0	-
Hydraulics Wgt.	1	1	0	-
Furnishing and Equip. Wgt.	1	1	0	-
VT Area	117.65	117.65	0	ft^2
HT Area	176.55	176.45	0	ft^2
Engine Wgt.	6466	5509.032	14.8	lb
Fuel Consumption	1	0.907	9.3	-
RDT&E Costs	0	-0.064	6.4	-
O&S Costs	0	-0.112	11.2	-
Production Cost	0	-0.113	11.3	-
Utilization	3900	4341.48	11.2	hrs
Wing Area	1500	1500	0	ft^2
Thrust-to-Weight ratio	0.3098	0.3098	0	-

Table XL: K-Factors for a Feasible Space Based on Performance Metrics

K-factor	Baseline Value	Performance Metrics Only	Change (%)	Units
Wing Weight (skin or structure)	1	1	0	-
Fuselage Weight (skin or structure)	1	1	0	-
Horizontal Tail Wgt. (skin or structure)	1	1	0	-
Vertical Tail Wgt. (skin or structure)	1	1	0	-
Cdi	1	0.879	12.1	-
Cdo	1	0.870	13	-
Landing Gear Wgt.	1	1	0	-
Avionics Wgt.	1	1	0	-
Hydraulics Wgt.	1	1	0	-
Furnishing and Equip. Wgt.	1	1	0	-
VT Area	117.65	117.65	0	ft^2
HT Area	176.55	176.45	0	ft^2
Engine Wgt.	6466	6466	0	lb
Fuel Consumption	1	0.962	3.8	-
RDT&E Costs	0	0	0	-
O&S Costs	0	0	0	-
Production Cost	0	0	0	-
Utilization	3900	3900	0	hrs
Wing Area	1500	1500	0	ft^2
Thrust-to-Weight ratio	0.3098	0.3098	0	-

Table XLI: K-Factors for a Feasible Space Based on Economic Metrics

K-factor	Baseline Value	Economics Metrics Only	Change (%)	Units
Wing Weight (skin or structure)	1	1	0	-
Fuselage Weight (skin or structure)	1	1	0	-
Horizontal Tail Wgt. (skin or structure)	1	1	0	-
Vertical Tail Wgt. (skin or structure)	1	1	0	-
Cdi	1	1	0	-
Cdo	1	1	0	-
Landing Gear Wgt.	1	1	0	-
Avionics Wgt.	1	1	0	-
Hydraulics Wgt.	1	1	0	-
Furnishing and Equip. Wgt.	1	1	0	-
VT Area	117.65	117.65	0	ft^2
HT Area	176.55	176.45	0	ft^2
Engine Wgt.	6466	4837	25.2	lb
Fuel Consumption	1	0.903	9.7	-
RDT&E Costs	0	0	0	-
O&S Costs	0	-0.126	12.6	-
Production Cost	0	-0.132	13.2	-
Utilization	3900	4459	14.3	hrs
Wing Area	1500	1500	0	ft^2
Thrust-to-Weight ratio	0.3098	0.3098	0	-

If only the performance metrics are to be analyzed, Table XL lists that the main factors to be altered are the drag coefficient factors. These two will significantly change the emission metrics to allow for feasible space. From the study, one can conclude that if the drag coefficients can be reduced by about 13%, with a 4% reduction in fuel consumption, then the design becomes feasible.

On the other hand, for a viable space only, it is necessary to reduce the operation cost, the production cost and to increase utilization. The large changes (about 13% each) will provide a viable space along with a large reduction in engine weight (25%) and a fuel consumption reduction of about 10%. The engine and fuel consumption reductions would be achieved by implementing related technologies, while the others are results of the materials, process, and technologies to be implemented.

For the study in which all the responses were considered, smaller reductions were necessary to obtain a feasible and viable space, but more factors needed to be altered. For example, a feasible space required a 14% reduction in wing weight, which can be accomplished using composites or other materials. Smaller changes (about 8%) in drag coefficients were required, due to the interaction of them with other k-factors. Also, the engine weight and fuel consumption need to be reduced a smaller percentage when only economic responses were studied. Finally, the RDT&E costs, O&S costs, and Utilization were required to change a smaller percentage as well due to the advantages of the other reductions.

Deterministic Technology Evaluation

Once it has been proven that the implementation of technologies will allocate a feasible and viable space, the technologies are grouped into categories for yearly implementations. For this report, the technologies were grouped as listed in Table XLII. These technology combinations mainly consist of two main categories of technologies. One is the baseline technology and the other is consisted of technology alternatives available for infusion in a given year. The baseline technologies are the technologies that are already matured (TRL=9) at the given year and also are compatible with every other technology alternatives available. This also corresponds to technologies that have application that is different than any other technology alternatives. The technologies for a given year are made of selected technology alternatives that are matured in that year (TRL=9). These technologies may or may not be compatible with each other.

Table XLII: Technologies Implemented by Year

Year	Baseline Technologies	New Technologies
2006		1, 2, 3, 4, 5
2007-2008		1, 2, 3, 4, 5, 6, 7
2009	1	2, 3, 4, 5, 6, 7, 8, 9, 10, 11
2010	1, 6, 7	2, 3, 4, 5, 8, 9, 10, 11, 12, 13, 14, 15
2011-2012	1, 6, 7	T2-3, T4-5, T11-12, T14-15, 8, 9, 10, 11, 16, 17, 18, 19, 20
2013	1, 6, 7, 10, 11, 20, 27, 28	T2-3, T4-5, 8, 9, 16, 17, 18, 21, 22, 23, 24, 25, 26
2014	1, 6, 7, 10, 11, 20, 26, 27, 28	T2-3, T4-5, 8, 9, 17, 18, 21, 22, 23, 24, 25, 29, 30
2015 -2016	1, 6, 7, 10, 11, 20, 26, 27, 28, 29	25, 30, 31, 32, 33, 34, 35, 36

There are 36 different technology alternatives that have been identified for consideration on improving the design performance in achieving the target goals. However, to run a deterministic evaluation on all or even half of these technology impacts concurrently for a given year would be too time consuming since a full-factorial design of experiments for 36 alternatives will corresponds to almost 6.872×10^{10} different combination cases. Thus, tradeoffs between the technologies (with the exception of the baseline technologies since they are compatible to every other technology and they are corresponding to unique application that is different from the others) must be made for each year.

The technology tradeoffs process can be approached in many ways. As for the selection in the Table XLII, tradeoffs have been made between cost and performance. The process of eliminating the technology options are done to the different alternatives that are providing the same improvements on the same design parts or impact factors. These technology alternatives are compared to each other relative to the cost incurred with the implementation on the design as well as to the resultant performance from the implementation. For example, for the year 2013, one of the technology alternatives that have been discarded is the Russian Aluminum Lithium Fuselage skin. The Russian Aluminum Lithium fuselage skin has a higher cost for implementation as well as less of a performance improvement than the superplastic forming technology. If both the technologies have comparable cost and performance characteristics, then both of them are considered. This is the case for the superplastic forming technology and the composite technology on wing and tail parts for the 2013 year.

In contrast, another approach for tradeoffs are comparing technology alternatives for the same application and considering either the alternative with the best cost or the alternative with the best performance. By doing the former, the design is expected to have improved performance with lowest possible additional costs of technology implementation. On the other hand, the latter approach will correspond to considering only the technology that has superior performance, regardless of the cost incurred by the technology implementation. In this approach, the alternatives selected will most likely be the latest technology improvements that have greater improvements in performance with association of higher costs. The tradeoff processes used in selecting the technology alternatives for this design are a balance between the total cost and the total performance.

For each one of the years listed in Table XLII, a full factorial deterministic analysis was performed. The first step was to get the DoE using JMP. The DoE was then copied to the provided excel workbook. The workbook contains three main spreadsheets and one macro. The first spreadsheet contains the DoE, and the calculated k factors depending on the TIM and the combination of active technologies. The third spreadsheet contains the RSEs previously calculated. The second spreadsheet is used to calculate the responses using the RSEs and the k-factors. The k-factors are calculated using some logic statements that take in consideration incompatible technologies. For the cases at which two or more technologies that are incompatible are on, the latest technology is chosen as active. It is assumed that a latter technology will have more advantages that might not be considered in the time matrix, such as time required to obtained part from contractor might be shorter, among others. The following logic statement is a sample for one of the k-factors for one of the implemented years.

> k-factor=1 + (0) + (0) + (0) + (0) + (0) + (0) + (0) + (0) + (-0.05) + IF($H8151=1,0,0) + IF($I8151=1,0,0) + IF($L8151=1,0,0) + IF($M8151=1,0,0) + IF($N8151=1,0,0) + IF(AND($J8151=-1,$F8151=-1,$D8151=-1,$B8151=1),0,0) + IF(AND($K8151=-1,$G8151=-1,$E8151=-1,$C8151=1),-0.16,0) + IF(AND($J8151=-1,$D8151=1),0,0) + IF(AND($K8151=-1,$E8151=1),-0.2,0) + IF($F8151=1,0,0)+IF($G8151=1,-0.03,0) + IF($J8151=1,0,0) + IF($K8151=1,-0.15,0)

In the logic statement above, the if statements refers to whether the technologies are on (1) or off (-1) and a ‘TRUE’ response results in the first number after the coma and a ‘FALSE’ results in the second number after the coma. The statement also takes in consideration incompatible technologies. For example: IF(AND($J8151=-1,$F8151=-1,$D8151=-1,$B8151=1),0,0) states that if the technologies in cells J, F, and D are off (-1), and the technology in cell B is on (1), the statement will result in ‘TRUE’ and only the contribution of B is added or subtracted from the k factor.

The logic statements for the RDT&E costs are slightly different. Besides the AND statements, they contain ‘OR’ statements to account for only one of the related technologies to be on (1) to add or subtract the contribution of those technologies to the k-factor.

After calculating the responses using the macro for each implementation year, the responses were copied to JMP and prediction profiles were obtained. The prediction profiles include a "Compatability" response easily calculate for each case of the full factorial analysis using similar logic statements as shown above. The prediction profiles are a way of assessing the impact of turning a technology on. The purpose of the compatibility response is to indicate that if when a technology is turned on, and the compatibility drops below one, the results are bogus, meaning that the set technology choices are not compatible, therefore, non existent.

Figure 59 is the prediction profile of the technologies for the year 2007. This picture shows how each of the seven technologies affect the responses. As technology 1 (adaptive performance optimization) is turned on, all the metrics except for acquisition price are reduced. The increase in acquisition price is small, which indicates that this technology is extremely advantageous because even though it increases the initial price of the aircraft, the operation cost over its life ends up saving money for the airline company. The main responses altered by this technology are the emission responses, $/RMP, TAROC, and DOC+I. Technologies 2 though 5 implement composite materials in several sections of the aircraft. These technologies reduce all of the performance metrics because of the reduced weight and smoother surfaces, but all the economic metrics increase because of the complexity of maintaining, manufacturing, and extra research needed for implementation. Technologies one through 4 highly affect the economic metrics, while technology 5 (composite on wing structure) encompasses more surface area are is largely related to the performance metrics, therefore, the performance metrics are highly improved using technology 5. Technology 6 (airframe methods) decreases all the metrics, including performance and economic metrics. A large decrease in gas emissions and RDT&E costs are results of this technology being turned on. Technology 7 (fire suppression) does not seem to affect any metric in a suitable manner. This technology decreases slightly the performance metrics and increases slightly the economic metrics.

Figure 60 is the prediction profile of the technologies over the responses for the years 2015-2016. This combination included 10 technologies that are compatible with all other technologies, therefore they are considered as baseline technologies. Another 8 technologies are analyzed for this year. This combination has 6 technologies that are not fully compatible (3 groups of 2 incompatible technologies). The prediction profiles for technology 25 (composite fuselage shell) show minimal improvement for the performance metrics with a large increase in economic metrics. This most probably indicated that this technology will not be selected for the design. Technology 30 (adaptive wing shaping) shows a very large improvement in the performance metrics, mainly the emissions, with decreasing yield required and operation costs. This indicated that this technology requires a higher RDT&E investment and initial aircraft price, but with life cycle cost reductions. Technologies 31 (bio materials on fuselage) and 34 (BIOSANT on fuselage) have very comparable effects on the metrics. These show reducing performance metrics, reducing O&S costs, yield per RPM, TAROC, and DOC+I with increasing responses to RDT&E and acquisition price. This allows to conclude that either would be beneficial for a higher initial investment of both parts, the manufacturer and the airliner. Technologies 32 (bio materials on tail) and 35 (BIOSASNT on tail) show no improvement in any metric and it highly increases RDT&E and acquisition price, therefore this technology is not beneficial and should not be included as an option. Technologies 33 (bio material on wing) and 36 (BIOSANT on wing) show a large improvement in all the responses with a very small changes in RDT&E costs and acquisition price. Either of these technologies should be highly considered when selecting technologies because of the low price of implementation. The rest of the year combinations can be found in Appendix L.

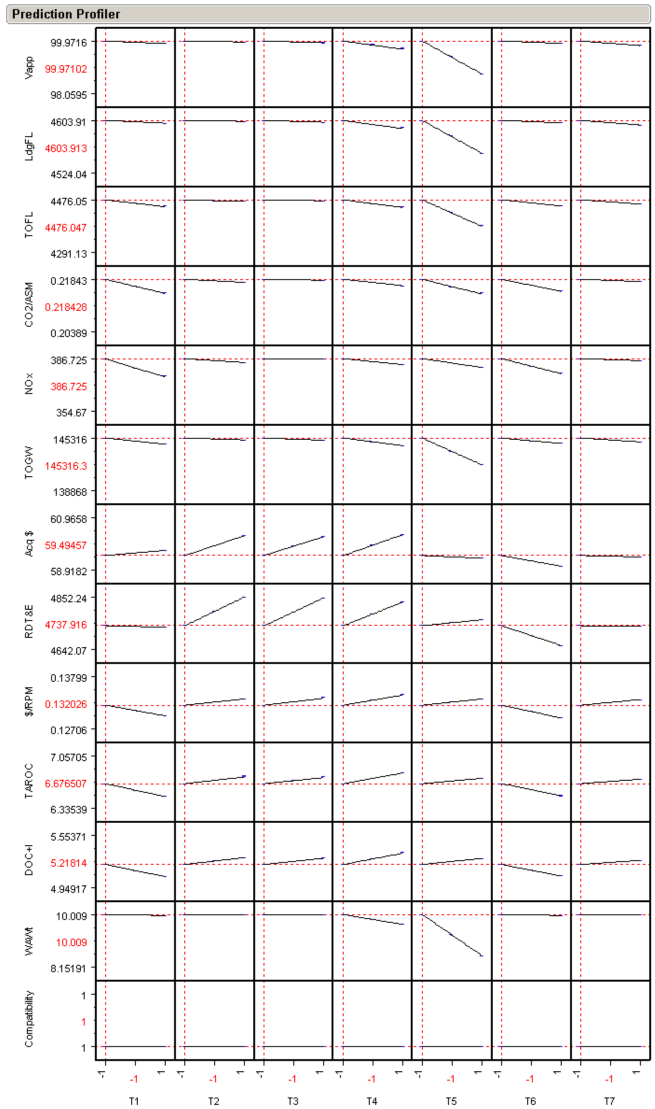


Figure 59: Prediction Profile for the Year 2007

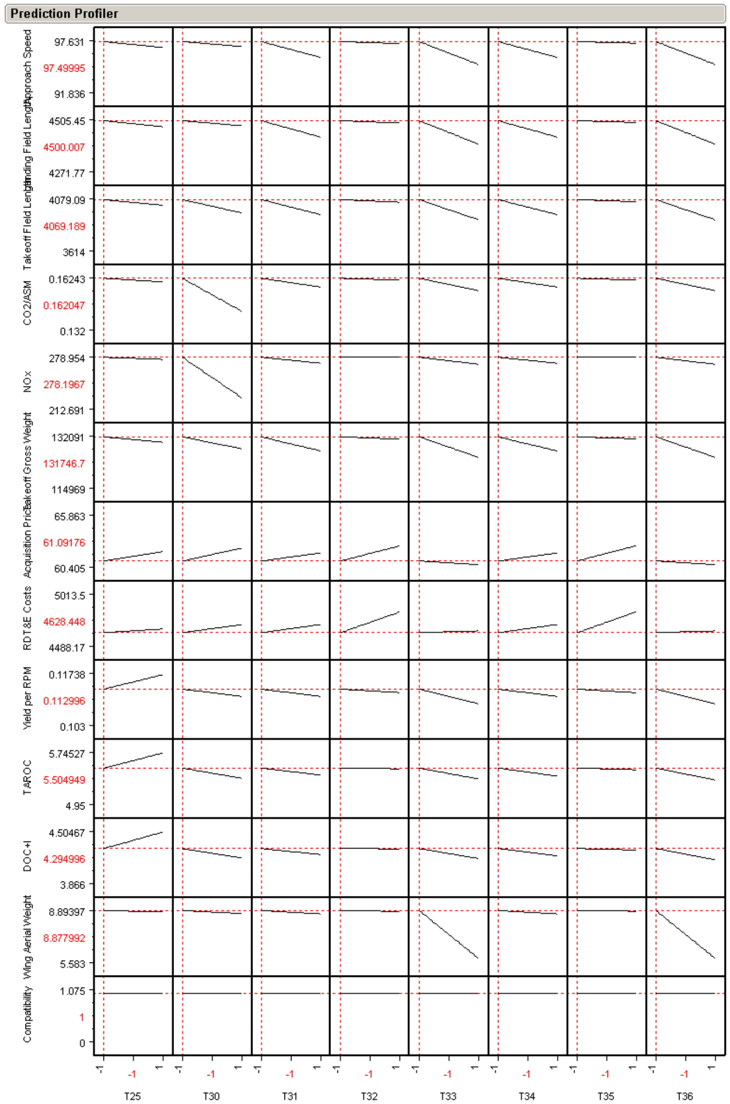


Figure 60: Prediction Profile for the Years 2015-2016

After each of the technologies were examined separately, a full range of technology combinations were explored. In order to determine how multiple technologies effect the vehicle, it was assumed that the effects were additive. By summing all of the k-factors associated with the technologies that are implemented into the vehicle, a new vector of k-factors, representing the combinational effects, is created as illustrated in Figure 61 [16]. In reality, some of the impacts of the different technology infusions on the same application may or may not be independent of each other. If the implementation of technology is in such a way that the effects of one technology is totally isolated than the other, then the impacts may be independent with each other. However, if the implementation of the different technologies allows the effects of one technology to have interaction with that from the other, then the technology impacts are not additive. This condition occurs due to the interaction effects between the different technology performance that may degrade or even enhance the performance of the other. For example, the implementation of both leading edge slat and trailing edge slotted flap on the wing will increase the lift independently by approximately 71% and 107 %, respectively [75]. However, by implementing both devices, the increment in lift will not be simply the addition of 71% and 107%, which is 178% in total. In fact, the total increment may just be around 130% since by implementing the leading edge slat, the flow characteristics and behavior are changed before it comes to the effect of the trailing edge slotted flap. This will reduce the performance effects of the flap compared to that when it encounters the fresh free flow. Therefore, the impact of implementing these two high-lift devices technology on the generated lift is not additive in nature. However, for all the technology combinations presented in this study, an additive assumption captures the interactions and is a valid assumption [76].

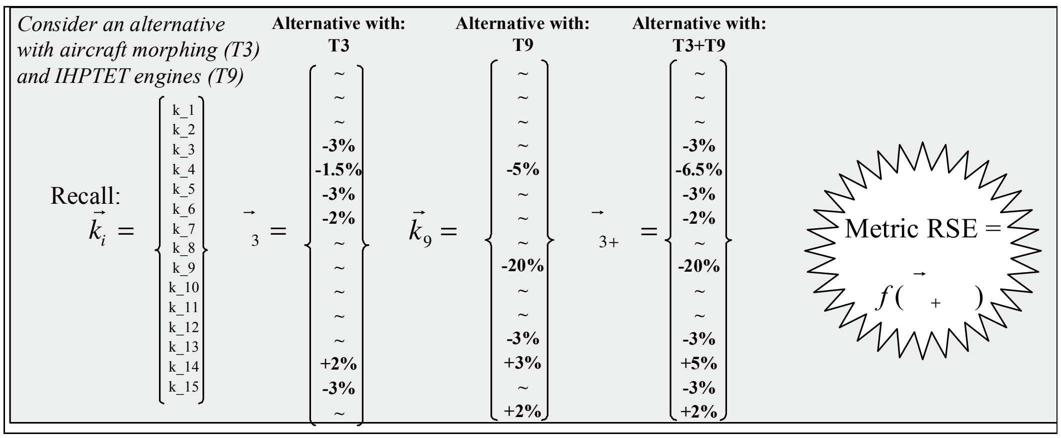


Figure 61: Example Technology Evaluation with "K" Vectors

In order to truly capture the non-additive nature into account, each of the technology combinations would have to be individually studied and appropriate k-factors derived. For this project, the assumption that the effects of multiple technologies are additive is appropriate since the interdependence was considered to be a secondary effect, which would not need to be examined to capture the main technology impacts.

Other Methods for Evaluating Technologies

There are two ways to evaluate the impact of technologies on the design. The first is the deterministic approach, which has been the method for the evaluation of the new technologies. This is a "first cut" attempt at examining the influence of technologies. The impact of the technologies has been evaluated on a fixed vehicle configuration. One of the reasons for this is to identify if by implementing technologies a feasible and viable design space could be achieved simply by incorporating new technologies. Another reason is that the k-factors already include the influence on the geometry [77]. Investigating the technology space and design space concurrently would allow for the best mix of technologies to be implemented on an aircraft where the configuration best suits the technologies. In order do this, a DOE must be created that will capture the effects of every possible configuration with every possible combination of technologies. This would result in a DOE of thousands of cases, a large computational expense. In order to reduce the number of variables, a screening test on the variables can be performed. A DOE that incorporates the most important variables can be used to crate an RSE. The k-factors and economic variables can then be incorporated to each of the cases in the DoE table and a Fast Probability Integration (FPI) can be performed by using normal distributions. A Monte Carlo Simulation can be executed to create CDF probabilities. If the fixed configuration with added technologies does not prove to produce a feasible and viable design space, examining the technology space and design space concurrently may open up the solution space [77].

Another approach in evaluating the impact of new technologies is the probabilistic approach. This method can account for those technologies that are not fully matured, where there is a chance they may not reach the maximum impact [3]. The probabilistic approach will take into consideration this variability. Using a probabilistic approach would be completed in a similar manner as was done in the design space exploration. A Monte Carlo simulation of a distribution shape would need to be defined for each response and approximately 2000 random cases would be run. This would give the statistical information as well as CDF for all of the responses. The computational expense is that for a large number of variables, in order to conduct a full factorial investigation, millions of cases would need to be run. One way to reduce the computation time is to reduce the number of variables. This can be done using a genetic algorithm approach, which "is a search strategy based on a Darwinian evolution of survival of the fittest" [17]. A genetic algorithm uses a fitness function and iterates through crossovers and mutations of an initial random set of concepts. The function will converge to a set of data that will meet an overall measure of value [17]. When selecting the best family of alternatives, a Pugh Evaluation Matrix is used. The concept alternatives, or cases with different technology combinations, go in the first column of the matrix and the important metrics go in the first row. Using the data from the CDFs created, for each concept alternative the corresponding metric at a specific confidence level is placed in the correct cell. This confidence level is related to the risk or uncertainty for a technology and is chosen subjectively [17].

SELECT THE BEST FAMILY OF ALTERNATIVES

The final step of the TIES process is to select which combination of alternatives will best create a feasible and viable system. Three approaches will be used in the analysis of technology mixes including:

- Multi-Attribute Decision Making (MADM) techniques in the form of TOPSIS
- Technology Frontiers: Performance and Economic Effectiveness
- Technology Sensitivities: One-to-one technology comparison

The final combination of alternatives is up to the discretion of the design team based on the output of all four analyses [16].

Multi-Attribute Decision Making: TOPSIS

Multi-Attribute Decision Making (MADM) is a tool to aid in selecting the best alternative. A "compensatory" model allows for trade-offs among attributes to be made. One of these models is the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS). This approach is based on the idea that the best solution is the shortest Euclidean distance from the "ideal" solution and the farthest from the "negative-ideal" solution. This allows for all of the alternatives to be ranked from this numerical analysis [78].

There are six steps for executing a TOPSIS analysis explained in reference [79] and outlined briefly here. The first step is to create a decision matrix that lists the different alternatives in the first column and the criteria are in the first row. Each of the responses to the evaluation criteria are placed in the appropriate cell and then normalized by dividing each criterion by the norm of the total outcome vector, Eqn 11.

$$norm = \frac{r_{ij}}{\sqrt{\sum_{i=1}^{m} r_{ij}^{2}}} \qquad \text{Eqn. (11)}$$

where r_{ij} is the numerical outcome of the i^{th} alternative with respect to the j^{th} criteria of *m* alternatives. The second step is to multiply each of the normalized responses by the weights of for each criterion that is based on the decision makers' importance rating. The next step is to determine the positive-ideal and negative-ideal solutions. The positive-ideal solution, A^*, is a vector containing the maximum value for criteria that are a benefit criteria (criteria that a maximization is desired) or the minimum value for the cost criteria (criteria the a minimization is desired). The negative-ideal solution, A^-, is the opposite; a vector of the minimum value for benefit criteria or the maximum value of the cost criteria. The fourth step in the TOPSIS analysis is to calculate the separation, or the Euclidean distance, between each alternative and the positive-ideal, S_i^*, and negative-ideal, S_i^-, solutions, given by Eqn. 12.

$$S_i^{*/-} = \sqrt{\sum \left(AlternativeValue - A^{*/-}\right)^2} \qquad \text{Eqn. (12)}$$

The next step is to determine the relative closeness of each alternative to the positive-ideal solution, given by Eqn. 13.

$$C_i = \frac{S_i^-}{S_i^* + S_i^-} \qquad \text{Eqn. (13)}$$

The solutions for the closeness will range from zero and one, where C_i=1 for A^* and C_i=0 for A^-. The final step in the TOPSIS analysis is to rank the alternatives in descending order of C_i. The largest value of closeness is the best alternative.

TOPSIS requires the use of deterministic values for creating the decision matrix and for ranking the alternatives so information about the variability of technology mixes, costs, and time may be lost. In order to overcome this shortcoming, the decision maker can analysis the top alternatives for different confidence levels and weighting scenarios. The decision maker should compare the results and look for a combination that consistently ranks within the top ten or so regardless of confidence level [79].

Weighting Scenarios

In order to evaluate the different sets of technologies combinations, ten different weighting scenarios were developed. The basis on the development on these different scenarios is the weighted consideration of the design performance and economics. Emphasis has been made to the metrics that are found to govern the feasibility space of the design, namely the CO2/ASM, NOx, and also the DOC+I. The ten weighting scenarios are tabulated in Table XLIII.

Table XLIII: Weighting Scenarios

Metrics	**Weighting Scenario Number**									
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Vapp	0.10	0.10	0.05	0.05	0.05	0.00	0.00	0.00	0.00	0.00
LndgFL	0.10	0.05	0.05	0.05	0.00	0.00	0.00	0.00	0.00	0.00
TOFL	0.10	0.05	0.05	0.05	0.00	0.00	0.00	0.00	0.00	0.00
CO2/ASM	0.25	0.25	0.20	0.15	0.15	0.15	0.10	0.05	0.05	0.00
NOx	0.25	0.25	0.20	0.15	0.15	0.15	0.10	0.05	0.00	0.00
TOGW	0.15	0.15	0.10	0.05	0.05	0.00	0.00	0.00	0.00	0.00
Acq$	0.00	0.00	0.05	0.05	0.10	0.10	0.15	0.15	0.20	0.20
RDT&E	0.00	0.00	0.00	0.05	0.10	0.10	0.15	0.15	0.15	0.15
$/RPM	0.00	0.00	0.10	0.10	0.10	0.15	0.15	0.20	0.20	0.20
TAROC	0.00	0.00	0.00	0.10	0.10	0.15	0.15	0.15	0.15	0.15
DOC+I	0.00	0.10	0.15	0.15	0.20	0.20	0.20	0.25	0.25	0.30
WAWt	0.05	0.05	0.05	0.05	0.00	0.00	0.00	0.00	0.00	0.00
SUM	***1.00***	***1.00***	***1.00***	***1.00***	***1.00***	***1.00***	***1.00***	***1.00***	***1.00***	***1.00***

As can be seen from the Table XLIII, the weighting scenarios are defined to the extreme of either performance considerations or the economics considerations, where scenarios 1 and 10 are the extreme conditions, respectively. As the scenario goes from 1 to 10, the main consideration is shifting from the extreme of performance-based to the economics- based. The scenarios 3 to 8 can be taken as the transition phase between the extremes of the performance and economics considerations. It is important to have this variation to see which of the technology combinations will top both in the event of performance and economics considerations concurrently.

To further visualize the different scenarios, each of the metrics is depicted on Figure 62, where the plots are depicting the respective share of each metric for the different scenarios. As can be seen, three major considerations for almost all scenarios are the three metrics that govern the feasibility space of the design, namely the emissions level of NOx and C02/ASM, and also the direct operating cost plus interest (DOC+I).

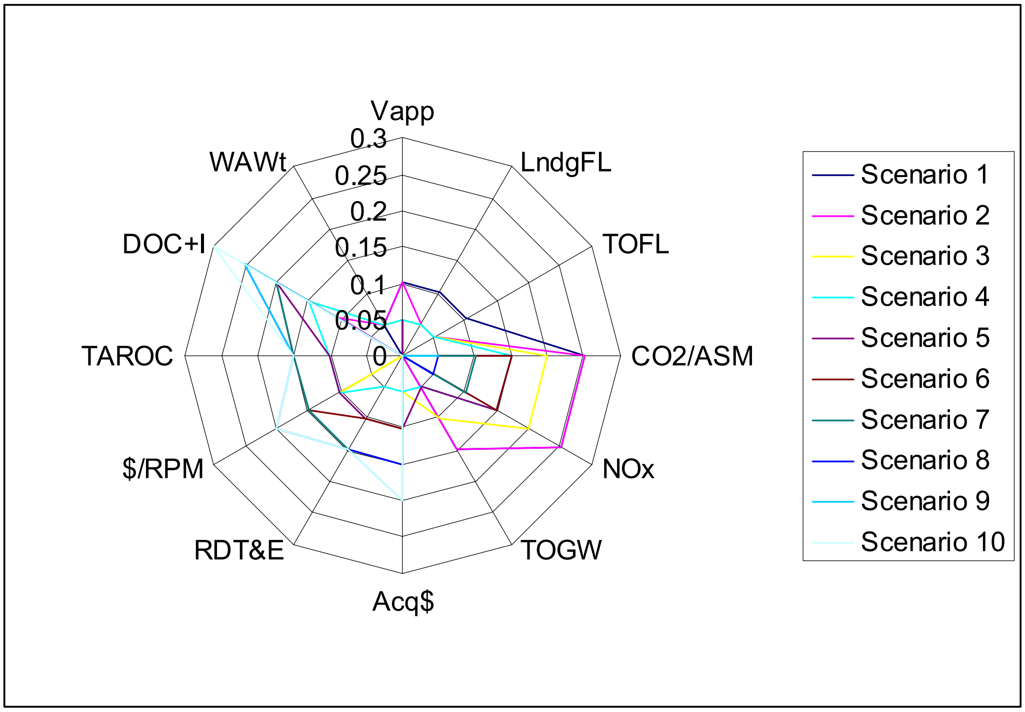


Figure 62: Metrics Considerations for the Different Weighting Scenarios

The results of the TOPSIS evaluation for the different weighting scenarios for the year 2007 are tabulated in Table XLIV as follows.

Table XLIV: Top Rankings Technology Mixes for Different Weighting Scenarios for Year 2007

	Weighting Scenarios									
Ranking	1	2	3	4	5	6	7	8	9	10
1	128	111	103	71	71	71	67	67	67	67
2	112	80	71	103	72	67	71	68	68	68
3	127	79	79	72	67	68	68	71	71	71
4	111	112	72	87	103	72	99	83	83	83
5	96	95	87	79	68	103	83	99	99	99
6	80	127	104	104	87	87	72	87	87	87
7	95	96	119	88	99	99	87	72	72	72
8	79	104	88	119	83	83	103	103	103	103
9	120	120	111	80	75	75	75	75	75	84
10	104	128	80	111	79	100	84	84	84	75

From the table above, a few technology mixes can be seen to appear in most of the different weighting scenarios. However, the results for the performance-based scenarios are not as consistent as that for the other scenarios, which are accounted from scenarios 3 to 10. The latter group of weighting scenarios consists of those defined to consider the economics considerations and also the transition scenarios between the extremes of either performance or economics considerations. This condition can be indirectly interpreted to show that the implementation the technology mixes for sole purpose of performance consideration will also has significant disadvantage of increasing the costs and economics of the design. These can be seen by the disappearances of the topping technology mixes for scenarios 1 and 2 as the metrics weighting starts to include economic parameters into consideration.

On the other hand, the top technology mixes for economic-based scenarios are quite consistent with those appear when performance parameters are being taken into consideration. This indicates that the technology mixes are good for both scenarios categories and further shows that whenever both the performance and economic parameters are being considered concurrently, the economic factors are more dominant in driving the technology mix rather than the performance.

For the summary of the results for the year 2007, the top ten technology mixes that have the highest frequency of appearances in the high rankings of the different scenarios are tabulated in Table XLV and their representative closeness ratings to the ideal solutions for the different scenarios are depicted in Figure 63.

Table XLV: Top Ten Rankings of the Technology Mixes for Year 2007

Rankings	Technology Mix	Technologies
1	71	T1+T5+T6
2	103	T1+T2+T5+T6
3	72	T1+T5+T6+T7
4	87	T1+T3+T5+T6
5	67	T1+T6
6	79	T1+T4+T5+T6
7	68	T1+T6+T7
8	104	T1+T2+T5+T6+T7
9	88	T1+T3+T5+T6+T7
10	119	T1+T2+T3+T5+T6

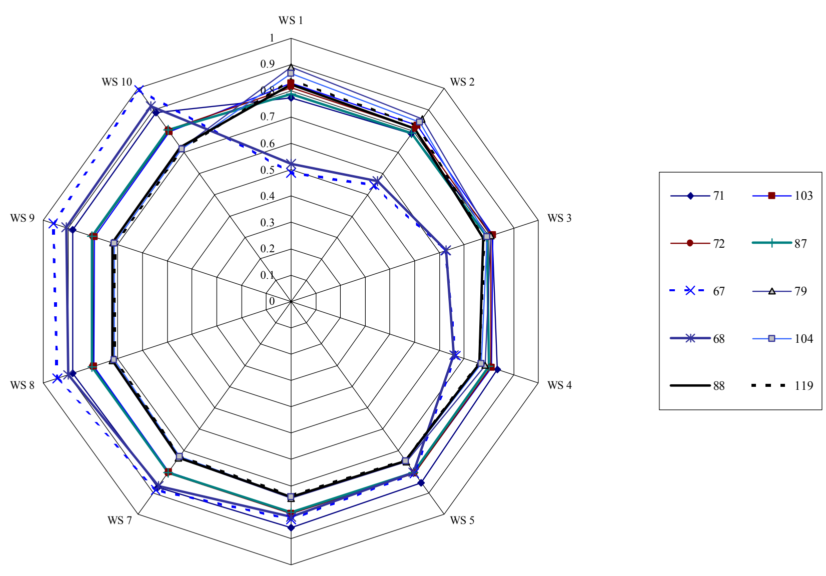


Figure 63: Top Ten Rankings Technology Mixes Closeness Ratings to Ideal Solution for the Different Weighting Scenarios for the Year 2007

The figure above shows that the top ten technology mixes are well distributed over the different weighting scenarios. Each of the different technology mixes has strengths and weaknesses that can be derived from their closeness ratings for the different scenarios. For example, technology mix 67 has very good results in the scenarios defined for economics parameters (i.e. WS 8, 9, 10) but has a very bad results for the performance-based scenarios (i.e. WS 1, 2, 3).

The results of the TOPSIS evaluation for the different weighting scenarios for the year 2016 are tabulated in Table XLVI. The table indicates that a few technology mixes can be seen to appear in most of the different weighting scenarios. Similar to the results for the year 2007, the results for the performance-based scenarios for the year 2016 are not as consistent as that for the other scenarios, which are accounted from scenarios 3 to 10. The latter group of weighting scenarios consists of those defined to consider the economics considerations and also the transition scenarios between the extremes of either performance or economics considerations. This condition can be indirectly interpreted to show that the implementation the technology mixes for sole purpose of performance consideration will also has significant disadvantage of increasing the costs and economics of the design. These can be seen by the disappearances of the topping technology mixes for scenarios 1 and 2 as the metrics weighting starts to include economic parameters into consideration.

Table XLVI: Top Rankings Technology Mixes for Year 2016

	Weighting Scenarios									
Ranking	1	2	3	4	5	6	7	8	9	10
1	205	207	72	72	72	72	72	72	72	72
2	226	228	86	121	121	121	121	121	121	121
3	207	214	79	86	70	70	70	70	70	70
4	228	200	100	79	86	86	86	86	86	86
5	214	205	121	100	79	79	105	79	79	79
6	235	226	93	70	100	100	79	100	100	100
7	221	235	114	93	105	93	100	93	93	93
8	242	221	200	114	93	114	93	114	114	114
9	198	242	107	107	114	107	114	105	107	107
10	233	198	70	105	107	105	107	107	105	105

On the other hand, the top technology mixes for economic-based scenarios are very consistent with technology mixes 72, 121, 70 and 86 appear to top the rankings when performance parameters are being taken into consideration. This indicates that the technology mixes are good for both scenarios categories and further shows that whenever both the performance and economic parameters are being considered concurrently, the economic factors are more dominant in driving the technology mix rather than the performance.

For the summary of the results for the year 2016, the top ten technology mixes that have the highest frequency of appearances in the high rankings of the different scenarios are tabulated in Table XLVII and their representative closeness ratings to the ideal solutions for the different scenarios are depicted in Figure 64.

Table XLVII: Top Ten Rankings of the Technology Mixes for Year 2016

Rankings	Technology Mix	Technologies
1	72	T30+T34+T35+T36
2	121	T30+T31+T32+T33
3	70	T30+T34+T36
4	86	T30+T32+T34+T36
5	79	T30+T33+T34+T35
6	100	T30+T31+T35+T36
7	93	T30+T32+T33+T34
8	114	T30+T31+T32+T36
9	107	T30+T31+T33+T35
10	105	T30+T31+T33

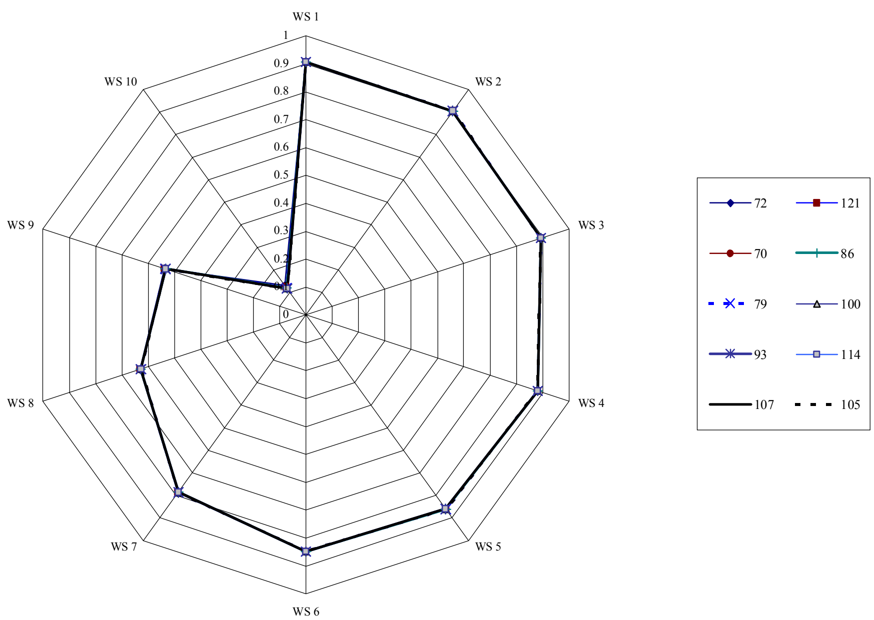


Figure 64: Top Ten Rankings Technology Mixes Closeness Ratings to Ideal Solution for the Different Weighting Scenarios for the Year 2016

From the figure above, it can be seen that all the top ten technology mixes have the same behavioral pattern over the different weighting scenarios. All of them seem to fare very good in the performance-based scenarios but their good results start to degrade when the economics parameters are being introduced into consideration. Their worst results are recorded for WS10, which is to the extreme of the economics parameters. However, they fare good results when both performance and economics parameters are being considered concurrently as depicted for WS 3, 4, 5 and 6.

The top ten ranking technology mixes for the remaining years are located in Appendix M – Annual TOPSIS Scenarios.

Technology Frontiers

Another means for evaluating the best family of alternatives is through the use of Technology Frontiers. "Technology Frontiers are defined as the limiting threshold of an 'effectiveness' parameter" [31]. This method employs user-defined functions based on the baseline metric values and the metric values for each alternative. The maximization of the functions is the goal of the approach. For the study of the 150 passenger aircraft, two functions were defined as shown in Equation 14 and Equation 15.

$$PE_{Alti} = \alpha \frac{CO2/ASM_{BL}}{CO2/ASM_{Alti}} + \beta \frac{NOx_{BL}}{Nox_{Alti}} \qquad \text{Eqn. (14)}$$

$$EE_{Alti} = \alpha \frac{DOC+I_{BL}}{DOC+I_{Alti}} \qquad \text{Eqn. (15)}$$

where: PE is performance effectiveness
EE is economic effectiveness
i is the alternative number
Coefficients are the importance factor given to each metric

For this study, the baseline values change due to additions of technologies each year, resulting in new baselines.

Table XLVIII lists all the weights given to the metrics for calculating the PE and EE.

Table XLVIII: Weights Established to Metrics

Performance		Economics	
Metric	Weight	Metric	Weight
CO2/ASM	50%	DOC+I	100%
NOx	50%	Total	100%
Total	100%		

In order to observe how the Performance Effectiveness and the Economic Effectiveness are related to the system, the thresholds for both of these were calculated using the 2007 constraints and the following two equations:

$$PE_{threshold} = \alpha \frac{CO2/ASM_{BL}}{0.1845 lb/ASM} + \beta \frac{NOx_{BL}}{342 lb} \qquad \text{Eqn. (16)}$$

$$EE_{Alti} = \alpha \frac{DOC+I_{BL}}{3.959 c/ASM} \qquad \text{Eqn. (17)}$$

Where:
Baseline is the value of that specific metric for the specific year
Constraint is the constraints originally established for each metric

Only the constraints for the year 2007 were used as objectives because as previously mentioned the constraints for the year 2022 cannot be met with the studied technologies.

Figure 65 is the PE versus EE plot for the year 2007. The 'ideal' solution corresponds to the maximum PE and the maximum EE. The alternatives closest to the 'ideal' alternative can be considered the best compromises. For this case, year 2007 with the 7 technologies possible added to the system, the system is not feasible or viable. The conclusion is that more technologies need to be added. Table XLIX, below, list the best compromises of technology combinations, even tough none of these make the system feasible.

Table XLIX: Best Compromises of Technologies for 2007

Case #	Technology Mix
71	T1+T5+T6
72	T1+T5+T6+T7
87	T1+T3+T5+T6
103	T1+T2+T5+T6

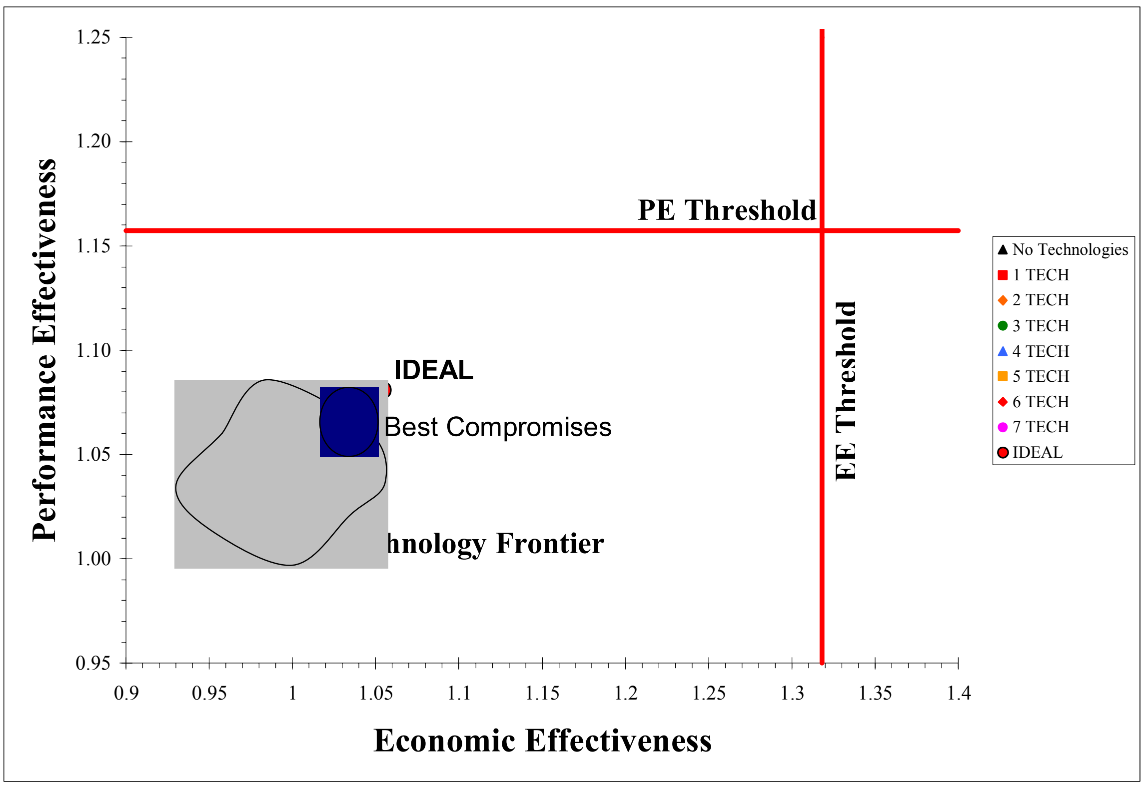


Figure 65: Tech Front 2007

Figure 66 is the PE versus EE plot for the years 2015-2016. The baseline system already contains technologies 1, 6, 7, 10, 11, 20, 26, 27, 28, and 29. These baseline technologies allow for reduced thresholds. As the plot shows, by the year 2015-2016 every compatible combination of technologies result in a feasible solution, and 6 of them contain EE that surpass the economic threshold. Like in the previous figure, the 'ideal' case represents a fictitious combination of maximum PE and EE. The cases closest to this 'ideal' represent the combinations of best compromises. Table L lists the best compromises of technologies.

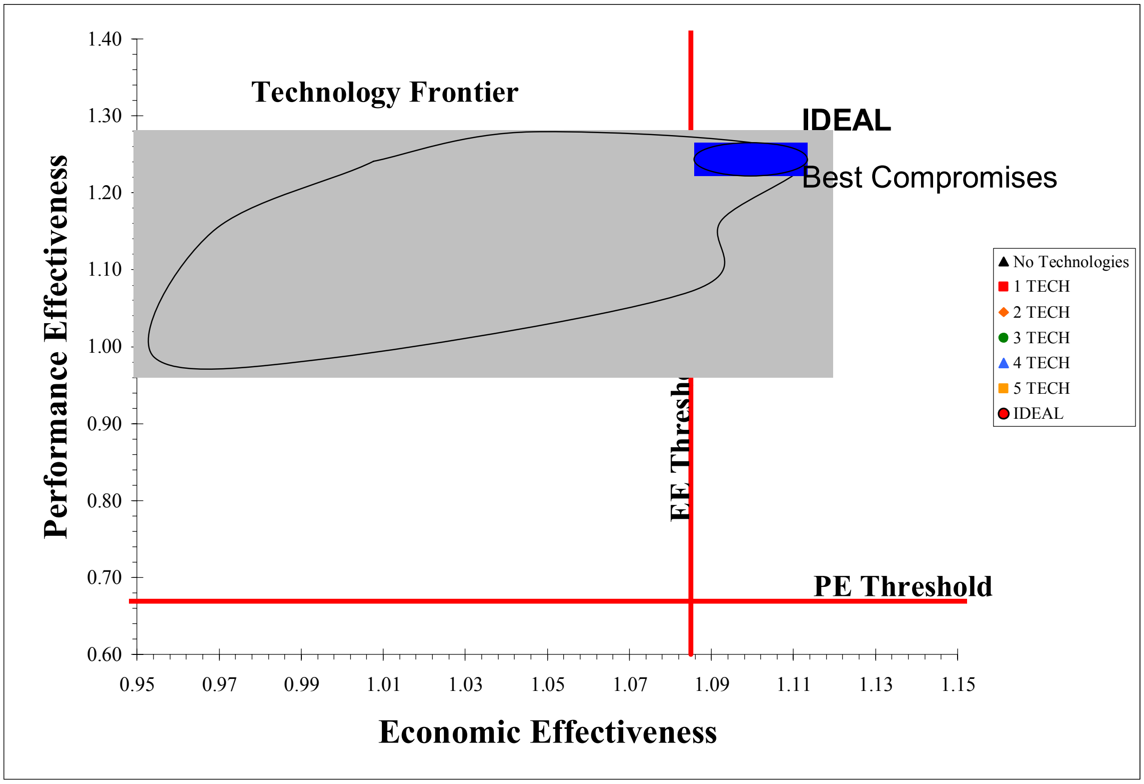


Figure 66: Tech Front 2015-2016

Table L: Best Compromises of Technology Mixes for 2015-2016

Rankings	Technology Mix	Technologies
1	72	T30+T34+T35+T36
2	121	T30+T31+T32+T33
3	70	T30+T34+T36
4	86	T30+T32+T34+T36
5	79	T30+T33+T34+T35

Appendix N contains the Technology Frontiers plots for the years 2011-2012 and 2014. As expected, with the addition of technologies every year, more alternatives become feasible and viable. The plot for the year 2011 shows that there are no combinations that make the system viable. On the other hand, the PE versus EE plot shown in the appendix for the year 2014 shows that several combinations overcome the constraints. Two sets of best compromises are identified in the picture. The one on the top of the graph represent the best performance compromises. The ones below represent the best economic compromises. Table LI, below, lists the best two of each set.

Table LI: Best Compromises for 2014

	Case #	Technology Mix
Performance	492	T17+T18+T21+T22+T24+T29+T30
	508	T17+T18+T21+T22+T23+T24+T29
Economic	443	T17+T18+T22+T23+T24+T29
	505	T17+T18+T21+T22+T2.+T24

Technology Sensitivities

Another approach in selecting combinations of technologies is to look at the individual technology impacts on each of the metrics. This allows for the designer to see how the technologies influence the responses and decide which technologies should be researched and developed, since a single company does not have the resources to invest in a large number of technologies [79].

Since the emissions and DOC+I metrics were not met, the technology sensitivities will be discussed in the body of this report. The remaining graphs are provided in Appendix O – Technology Sensitivities. As can be seen in Figure 67, the majority of the technologies will actually increase CO_2 emissions. However, by implementing T20 and T30, a reduction in CO_2 emissions of 9% and 17%, respectively, can be achieved.

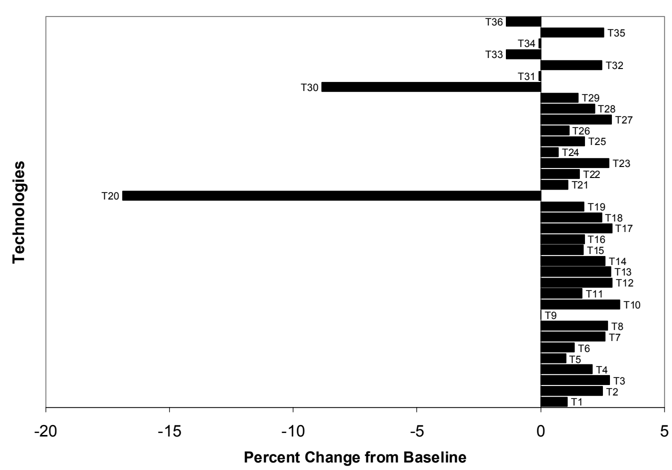


Figure 67: Technology Sensitivity for CO_2

Figure 68 illustrates the effects of the technologies on NOx emissions. The graph shows that a few technologies will slightly increase NOx, and again T20 and T30 will greatly decrease NOx by over 15% each.

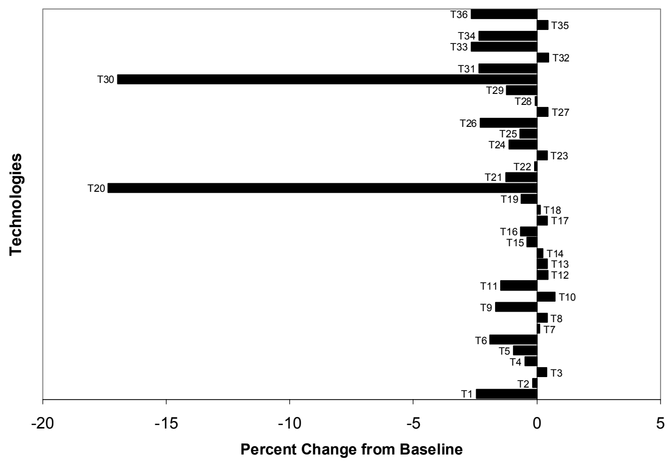


Figure 68: Technology Sensitivity for NOx

The technology sensitivities for DOC+I is shown in Figure 69. Several technologies will increase the DOC+I by as much as 5%. Conversely, a large number of technologies will improve the DOC+I. T20 can reduce the DOC+I by 5.5%.

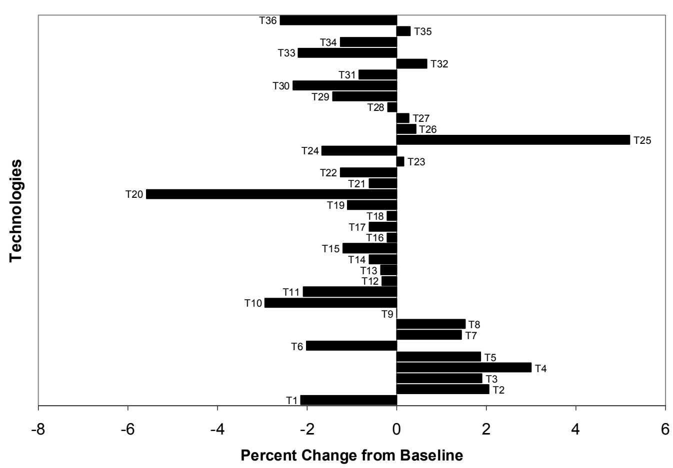


Figure 69: Technology Sensitivity for DOC+I

This analysis has been a deterministic approach, assuming no uncertainty. However, if a probabilistic analysis had been done, confidence intervals would have to be created to capture the uncertainty that the technologies would not perform as expected. The percent reduction will decrease for a low percent confidence.

Another way of looking at the technology sensitivities is to graph a single technology to see how it influences the metrics. Two technologies that largely affect the emissions constraints are T20 and T30. Figure 70 shows that by implementing T20, all of the metrics are decreased; mainly CO^2 and NOx are decreased by approximately 17%. Similarly, Figure 71 shows that T30 benefits a majority of the metrics and especially our constrained emissions metrics.

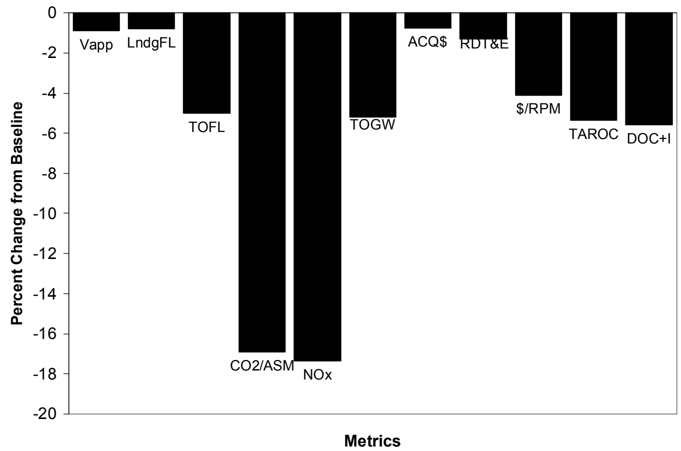


Figure 70: Effect of Technology 20

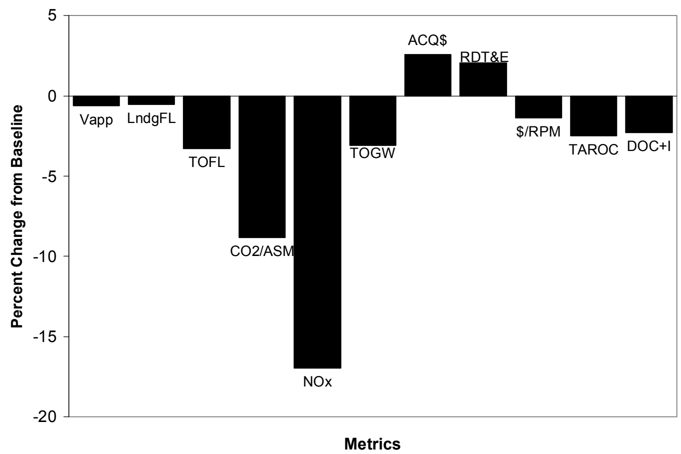


Figure 71: Effect of Technology 30

The rest of the graphs are provided in Appendix P – Effects of Technologies on the Metrics. The graphs show degradations (positive percent change from baseline) and benefits (negative percent change from baseline) of all the metrics.

Summary of Results and Best Alternative Selection

The results from TOPSIS and Technology Frontiers along with the observations made from Technology Sensitivities were analyzed in order to obtain the best compromise for which the design space will be re-investigated. For the decision it was assumed that the most important factor was to meet all the constraints with the minimum amount of technologies. From Technology Frontiers, only combinations from the year 2014 and 2015 were observed as both feasible and viable, therefore it narrowed down the combination to those previously mentioned in the Technology Frontiers section for those years. All of those 9 (4 from 2014 and 5 from 2016) were feasible and viable at different levels. The main difference is that the combinations from 2014 require more technologies than the combinations from 2016, therefore only the last 5 were considered. Table LII and LIII lists the metrics for which strict constraints were applied for the top 5 technology combinations. The last two rows of this table lists the constraint values. From this table, one can conclude that the first top choice (T30+T34+ T35+T36) is the best combination because it meets the emissions constraints at a level similar to the other four combinations but it has the lowest DOC+I cost, with at least twice as much difference from the constraint than the other ones. The reinvestigation of the best combination was done based on this assumption. Unfortunately, this combination requires a total of 14 technologies to be applied to the 1997 baseline aircraft. This would require a tremendous investment for the manufacturer. A solution for this problem is to have the manufacturer invest in those technologies with high TRL numbers, and request the government to sponsor research on the technologies with low TRLs. This would allow the manufacturer to invest less money and still be able to employ all of the technologies into the aircraft.

Table LII: Metric Comparison for top 5 Alternatives

Metric	T30+T34+ T35+T36	T30+T31+ T32+T33	T30+T34+ T36	T30+T32+ T34+T36	T30+T33+ T34+T35	Constraint (2007)	Constraint (2022)
CO2/ASM	0.1329	0.1329	0.1335	0.1328	0.1329	0.1845	0.123025
NOx	216.2	216.7	215.0	216.0	215.7	342	228
DOC+I	3.866	3.908	3.913	3.918	3.919	3.959	2.6395

Table LIII: Percentage below the Constraint

Metric	T30+T34+ T35+T36	T30+T31+ T32+T33	T30+T34+ T36	T30+T32+ T34+T36	T30+T33+ T34+T35
CO2/ASM	-27.97%	-27.97%	-27.64%	-28.02%	-27.97%
NOx	-36.78%	-36.64%	-37.13%	-36.84%	-36.93%
DOC+I	-2.35%	-1.29%	-1.16%	-1.04%	-1.01%

CLOSING THE LOOP

This step reinvestigates the design space with all the selected technologies to determine the best airplane configuration. This process was similar to those mentioned in Steps 4-5. The k-factors were changed in the baseline file and a DoE of the design variable was created and ran through FLOPS to get the responses. Theses were put into the program JMP and RSEs were created. Again a Monte Carlo simulation was performed to determine the system feasibility and viability.

As concluded from the previous step, the best compromise of technology mix includes T30, T34, T35, and T36. The baseline for the year 2016 already includes T1, T6, T7, T10, T11, T20, T26, T27, T28, and T29. There are a total of 14 technologies that needed to be added to the original baseline to produce a feasible and viable design. These 14 technologies are listed in Table LIV, with the italicized technologies representing the ones selected from the possibilities for 2016.

Table LIV: Technology Vector for Selected Family of Technologies

ID #	Technology Description	Current TRL	TRL=9 Date
T1	Adaptive Performance Optimization (APO)	9	2000
T6	Airframe Methods	4	2007
T7	Fire Suppression	3	2007
T10	Propulsion System Health Management	2	2009
T11	Smart Nacelle – Propulsion-Airframe Integration (PAI)	3	2009
T20	Adaptive Engine Control System (ADECS)	4	2011
T21	Revolutionary Metallic Materials Systems on Fuselage Structure	2	2013
T26	Living Aircraft	2	2013
T27	Active Load Alleviation on Tail	4	2013
T28	Active Load Alleviation on Wing	4	2013
T29	Antenna Systems	2	2014
T30	*Adaptive Wing Shaping*	*3*	*2014*
T34	*BIOSANT on Fuselage Structure*	*1*	*2015*
T35	*BIOSANT on Tail Structure*	*1*	*2015*
T36	*BIOSANT on Wing Structure*	*1*	*2015*

Table LV lists the technology vector values for the technology combination selected as the best and for baseline configurations. The first column of numbers represents the basic design with no technologies added. The second column corresponds to the technology vector values for the 2016 baseline configuration. Finally, the last column lists the technology vector values for the selected combination of technologies.

Table LV: Technology Vector Values for Baselines and Selected Technology Mix

Tech. Impact Vector	Variable	Baseline Value / Original Optimum	Baseline Year 2016	Y2016 + T30 + T34 + T35 + T36
Wing Weight	FRWI	1	0.95	0.65
Fuselage	FRFU	1	1	0.82
Horizontal Tail Wgt	FRHT	1	0.95	0.65
Vertical Tail Wgt	FRVT	1	0.95	0.65
Cdi	FCDI	1	0.92	0.829
Cdo	FCDO	1	0.96	0.869
Landing Gear Wgt.	FRLGM	1	1	1
Avionics Wgt.	WAVONC	1	0.59	0.6
Hydraulics Wgt.	WHYD	1	0.5	0.5
Furnishing+Equip. W..	WFURN	1	0.98	0.98
VT Area	SVT	118	118	100
HT Area	SHT	176	176	150
Engine Wgt.	WENG	6466	6790	6790
Fuel Consumption	FACT	1	0.83	0.83
RDT&E Costs	AKRDTE	0	0.027	0.107
O&S Costs	AKOANDS	0	-0.13	-0.175
Production Cost	AKPRICE	0	0.072	0.172
Utilization	U	3900	4231.5	4504.5
Wing Area	SW	1500	1500	1500
Thrust-to-Weight ratio	TWR	0.3098	0.3098	0.3098

Compared to the baseline configuration, there was no need to reduce the landing gear weight, and the furnishing weight was slightly reduced. All other k-values were modified according to the active technologies in order to minimize and met the constraints established for the year 2007.

Table LVI, lists the metrics of the new alternative with the applied technologies. The last column shows the comparison to the baseline metrics established at the beginning of the project, repeated here for reference. The application of technologies allowed the reduction of most metrics, except acquisition price. Fortunately for the airliners, the increase in acquisition price is balanced by the decrease in operating costs (approximately 25 % percent below the baseline values). The reduction of emissions, approximately 50 % from the original baseline, are very close to meeting the 50 % reduction of both by the year 2022. Also, the application of technologies allows for the reduction of the Yield per RPM to a more rational 10.5 cents, rather than the original 12.4 cents.

Table LVI: Comparison of Baseline Metrics to New Alternative Metrics

Metric	Baseline	New Alternative	Units	% Change
Approach Speed (knots)	106.8	92.6	kts	-13.3
Landing Field Length (ft)	4897	4301	ft	-12.2
Takeoff FIeld Length (ft)	5367	3659	ft	-31.8
CO2/ASM (lb/ASM)	0.24605	0.1329	lb/ASM	-46.0
Nox (lb)	456	216	lb	-52.6
Takeoff Gross Weight (lb)	148,219	116,666	lbf	-21.3
Acquisition Price (M$)	59.259	62.186	M$	4.9
RDT&E Costs (M$)	4721.8	4568	M$	-3.3
Yield per RPM ($)	0.134	0.103	$	-23.1
TAROC (c/ASM)	6.752	4.95	c/ASM	-26.7
DOC+I (c/ASM)	5.279	3.866	c/ASM	-26.8
Wing Aerial Weight (lb/ft^2)	10.48	5.6	lb/ft^2	-46.6

Response Surface Equations

Based on the resultant fixed value the k-factors as mapped to the analysis codes' inputs (modified baseline input files), the corresponding response surface equations for each of the metrics can be generated. Similar to Step 4 and 5, the process of creating these equations will be of similar procedures as before. In a brief description, the creation of the equations start by inputting the new baseline file into the analysis codes by means of the design of experiments table set-up for the design variables. The data results from the analysis codes (FLOPS and ALCCA) are then extracted and input into the statistical software package, JMP, where the data is manipulated to create corresponding response surface equations by means of least squares method.

The corresponding response surface equations for the system level metrics are created in JMP. The coefficients of the response surface equations generated are listed in Appendix Q. The accuracy of the response surface equations can then being investigated through the examination of the corresponding R^2 value, whole model test, residual plot of the RSE, and error distribution of a given metric. The figures in Appendix R – Goodness of Fit for Closing the Loop show the summary fit of each one of the metrics under study, and show that the RSE is a good fit. Table LVII lists the R^2 values, the maximum and minimum errors of the distributions, the standard deviation of the error distribution, and the mean of the error distribution.

Table LVII: Summary of FIT for Responses

Metric	Minimum Error (%)	Maximum Error (%)	Standard Deviation of Error Distribution	Mean of Error Distribution	R^2 Value
Approach Speed	-0.1118	0.1128	0.0374	0.0000136	0.999982
Landing FL	-0.0943	0.0954	0.0315	0.0000091	0.999985
TOFL	-1.5870	1.1120	0.2033	0.0001004	0.999898
CO2/ASM	-1.0670	1.0340	0.4828	0.0022091	0.997454
NOx	-2.6790	2.5880	1.0401	0.0085326	0.995841
TOGW	-0.3491	0.3086	0.1249	0.0001559	0.995110
Acquisition $	-0.2321	0.2381	0.0769	0.0000583	0.998672
RDT&E	-0.1394	0.1099	0.0464	0.0000209	0.999505
$/RPM	-0.1732	0.1894	0.0622	0.0000388	0.995202
TAROC	-0.2064	0.1623	0.0751	0.0000562	0.996729
DOC+I	-0.2278	0.1669	0.0803	0.0000641	0.996819
WAWt	-0.6051	0.6846	0.2225	0.0000005	0.999788

Feasibility and Viability Study of the New Alternative

The infusion of the selected technologies has driven significant improvements in some of the interested metrics. This can be seen from the CDF plots of the corresponding metrics where an increase in the percent feasibility or viability of the design in complying with the constraints or target values for that particular metrics is recorded. However, the infusion of these technologies also has some degradation effects on other metric, following the Pareto Frontier theory.

The plots of the CDF resulting from the infusion of the technologies and that of the original plots without the technologies for each of the interested metrics are plotted concurrently as to see the direct comparison of the technology impacts on the design.

As can be seen from the Figure 72, the infusion of the selected technologies has improved the approach speed performance of the design. Although the original plot without the technology infusion already shows 100% feasibility against the target speed of 130 knots, the infusion of the new technologies enables the design to achieve a much better performance. As a rough comparison, the lowest approach speed that can be achieved without the technology infusion is about 100 knots whereas that same speed is about 40% feasible when the technologies are implemented on the design. Since the plot pattern is the same, it can be said that the technologies improve the approach speed by approximately 7% with respect to the respective percent feasibility.

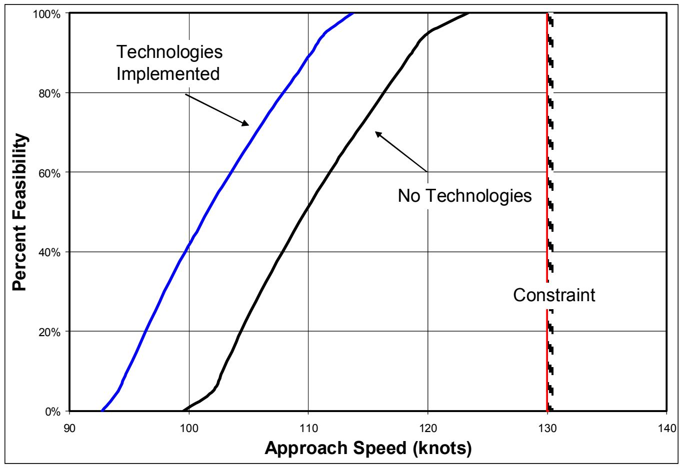


Figure 72: CDF Plot of Approach Speed

As can be seen from the Figure 73, the infusion of the selected technologies has improved the landing field length needed for the design operation. Although the original plot without the technology infusion already shows 100% feasibility against the target field length of 7,000 ft, the infusion of the new technologies enables the design to achieve a much better performance. The plot pattern is still the same and the infusion of the technologies just shifted the original plot to further left of the feasible design space. As a rough comparison, the shortest landing field length for the design without the technologies is about 4,650 ft whereas the same length is 40% feasible with the technologies. Since the plot pattern is the same, it can be said that the technologies improve the required landing field length by approximately 7% with respect to the respective percent feasibility.

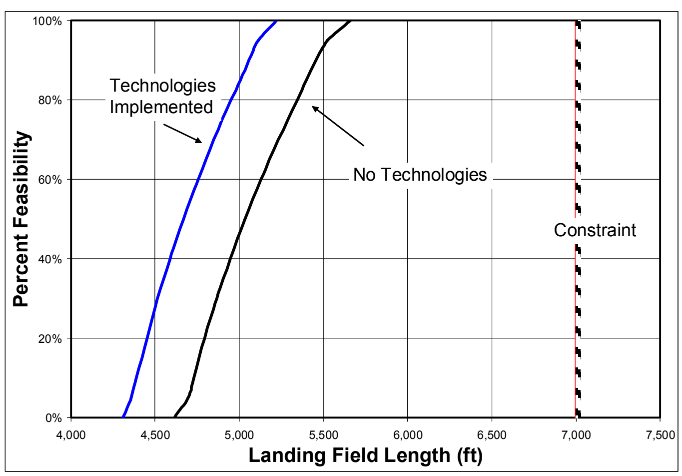


Figure 73: CDF Plot of Landing Field Length

Figure 74 shows the CDF plot for the required takeoff field length. As can be seen from the plot, without the technologies infusion, the design has only 97% feasibility against the required constraint of 7,000 ft. The percent feasibility is increased to a total 100% feasibility by the technologies. As with the previous two metrics discussed before, the infusion of the technologies just shifted the plot to the further left of the feasible design space without changing the plot pattern. The percent improvement of the metric, however, is much more than the previous two, with about 22% improvement for a given percent feasibility.

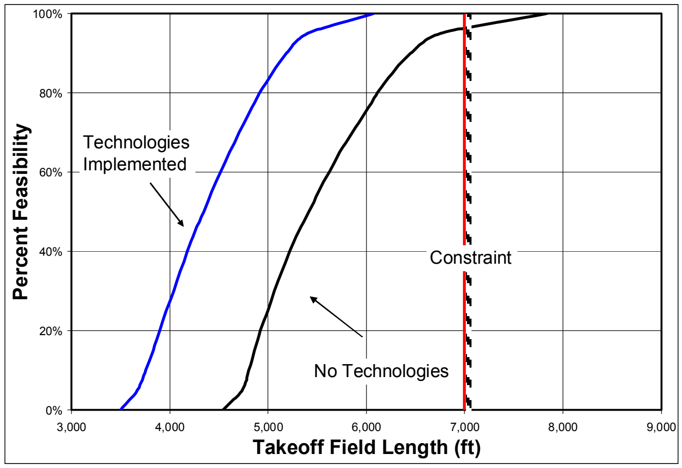


Figure 74: CDF Plot of Takeoff Field Length

Figure 75 shows the tremendous improvement in the CO_2/ASM emission level performance of the design. From 0% feasibility, the infusion of the selected technologies has shifted the plot fully into the feasible design space, with 100% feasibility against the target value of 0.1845 lb/ASM for the year 2007. However, there is a zero percent feasibility for the 2022 constraint. As can be seen from the plot, the infusion of the technology does not just improve the emission performance by shifting the plot to the left of the target line but also reduces the variability of the metric performance. This is evident by the steeper slope of the new CDF plot of the metric.

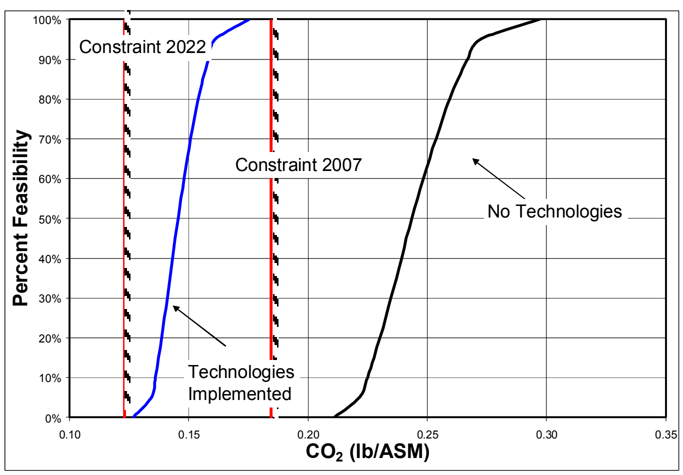


Figure 75: CDF Plot of CO_2/ASM

Figure 76 also shows a tremendous improvement in the NOx emission level performance of the design. From only 4% feasibility, the infusion of the selected technologies has shifted the plot fully into the feasible design space, with 100% feasibility against the target value of 342 lb for the year 2007. As can be seen from the plot, the infusion of the technology does not just improve the emission performance by shifting the plot to the left of the target line but also reduces the variability of the metric performance. This is evident by the steeper slope of the new CDF plot of the metric. Although the improvement with the technology infusion enables 100% feasibility of the design with respect to the year 2007 constraint, these resultant improvements are still inadequate to enable the design to fully meet the required constraint emission value of 228 lb for the year 2022. Even with the infusion of the selected technologies, the design is just 30% feasible against that year 2022 constraint value.

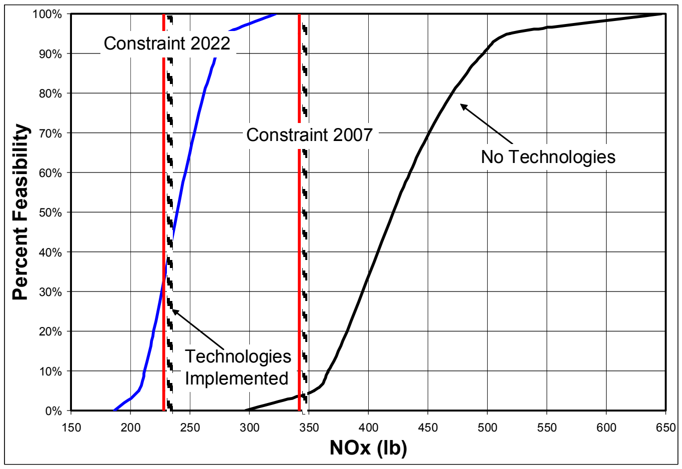


Figure 76: CDF Plot of NOx

As can be seen from the Figure 77, the infusion of the selected technologies has improved the takeoff gross weight of the design. Although the original plot without the technology infusion already shows 100% feasibility against the target gross weight of 175,000 lb, the infusion of the new technologies enables the design to achieve a much better performance. The variability of the metric performance is reduced a bit, as can be concluded from the steeper new plot slope compared to the original plot, and the infusion of the technologies also shifted the original plot to further left of the feasible design space. As a rough comparison, without the technology infusion, the lightest gross weight that can be achieved by the design is about 143,000 lb, which is a definite 100% possibility with the new technologies since the heaviest design weight recorded with the technologies implementation is only 123,000 lb.

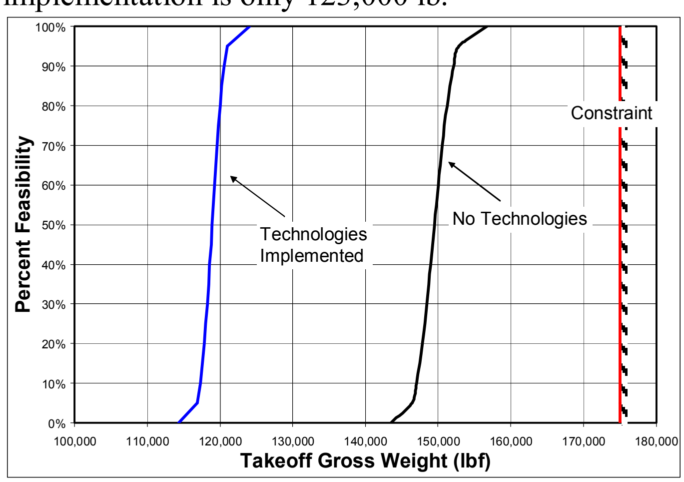


Figure 77: CDF Plot of Takeoff Gross Weight

The infusion of the new technologies has been found to negatively affect the acquisition price of the design. As can be seen from the CDF plot in Figure 78, the implementation of these technologies on the design will increase the acquisition price. This is opposing the intention of minimizing the aircraft price as much as possible. The resultant situation is reasonably inevitable since the implementation of new technologies obviously will increase the costs of the design as being discussed in previous section. Based on the plots, the cheapest price that can be achieved for the design with the implementation of all the selected technologies is about $60.8 million.

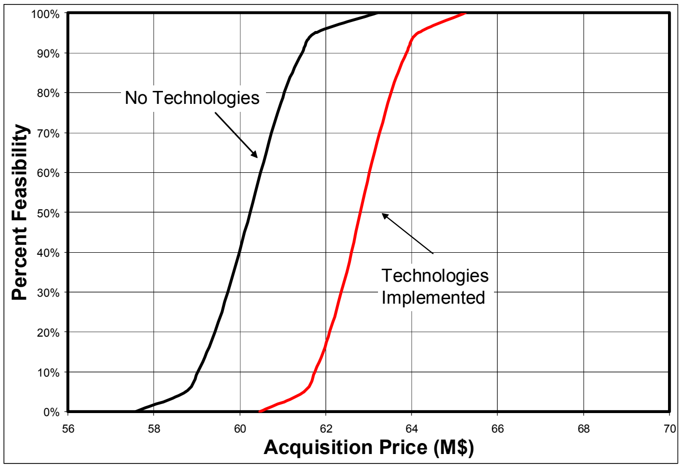


Figure 78: CDF Plot of Acquisition Price

Figure 79 shows that, with the implementation of the selected technologies, the overall RDT&E costs for the design will be further decreased from the original value. This condition is well aligned with the notion of minimizing the costs as much as possible. This situation may occur due to the reduction of the design cycle time and expensive experimental testing, which is due to the infusion of several of the selected technologies. With the technology infusion, the highest RDT&E costs that can be expected is about $4,800 million; a very much reduced amount compared to the value of that without the technologies, which is approximately at $5,025 million.

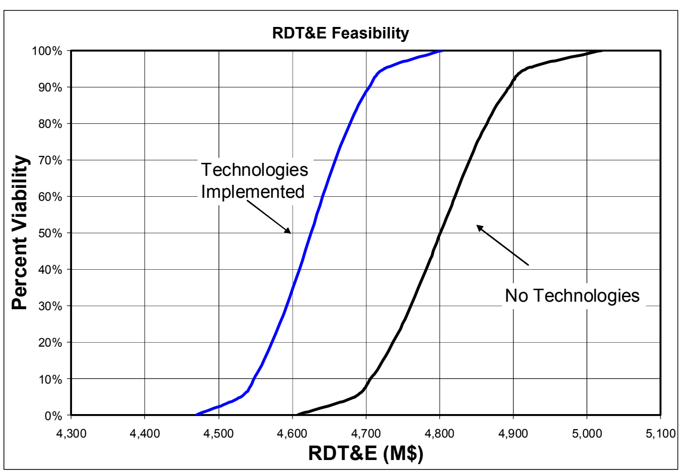


Figure 79: CDF Plot of RDT&E Costs

As for the required yield per revenue passenger-mile ($/RPM) metric, the technologies infusion also helped to improve the design. As being shown in Figure 80, the plots indicate that a great improvement in reduction of the metric value can be achieved with the help of the technologies. This condition is desired as the metric is intended to be minimized as much as possible. This situation might have close relationship with the subsequent reduction in the design operating costs. With the implementation of the technologies, the required yield per revenue passenger-mile can be as low as $0.10/RPM compared to $0.132/RPM without the technologies.

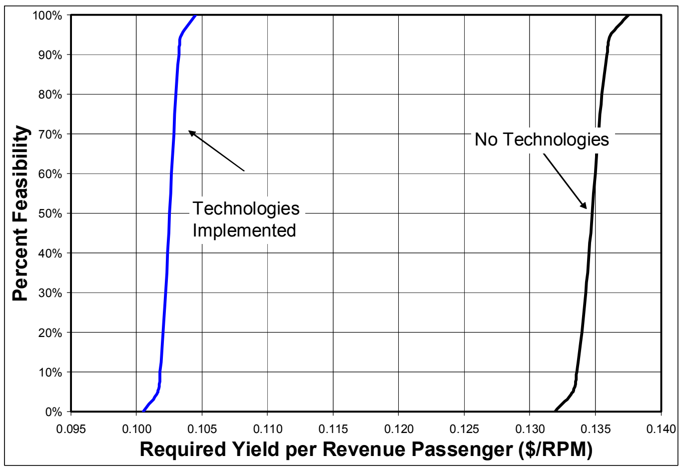


Figure 80: CDF Plot of Required Yield per Revenue Passenger-Mile ($/RPM)

Similar to the required yield per revenue passenger-mile ($/RPM) metric, the technologies infusion also helped to improve the total airplane related operating costs of the design. As being shown in Figure 81, the plots indicate that a great improvement in reduction of the metric value can be achieved with the help of the technologies. This condition is desired as the metric is intended to be minimized as much as possible. With the implementation of the technologies, the design TAROC can be as low as 4.85 cents/ASM compared to $6.6 cents/ASM without the technologies.

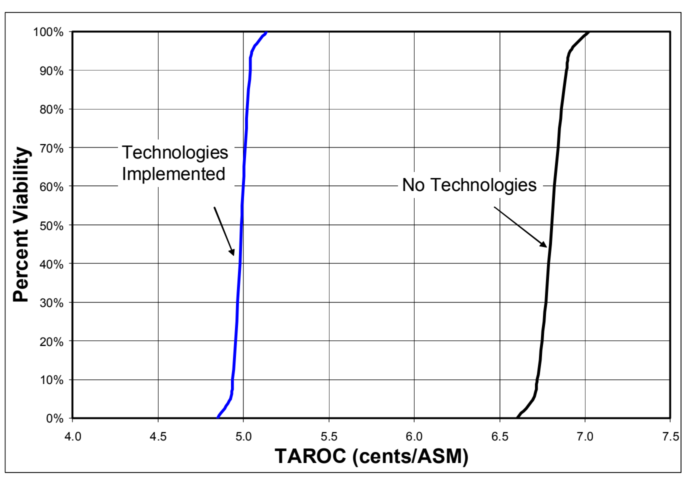


Figure 81: CDF Plot of Total Airplane Related Operating Costs

Figure 82 shows the tremendous improvement in the direct operating costs plus interest of the design. From 0% feasibility, the infusion of the selected technologies has shifted the plot into the feasible design space, with 95% feasibility against the target value of 3.95925 cents/ASM for the year 2007. As can be seen from the plot, the infusion of the technology does not just improve the metric performance by shifting the plot to the left of the target line but also reduces the variability of the metric performance. This is evident by the steeper slope of the new CDF plot of the metric. However, these resultant improvements are still inadequate to enable the design to meet the required constraint value of 2.6395 cents/ASM for the year 2022. Even with the infusion of the selected technologies, the design is still 0% feasible against that year 2022 constraint value. This is shown on the same plot where the lowest costs that can be achieved by the technology infusion is only about 3.78 cents/ASM.

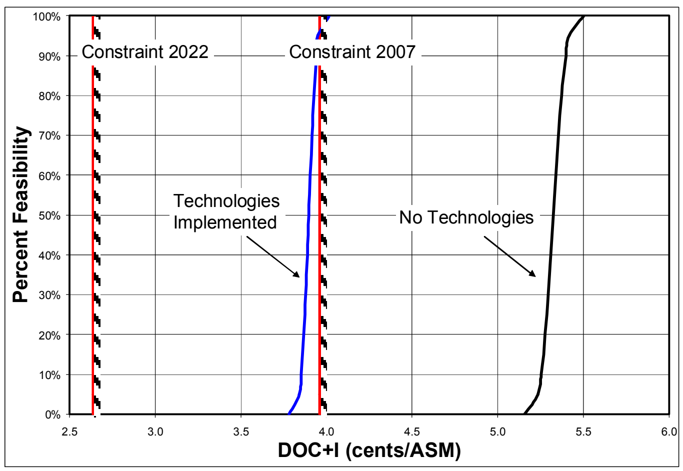


Figure 82: CDF Plot of Direct Operating Costs + Interest

It can be said that the infusion of the new technologies has improved all the performance and economics metrics of the design, with the exception of the acquisition costs. Although the governing design space metrics, which are the CO_2/ASM, NO_x and the DOC+I, are not entirely satisfied for the year 2022 constraints, little can be done to deal with that situation. One of the options to satisfy these metrics requirements is by revising the selected technologies for implementation.

The degradation in the acquisition price metric can be said to be well justified with the great improvement in the overall design performance with the help of the technologies infusion and the reduction in operation costs. Therefore, the selection of technology alternatives for the design is a good selection.

CONCLUSION

The focus of this study was to use the TIES methodology to determine the feasibility and viability of a 150 passenger commercial aircraft and to study the effects of technology infusion to open up the feasible design space. The main objective was to identify which technologies would be necessary to overcome the established constraints.

The requirements of the system were defined in the design metrics and their target values. Ranges for the variables that are under the designers' control were determined to create Response Surface Equations to model how the variables affect the design metrics. A Monte Carlo Simulation of 10,000 random cases was used to create CDFs, which allowed the design team to determine if the design was feasible and, if feasible, whether it was viable. This study showed that the emissions and DOC+I constraints could not be met by the baseline design.

In order to open up the design space, a technology study was performed. The first step was to determine how the 36 technologies identified affected the design variables (k-factors). A full factorial DoE was used to formulate RSEs that could model all possible technology combinations. By using TOPSIS, Technology Frontiers, and Technology Sensitivities the best family of all the technologies was chosen. This created a new aircraft alternative and the new design space was studied with the applied technologies. The study led to a new set of RSEs, for which a Monte Carlo Analysis was performed to determine the feasibility and viability of the new system.

Fourteen technologies were needed to create a feasible and viable design space for the 2007 constraints. It was previously determined, while the k-factors were studied, that the constraints for the year 2022 would not be met with the identified technologies. If this project was directed to a manufacturer, the group would recommend investing in only some of the fourteen needed technologies. The manufacturer would then need to request from the government research programs to develop the rest. Table LVIII summarizes the technologies concluded to be necessary for the new design in order to meet the constraints.

Table LVIII: Technologies Needed to Meet 2007 Constraints

ID #	Technology Description	Current TRL	TRL=9 Date
T1	Adaptive Performance Optimization (APO)	9	2000
T6	Airframe Methods	4	2007
T7	Fire Suppression	3	2007
T10	Propulsion System Health Management	2	2009
T11	Smart Nacelle – Propulsion-Airframe Integration (PAI)	3	2009
T20	Adaptive Engine Control System (ADECS)	4	2011
T21	Revolutionary Metallic Materials Systems on Fuselage Structure	2	2013
T26	Living Aircraft	2	2013
T27	Active Load Alleviation on Tail	4	2013
T28	Active Load Alleviation on Wing	4	2013
T29	Antenna Systems	2	2014
T30	*Adaptive Wing Shaping*	*3*	*2014*
T34	*BIOSANT on Fuselage Structure*	*1*	*2015*
T35	*BIOSANT on Tail Structure*	*1*	*2015*
T36	*BIOSANT on Wing Structure*	*1*	*2015*

PROJECT WORK PLAN ASSESSMENT

The initial plan for team in approaching this project was basically to go through the working process of each step requirements in a sequential manner. This can be seen from the initial project planning Gantt Chart, shown in Figure 83. However, as the team went through the project requirements, the time necessary for each step slightly changed from the time allocated.

Steps 1-5 were performed as planned in the Gantt Chart. For Step 6, the requirements were found to be independent from each other and the team was able to work on each of these requirements at the same time when doing the requirements in Step 4. After establishing the needed optimized baseline parameters, the team decided that two of team members will do the feasibility and the viability study of the design respectively and the other will start on Step 6 requirements concurrently. This allowed for the team to jump into Step 7 sooner. Some mistakes took place, but with the extra time, Deliverable 4 was turned in on time.

Since some of the deliverable due dates were postponed, the team deviated from the proposed time schedule. The write up for Steps 6-7 was extended an extra week and the final report was due three days after the initial due date. Because of this, the team had less time to do Step 8. The team also did not start preparation of the presentation until December 2, only allowing for four days to get the slide show ready. After the presentation was complete, the team then focused on the final report. This was complete on December 9. Although the team did not follow the time schedule, all of the requirements were met on time.

This project has helped the team in realizing a new approach in the sizing and synthesis process of an aircraft design as compared to the traditional approach. The TIES methodology, which is the main backbone of this project, gives more flexibility in assessing numerous design possibilities concurrently in less time than if was done through the conventional process. The methodology also allows for visualization and permits a structured approach in assessing new technologies into the design to achieve the target or constraint goals established for the design.

The TIES methodology is a universally structured approach for a conceptual and preliminary design process. The process can be applied to other complex systems. However, this methodology depends on the availability of analysis codes to assess a given complex system, which restrains its application. For the purpose of this project, FLOPS & ALCCA were available as sizing and synthesis tools. For use on another complex system, tools may not be as readily available.

Both FLOPS and ALCCA require the user to be familiar with most of its inputs. As first time users, the members of the design team had difficulties in identifying all the input variables that had to be modified, added, or removed from the input files. We encountered problems in some of the cases run in which FLOPS or ALCCA crashed. The inexperience of the team members made it difficult to understand what factors caused it to crash.

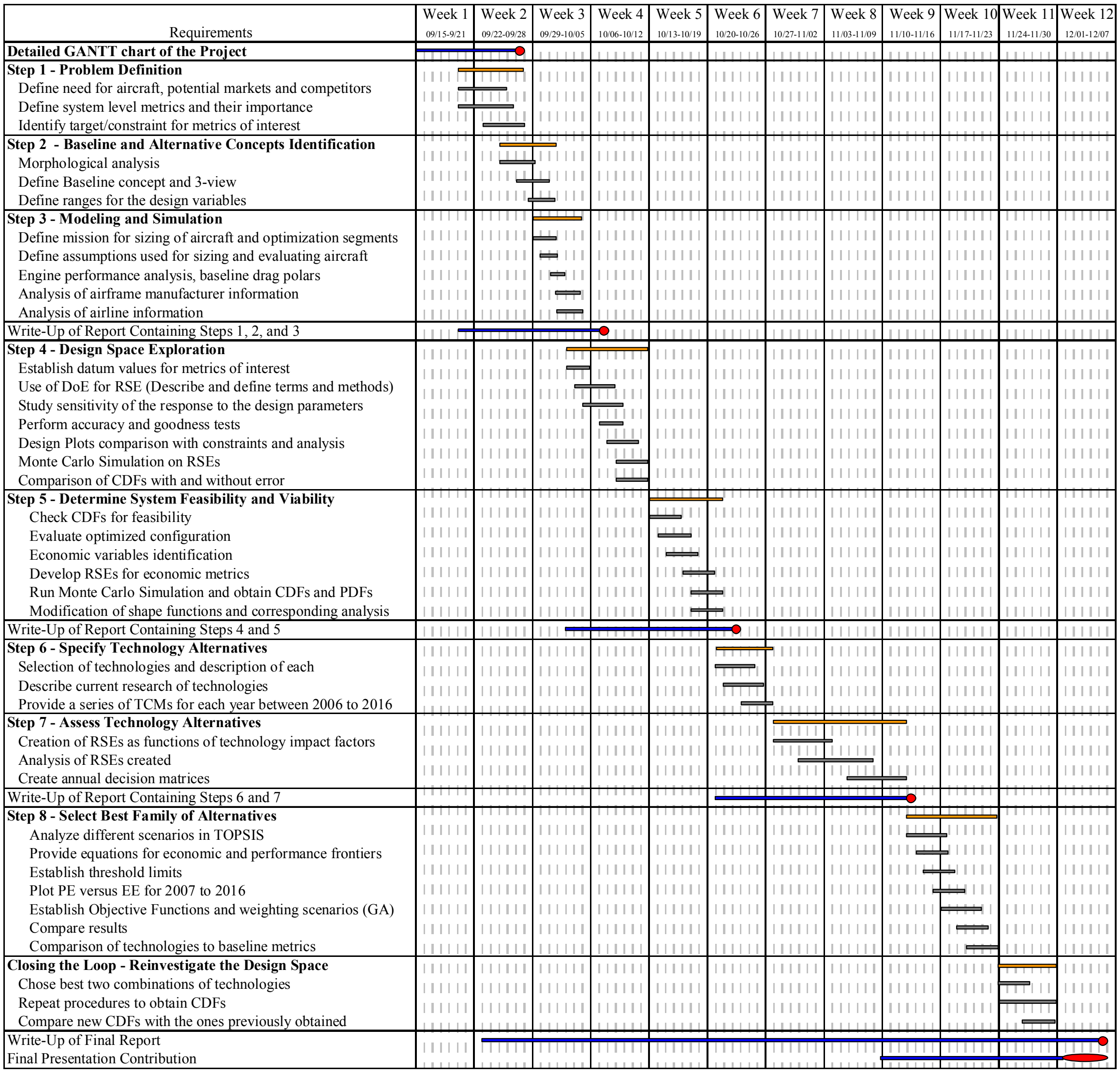


Figure 83: Gantt Chart

For future projects, it would be helpful to know the logics behind the tools that create their acceptance. This will enhance the knowledge about this methodology and opens up to other possibilities of approaching this methodology.

The workload associated with this project could be considered acceptable for experienced users. However, first time users tend to require extra time for iteration when corrections have to be made.

The TIES methodology would be a lot more effective with a complete integrated interface. This integrated interface would allow the user to use the sizing analysis code and the statistical analysis code by simply supplying one set of inputs. More ideas related to this can be discussed individually with the member of the design group.

APPENDIX A

Table AI: Sizing Assumptions

Parameter	FLOPS Data Name	Value
1.Geometric, Weight, Balance & Inertia Data		
Max. Optimum Mach Number	VMMO	0.825
Ultimate Load Factor	ULF	3.75
CG Reference Length (in)	CGREFL	12 X (Fuselage length)
Hydraulic System Pressure	HYDPR	3000
2.Wing Data		
Dihedral	DIH	2 degrees
Glove and Bat Area	GLOV	0
Control Surface Area Ratio	FLAPR	0.333
No Fraction of Composites in Wing Structures	FCOMP	-
No Aeroelastic Tailoring in Design of Wing	FAERT	-
No Wing Strut	FSTRT	-
Fixed-Wing Geometry	VARSWP	-
Load path sweep angle	SWL	0 degree
Fraction of load carried by defined wing	PCTL	1.0
Location of engines	ETAE	0.3 X (wing semi span)
3.Horizontal Tail Data		
Quarter Chord Sweep Angle	SWPHT	33.4 degrees
Location on Vertical Tail	HHT	0% of the vertical tail span
4.Vertical Tail Data		
Number of Vertical Tail	NVERT	1
Quarter Chord Sweep Angle	SWPVT	39.4 degrees
5.Fuselage Data		
Number of fuselage	NFUSE	1
Total Length	XL	117.83 ft
Maximum Width	WF	12.58 ft
Maximum Depth	DF	12.58 ft
6.Landing Gear Data		
Design Landing Weight	WLDG	[1-0.00004(Design range)] X (Takeoff Gross Weight)
Land Based Aircraft	CARBAS	-
7.Propulsion System Data		
Number of engines on wing	NEW	2
Number of engines on fuselage	NEF	0
Baseline engine rated thrust	THRSO	25805.3 lbf
Baseline engine weight	WENG	6466.0 lbf
Baseline nacelle average length	XNAC	10.29 ft
Baseline nacelle average diameter	DNAC	6.58 ft
Fuel Capacity Factor	FWMAX	23.5
Fuel Capacity on Fuselage	FULFMX	0
Fuel Capacity on Wing	FULWMX	Fuel Capacity Factor x [(Wing T/C x Wing Area^2) / Wing Span] x [(1-Wing Taper Ratio) / (1+Wing Taper Ratio)^2)]

Parameter	FLOPS Data Name	Value
Number of fuel tanks	NTANK	7
Parameter	**FLOPS Data Name**	**Value**
8.Crew and Payload Data		
First Class Passenger	NPF	12
Economy Class Passenger	NPT	138
Flight Crew	NFLCR	2
Cabin Crew	NSTU	4
Weight per passenger	WPPASS	165 lbf
Baggage per passenger	BPP	44 lbf
Cargo carried in wing	CARGOW	0
Cargo carried in fuselage (other than passenger baggage)	CARGOF	0
9.Configuration Variables		
Ramp Weight	GW	158000 lbf
Maximum Rated Thrust per Engine	THRUST	24474.2 lbf
Thrust-to-weight required per Engine	TWR	0.15490
10. Mission Variables		
Design Range	DESRNG	3000 nm
Cruise Mach Number	VCMN	0.785
Max. Cruise Altitude	CH	40000 ft
11.Aerodynamic Options		
Maximum camber at 70% semi span	CAM	0.5 Chord
Wing Technology Level	AITEK	1.9
Aero efficiency factor, e	E	0.8
12.Takeoff & Landing Data		
Maximum Landing Velocity, $V_{approach}$	VAPPR	130 kts
Takeoff Field Length	FLTO	7000 ft
Landing Field Length	FLLDG	7000 ft
Maximum Lift Coefficient in Takeoff Configuration	CLTOM	3.1
Maximum Lift Coefficient in Landing Configuration	CLLDM	3.8
Takeoff/Landing Air Density Ratio to Sea	DRATIO	1.0
13.Main Mission Data		
Takeoff Time	TAKOTM	2 minutes
Taxi-out Time	TAXOTM	9 minutes
Approach Time	APPRTM	4 minutes
Taxi-in Time	TAXITM	5 minutes
Minimum Climb Mach Number	CLMMIN	0.3
Climb Optimization	FWF	Minimum fuel-to-climb profile
Rate of Climb to Ceiling	RCIN	300 ft/min
Cruise Mach Number	CRMACH	0.785
Maximum Cruise Altitude	CRALT	40000ft
Cruise Optimization	IOC	Fixed Mach number, optimum altitude for specific range
Minimum Cruise Altitude	HPMIN	1000 ft
14.Descent Data		
Descent Lift Coefficient	DECL	0.8
Minimum Descent Mach Number	DEMMIN	0.3
Missed Approach Time	TIMMAP	2 minutes
Range to Alternate Airport	ALTRAN	150 nmi
Climb Profile	NCLRES	Similar to Main Mission

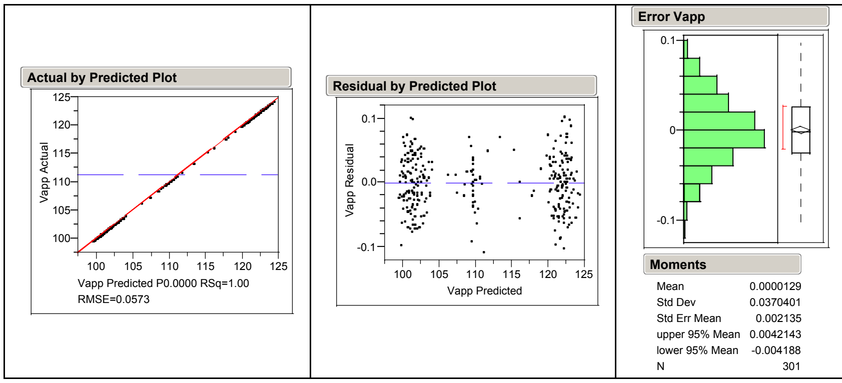
		Climb
Parameter	**FLOPS Data Name**	**Value**
14.Descent Data (cont)		
Maximum Cruise Mach Number	CRMACH	0.6
Cruise Altitude	CRALT	25000 ft
Cruise Optimization	IOC	Fixed Altitude, optimum Mach number for specific range
Minimum Cruise Altitude	HPMIN	1000 ft
15. Reserve Mission Data		
Start Reserve Mach Number	SREMCH	0.3
End Reserve Mach Number	EREMCH	0.3
Start Reserve Altitude	SREALT	0 ft
End Reserve Altitude	EREALT	0 ft
Hold Time	HOLDTM	45 minutes
Hold Profile	NCRHOL	Similar to Main Mission Cruise

Table AII: Economics Assumptions

Parameter	**ALCCA Data Name**	**Value**
1. Component Cost		
Airline Return on Investment	RTRTNA	10%
Average Annual Inflation	API	8.0%
Year of Program Initiation	PYEAR	2000
Fiscal Dollar Year	YEAR	1996
Manufacturer Return on Investment	RTRTN	12%
2. Miscellaneous Factors		
Manufacturer's Fee	FEE	0%
Airframe Spares Factor (of airframe price)	AFSPAO	6%
Engine Spares Factor (of engine price)	ENSPAO	23%
3. Learning Curve Factors		
Airframe LC for 1st Lot	LEARN1	81.5%
Airframe LC for 2nd Lot	LEARN2	85.0%
Avionics LC for 1st Lot	LEARNA1	81.5%
Avionics LC for 2nd Lot	LEARNA2	85.0%
Assembly LC for 1st Lot	LEARNAS1	76.0%
Assembly LC for 2nd Lot	LEARNAS2	79.0%
Fixed Eqpm. LC for 1st Lot	LEARNFE1	82.0%
Fixed Eqpm. LC for 2nd Lot	LEARNFE2	85.0%
Engine LC for 1st Lot	LEARNP1	100.0%
Engine LC for 2nd Lot	LEARNP2	100.0%
Production Line Learning Curve Breaking Point	PUNITS	200
4. Production Data		
Production Quantity	NV	800
Years of Production	-	15 years
Engineering Labor Rate	RE	$89.68/hr
Tooling Labor Rate	RT	$54.68/hr
5. Indirect Operating Cost		

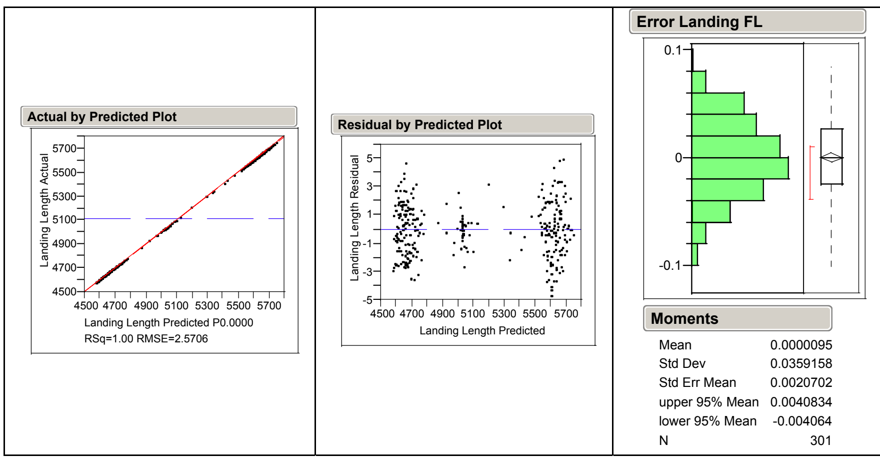
Rate of Interest of Financing	RINRST	8%
Parameter	**ALCCA Data Name**	**Value**
5. Indirect Operating Cost (cont)		
Depreciation Residual Value (price including spares)	RESDVL	10%
Economic Life	ECLIFE	20 years
Economic Range	SL	1000 nm
Financing Period	-	20 years
Fuel Cost	COFL	$0.70/gal
Hull Insurance Rate (of aircraft price)	FINSUR	35%
Passenger Load Factor (both seating class)	CLF	0.71
Maintenance Burden Rate (of direct labor)	BDMAIN	200%
Maintenance Labor Rate	RL	$25/hrs
Annual Aircraft Utilization	U	3900 hrs/yr
6. Maintenance		
Mean Time Between Failure	MTBF	10000 hrs
Mean Time To Repair	MTTR	1 hrs

APPENDIX B – RSE GOODNESS OF FIT FOR METRICS



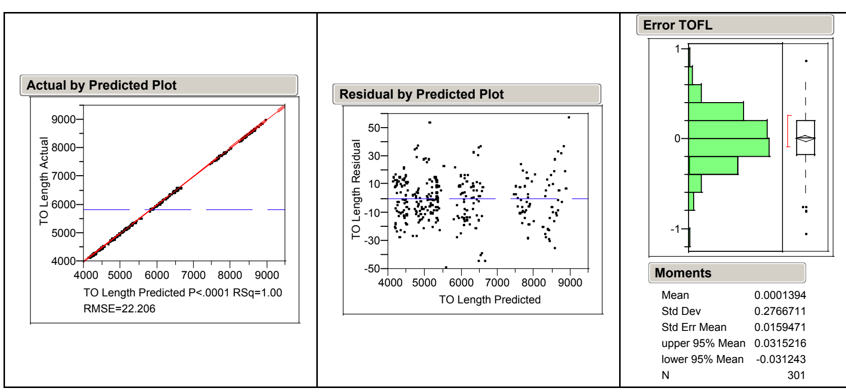
$R^2 = 0.9999$

Figure B1: Fit Analysis of Approach Speed



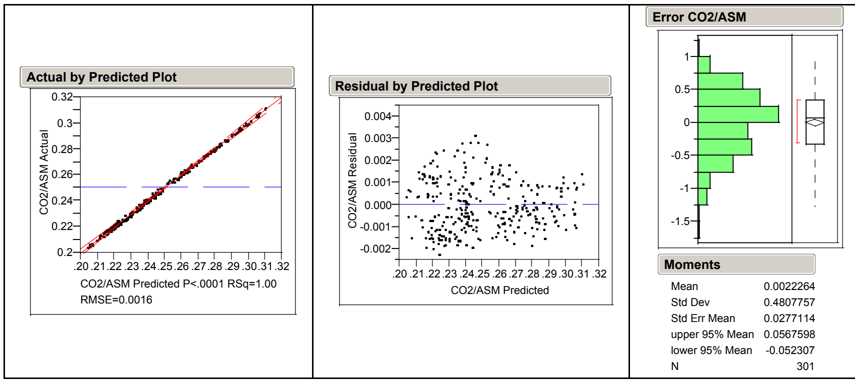
$R^2 = 0.99998$

Figure B2: Fit Analysis of Landing Field Length



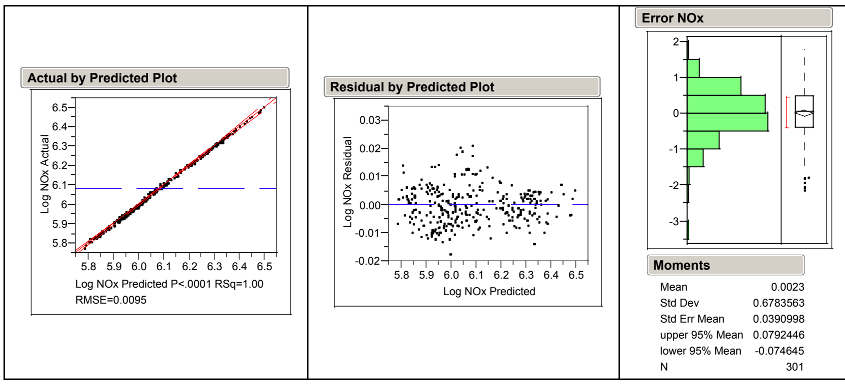
$R^2 = 0.9999$

Figure B3: Fit Analysis of Take Off Field Length



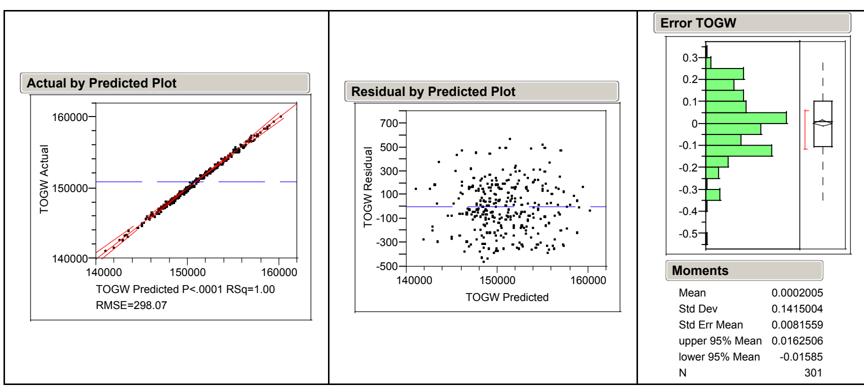
$R^2 = 0.9981$

Figure B4: Fit Analysis of CO2/ASM



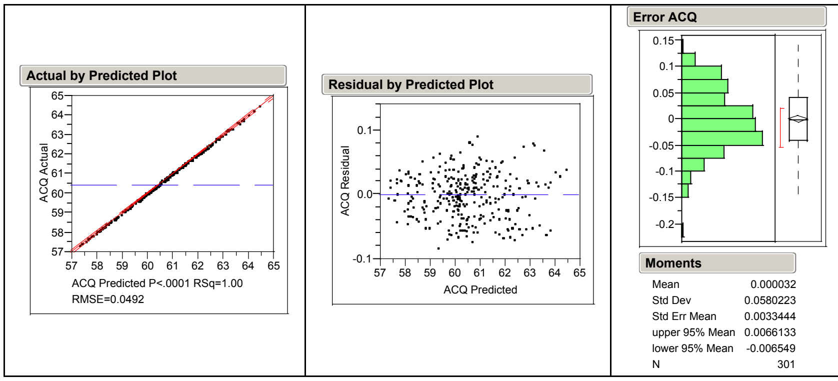
$R^2 = 0.9985$

Figure B5: Fit Analysis of NOx



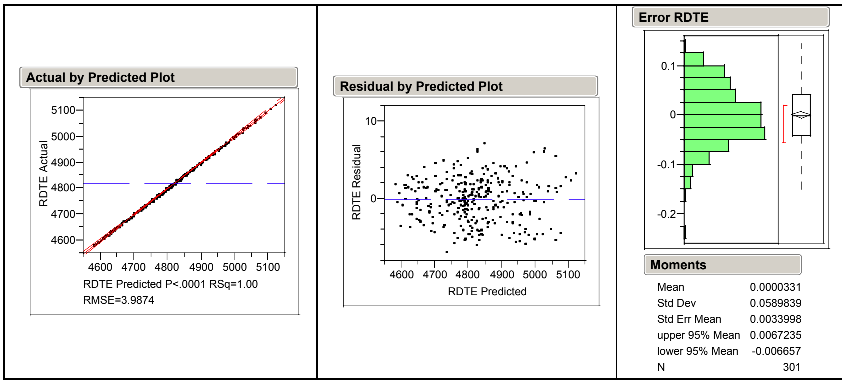
$R^2 = 0.9963$

Figure B6: Fit Analysis of Take Off Gross Weight



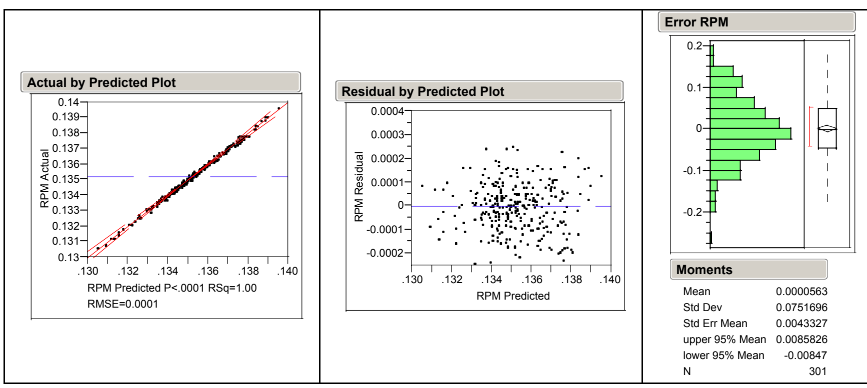
$R^2 = 0.9994$

Figure B7: Fit Analysis of Acquisition Price



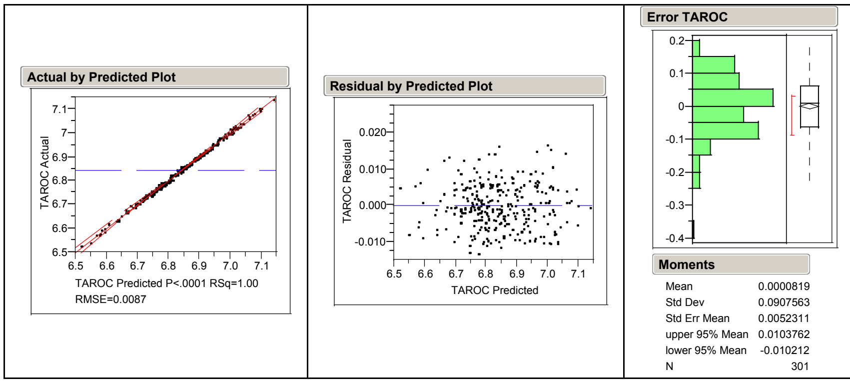
$R^2 = 0.9994$

Figure B8: Fit Analysis of RDT&E Costs



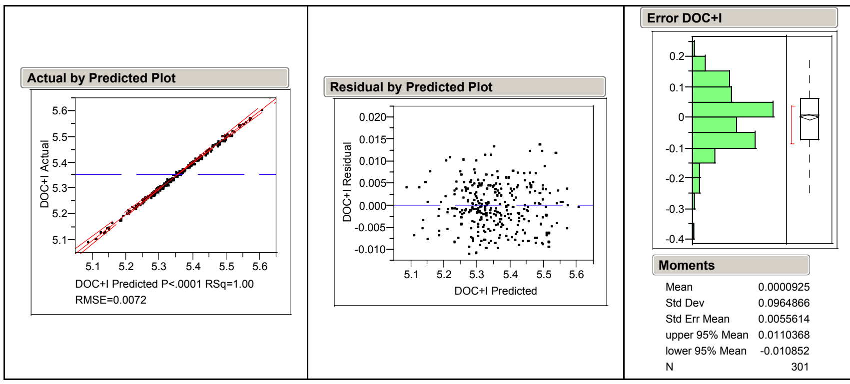
$R^2 = 0.9960$

Figure B9: Fit Analysis of Required Yield Per RPM



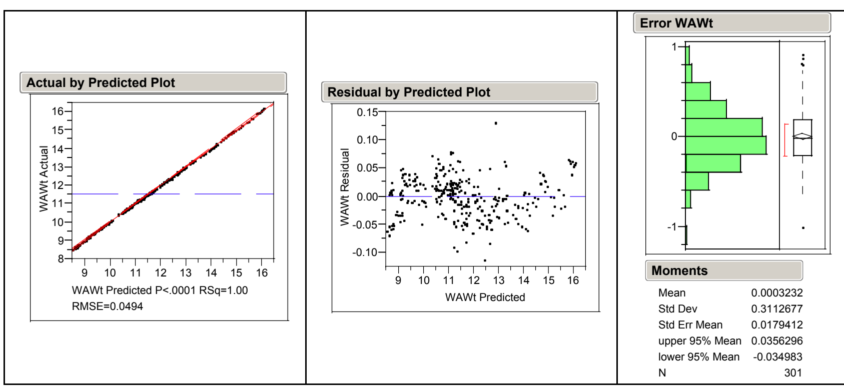
$R^2 = 0.9970$

Figure B10: Fit Analysis of TAROC



$R^2 = 0.9971$

Figure B11: Fit Analysis of DOC+I



$R^2 = 0.9996$

Figure B12: Fit Analysis of Wing Aerial Weight

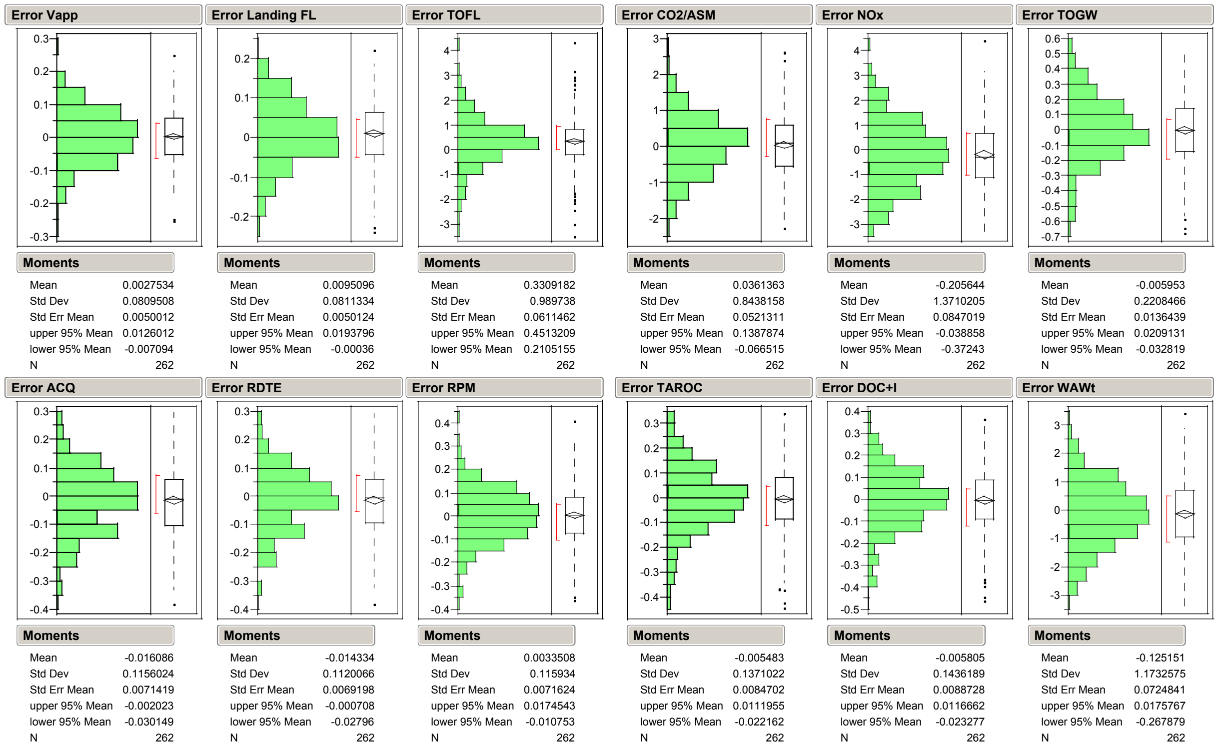


Figure B13: Error Analysis of Random Cases Using RSEs

APPENDIX C – DESIGN SPACE RSE COEFFICIENTS

	Vapp	Landing Length	TO Length	CO2/ASM	Log NOx	TOGW
Intercept	109.669474	5029.72104	5342.38392	0.24029826	6.01938149	148614.921
SW	-9.9894825	-459.16677	-1000.5185	-0.0089148	-0.0454606	772.088308
TWR	0.56179589	25.5943915	-128.42643	0.00227588	-0.0316908	1522.56577
AR	0.67666501	28.6708764	-375.51294	-0.0235667	-0.1609871	-2094.3861
TR	0.27388694	12.8974817	33.8366008	0.00163758	0.00746893	799.226456
TOC(1)	-0.4194318	-18.189024	-30.198177	0.00615819	0.05299316	199.734656
TOC(3)	0.05674929	2.50200546	67.073855	0.00380289	0.03619118	650.289482
SWEEP	0.00930561	0.57084188	0.87070779	-0.0004734	-0.006857	-49.962586
ARHT	0.00990195	0.4511563	3.63269351	0.00038113	0.0027371	74.1116161
TRHT	0.06609237	3.17393273	8.44182102	0.00025825	0.00084299	173.101142
TCHT	0.02595795	1.35533251	8.96150581	0.00101643	0.00678679	204.587485
SHT	0.22762986	10.6530434	42.9616731	0.00312232	0.01831856	910.633815
ARVT	0.00783409	0.42334717	2.40255029	0.00028678	0.00217487	58.0389534
TRVT	0.06927967	3.25756022	9.11297425	0.00038589	0.00155611	198.252576
TCVT	0.02195805	1.09058068	7.92361803	0.00084044	0.00554408	165.824618
SVT	0.22607012	10.6065639	43.9262634	0.00340273	0.02012867	943.729789
SW*SW	1.60342958	97.0803393	305.397474	0.00530582	0.03831431	825.128201
TWR*SW	-0.070504	-5.8488122	81.0565724	-0.0005816	-0.0037353	-103.19135
TWR*TWR	0.02534991	0.62242496	15.4350426	-0.0001189	0.00160029	-12.463375
AR*SW	0.13413222	3.70072201	308.491732	0.00326373	0.02935556	870.687931
AR*TWR	0.00074943	0.04849381	66.8125649	-0.0003636	0.00032842	-48.756527
AR*AR	0.17465444	7.01756258	219.439604	0.00411017	0.02959411	921.095564
TR*SW	-0.0090389	-1.5943379	-9.4971726	-0.0000072	-0.0000077	42.5204072
TR*TWR	0.00895998	0.32609732	0.16077813	0.0000515	-0.0002696	18.8080773
TR*AR	0.06836489	3.32171121	-1.1022409	-0.0000214	-0.0001112	142.734569
TR*TR	-0.0153743	0.57173222	-3.8631065	-0.0002347	-0.0037628	-29.409614
TOC(1)*SW	0.01312814	1.84289881	-3.7872339	0.00046084	0.00527415	23.766893
TOC(1)*TWR	0.00424987	0.34752534	-0.5309048	0.00009324	-0.0000037	27.7275518
TOC(1)*AR	-0.1257498	-5.988452	-15.31723	-0.0005394	0.00044358	-346.91866
TOC(1)*TR	-0.0319904	-1.5018583	-3.1790233	-0.0001376	-0.0007886	-87.816151
TOC(1)*TOC(1)	0.12720176	4.62473782	29.1321199	0.00173578	0.00680952	422.679624
TOC(3)*SW	0.00173666	-0.190475	-14.483361	0.00038598	0.00435795	68.1190567
TOC(3)*TWR	0.01579551	0.68625877	-2.1947067	0.0001531	0.00010606	49.8299403
TOC(3)*AR	-0.0342662	-1.5114845	-14.317968	-0.0003451	0.0013844	-119.53564
TOC(3)*TR	-0.00959	-0.3633635	-0.5927522	-0.0000512	-0.0003897	-25.412429
TOC(3)*TOC(1)	0.08524723	4.19511009	25.023449	0.00226405	0.01225195	501.449744
TOC(3)*TOC(3)	0.02842252	2.56460633	16.4873272	0.00081369	0.00542836	232.168708
SWEEP*SW	-0.0273198	-1.3567661	-7.6080622	-0.0009877	-0.01067	-199.60378
SWEEP*TWR	0.0084388	0.31279456	0.5784663	-0.0000037	-0.0004062	11.2472644
SWEEP*AR	-0.0213895	-0.8798051	-7.9585877	-0.0007535	-0.0049039	-142.4922
SWEEP*TR	0.00393223	0.00084625	0.06246084	0.00007176	0.00025626	10.576705
SWEEP*TOC(1)	-0.0299184	-1.5378842	-13.483405	-0.0015261	-0.0090328	-281.78204

SWEEP*TOC(3)	-0.0303474	-1.5115141	-13.408147	-0.0015105	-0.0090524	-277.60141
SWEEP*SWEEP	0.05123118	2.26610855	3.35306025	0.00015305	0.00184407	94.0928245
ARHT*SW	-0.0049806	-0.1079947	-1.7364606	-0.000069	-0.0001361	-11.402846
ARHT*TWR	0.00076601	0.08950638	-0.3585655	0.00003226	0.00003358	7.37376299
ARHT*AR	-0.0028583	-0.1186688	-1.6810968	-0.0000269	0.00021888	-8.4951304
ARHT*TR	-0.0007301	-0.0448605	-0.2011963	-0.0000186	0.00001661	-4.462264
ARHT*TOC(1)	0.00095555	0.03632643	0.09160779	0.00003153	0.00034886	5.9379703
ARHT*TOC(3)	0.00328469	-0.0011598	0.20959463	0.0000378	0.00032629	6.09703033
ARHT*SWEEP	-0.0027935	-0.0720894	0.0785051	-0.0000254	-0.0002264	-6.5746903
ARHT*ARHT	0.01947362	-0.3761089	4.14504104	0.00014348	-0.0014051	15.844466
TRHT*SW	-0.0079173	-0.6770542	-3.2650597	0.00000275	0.00007551	-0.6500129
TRHT*TWR	0.00120759	0.05500827	-0.3132872	-0.0000115	-0.0001587	-0.0979194
TRHT*AR	-0.0031242	-0.0009881	-2.2669551	-0.0000946	-0.0003129	-14.695071
TRHT*TR	0.00015129	0.1070211	4.55395584	-0.0000948	-0.0009469	-26.083204
TRHT*TOC(1)	0.00193694	-0.0061125	0.04098543	-0.0000487	-0.0005414	-9.1284093
TRHT*TOC(3)	-0.0044964	0.00002245	-0.1065665	-0.0000408	-0.0005105	-8.3259851
TRHT*SWEEP	0.00261816	0.05247688	0.03018284	0.00005524	0.00050608	9.24654114
TRHT*ARHT	-0.0024392	-0.0169067	-0.2315856	-0.0000413	-0.000163	-6.9576695
TRHT*TRHT	0.00030477	0.44481166	2.20267088	0.00073369	0.00297351	118.905616
TCHT*SW	-0.0046109	-0.2948744	-3.5686333	-0.0001488	-0.0006577	-23.822608
TCHT*TWR	0.00252786	-0.2675935	2.41742545	0.00006637	0.00006653	27.6934144
TCHT*AR	-0.000537	-0.200801	-2.3537658	-0.0001119	-0.0000234	-20.128519
TCHT*TR	0.00348943	0.13892591	-37.730687	0.00008494	-0.0002215	19.003094
TCHT*TOC(1)	0.00187886	-0.0505137	-0.8170762	-0.0000097	0.00015596	-2.30601
TCHT*TOC(3)	0.00141675	-0.0053234	0.00042358	0.00002308	0.00013134	4.454356
TCHT*SWEEP	-0.0018881	0.03378017	0.08373261	-0.0000095	-0.0003096	-1.6981959
TCHT*ARHT	-0.0005975	0.11309313	0.58028765	0.00007331	0.00057817	14.2587929
TCHT*TRHT	0.00669886	0.21275116	0.24064449	-0.0000081	-0.0002678	7.83571895
TCHT*TCHT	-0.0090835	0.72478102	-7.0845274	-0.0008849	-0.005293	-88.324324
SHT*SW	-0.0186722	-1.838366	-17.941365	-0.0002525	-0.0010009	-22.519277
SHT*TWR	-0.0078873	-0.6619443	-11.414717	0.00007029	-0.0000293	21.8924964
SHT*AR	-0.0078954	-0.4595744	-13.919413	-0.0004608	-0.0012095	-80.719977
SHT*TR	0.00033037	0.10538009	0.41463296	0.00003373	0.0000014	10.2267075
SHT*TOC(1)	-0.0056734	-0.4498328	1.01344285	-0.0000219	-0.0004733	-17.188634
SHT*TOC(3)	-0.0020361	-0.257159	0.89994374	0.00002297	-0.0004026	-4.3620578
SHT*SWEEP	0.00092338	0.08783894	0.12203636	0.00006468	0.00001368	13.527378
SHT*ARHT	0.00401351	0.15043353	8.91391887	0.00014172	0.00024611	25.4314428
SHT*TRHT	0.01629197	0.78682906	2.48439722	0.00010363	0.00053838	50.200898
SHT*TCHT	0.00541478	0.32815226	2.06146821	0.00018731	0.00108285	40.8136476
SHT*SHT	0.04733511	2.2681473	0.16844961	-0.0006587	-0.0053786	21.7756265
ARVT*SW	-0.0020878	-0.1114964	-1.0974188	-0.0000569	-0.0001588	-10.279758
ARVT*TWR	-0.0013406	0.01192987	-0.2160084	0.00003116	0.00014476	4.67960058
ARVT*AR	-0.0005169	0.0802748	-0.8248005	-0.0000197	-0.0000773	0.71184683
ARVT*TR	-0.0001032	-0.0097537	-0.1481375	-0.0000263	-0.0002533	-2.9786776
ARVT*TOC(1)	0.00003443	0.01790225	-0.0564179	0.00001361	0.00017091	2.59666599
ARVT*TOC(3)	0.00202543	0.053619	-0.098826	0.0000258	0.00020727	5.85167878
ARVT*SWEEP	0.00146831	-0.0388876	0.27395645	-0.0000201	-0.0002474	-4.2273041
ARVT*ARHT	0.00189681	-0.1296928	0.21409422	0.0000081	0.00000525	-0.9531439

ARVT*TRHT	-0.0047194	-0.0007552	-0.4103644	-0.0000222	-0.0000162	-4.3790602
ARVT*TCHT	-0.0001007	0.02478373	0.32716693	0.00003412	0.00021031	5.81479068
ARVT*SHT	-0.0003774	0.01668466	0.15013524	-0.0000133	-0.0003174	-0.9030219
ARVT*ARVT	0.00046284	-0.7405194	-4.0088313	-0.000288	-0.0011333	-85.176908
TRVT*SW	-0.0089344	-0.6385945	-3.3149974	-0.0000903	-0.0005622	-15.3223
TRVT*TWR	0.00300592	0.08352248	-0.9555982	0.00002695	0.00036155	7.79419629
TRVT*AR	-0.0007075	0.00173743	-2.6024682	-0.0000055	0.00018642	0.33549686
TRVT*TR	0.0040247	0.0722343	0.96407611	-0.0002221	-0.0011768	-27.219455
TRVT*TOC(1)	0.0002222	-0.018962	0.0129277	0.0000446	0.00024162	6.40073814
TRVT*TOC(3)	0.00083665	-0.0487897	0.03162118	0.00004877	0.00041718	7.58586763
TRVT*SWEEP	-0.0144441	-0.4840267	-0.4261685	-0.0000542	-0.0003035	-30.031332
TRVT*ARHT	-0.0060489	-0.0256218	0.06647907	0.00001666	0.00009735	2.29611182
TRVT*TRHT	0.00217802	-0.1059372	4.02671314	0.00020508	0.00181084	37.8738217
TRVT*TCHT	-0.0030871	-0.0705045	-0.8364546	0.00001442	0.00023858	1.84489062
TRVT*SHT	-0.001237	-0.0018408	0.07271942	-0.0000281	-0.0002663	-5.0453402
TRVT*ARVT	0.00136595	-0.0483962	-0.0996591	0.00001166	0.00002993	1.50800843
TRVT*TRVT	-0.0194852	0.27704456	4.41973053	-0.0002056	-0.0024524	-17.434763
TCVT*SW	-0.0024686	-0.3399462	-3.5007639	-0.00012	-0.0004065	-23.973266
TCVT*TWR	0.00192139	0.03464799	-0.212434	0.00003077	-0.0000023	6.5661021
TCVT*AR	-0.0009215	-0.0048796	-2.1897364	-0.0000695	5.89E-08	-12.090352
TCVT*TR	0.00104822	-0.0347263	0.17345849	-0.0000141	-0.0000685	-2.7037041
TCVT*TOC(1)	-0.001455	0.02711007	0.12704193	0.00002409	0.00015774	4.50431604
TCVT*TOC(3)	-0.0022075	0.05037186	0.36770323	0.00002642	-0.0000142	5.06214489
TCVT*SWEEP	0.00010186	0.00927133	0.05554062	-2.00E-07	-0.0001719	-0.461305
TCVT*ARHT	0.00009869	0.0186649	0.09264585	0.00005421	0.00043315	8.99667649
TCVT*TRHT	-0.0019696	-0.0401845	0.02167957	-0.000013	-0.0000386	-4.1009817
TCVT*TCHT	0.00030864	-0.0202896	-0.1317133	0.00002921	0.00041813	3.82468315
TCVT*SHT	-0.0017968	-0.0374833	0.01880089	-0.0000236	-0.0002843	-4.0016397
TCVT*ARVT	0.00040784	0.05991312	0.25784745	0.00007419	0.00049633	13.5287001
TCVT*TRVT	0.00103786	0.00807665	-0.0159993	0.00003847	0.00012724	6.2126246
TCVT*TCVT	-0.0309837	-0.6272784	2.39491354	0.00038054	0.00581837	27.5409698
SVT*SW	-0.0312869	-2.4679978	-18.373509	-0.0004504	-0.0022554	-80.299806
SVT*TWR	0.00127955	0.23284892	-3.0546395	0.00005465	-0.0000388	18.4184126
SVT*AR	-0.0032861	-0.1792786	-13.485557	-0.000411	-0.0004847	-66.181362
SVT*TR	0.00045891	0.03903553	0.40673892	0.0000033	-0.0000976	2.6538266
SVT*TOC(1)	-0.0009503	-0.0373417	0.10259283	0.0000392	0.00004546	1.47759411
SVT*TOC(3)	0.00140102	0.04570036	0.74942673	0.00005616	0.0000159	9.972136
SVT*SWEEP	0.00063944	0.01604365	0.21219723	0.00002065	-0.0000591	2.49533772
SVT*ARHT	0.01370895	0.6711826	9.52545981	0.0001666	0.00021334	50.1754917
SVT*TRHT	0.00179148	-0.0473104	-0.0332518	-0.0000077	0.00005537	-2.5215161
SVT*TCHT	-0.0009533	0.0770702	0.31898325	0.00004489	0.00027827	8.2521529
SVT*SHT	-0.0009511	0.0385706	1.23942239	0.00000409	-0.0002711	1.27881037
SVT*ARVT	-0.0023529	0.01666475	0.78954671	-0.0000442	-0.0009446	-9.8685509
SVT*TRVT	0.01875149	0.91430869	2.58341052	0.00012906	0.00042714	58.618872
SVT*TCVT	0.00926559	0.357815	2.30397684	0.00028434	0.00192287	55.9515784
SVT*SVT	-0.0019914	-0.698212	16.8473957	0.00084347	0.00430099	87.6747873
AR*AR*AR	-0.20445	-8.1383006	-173.28656	0.00111993	0.01901085	-91.128512
SW*SW*SW	-0.2913469	-22.837598	-120.74185	0.00036511	-0.0068136	-69.055478

TWR*TWR*TWR	0.00595382	1.35553628	-89.951917	0.00132178	0.00331807	150.289983
TOC(1)*TOC(1)*TOC(1)	0.12279157	3.81080846	32.3748549	-0.0018387	-0.0173723	-217.04493
TOC(3)*TOC(3)*TOC(3)	-0.0580676	-1.7384432	-47.970304	0.00164728	0.0034832	169.345374
SW*SW*TOC(1)	0.02399041	0.53654446	86.9113269	-0.0037147	-0.0103139	-611.27671
SW*SW*TOC(3)	-0.069433	-5.0034338	-116.76722	0.00116743	0.00799597	117.415524
AR*AR*TOC(1)	-0.0319711	-0.3474449	-80.352989	0.00446676	0.01220242	723.234207
AR*AR*TOC(3)	0.11376511	6.30079857	144.455262	-0.0001283	-0.0053248	74.588656
AR*AR*SW	-0.0199852	-2.0327724	-146.70524	-0.0002986	0.00139375	79.3593282
SW*SW*AR	0.08799571	5.3936873	-76.700736	-0.0018933	-0.0166189	-82.38016

Coefficients of RSEs (cont)

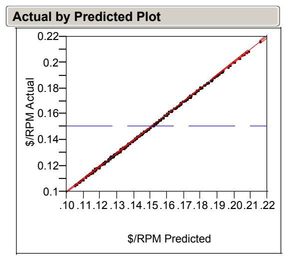
	ACQ	**RDTE**	**RPM**	**TAROC**	**DOC+I**	**WAWt**
Intercept	60.0965639	4789.50215	0.1343988	6.77923761	5.30438701	11.1967367
SW	0.93758556	70.9258103	0.00045289	0.03396877	0.02712051	-1.0393315
TWR	1.06751782	86.962112	0.00097097	0.0716317	0.06174044	0.17007814
AR	0.41762683	25.9487491	-0.000638	-0.0519486	-0.0433854	1.39904573
TR	0.25400714	19.5704904	0.00035478	0.02422511	0.01970814	0.34760647
TOC(1)	-0.2620023	-18.516066	-0.0000421	0.00274947	0.00179347	-0.6881722
TOC(3)	0.07738375	6.78535169	0.00023364	0.01915375	0.01564209	-0.0157377
SWEEP	-0.003858	-0.3730698	-0.000027	-0.0019011	-0.0016206	-0.0025831
ARHT	0.01072108	0.87238903	0.00002057	0.00210341	0.00175347	0.00341823
TRHT	0.06546465	4.07934383	0.00007454	0.00552717	0.00451774	0.01080095
TCHT	0.0306902	2.48559124	0.00008877	0.00580914	0.00475913	0.01190651
SHT	0.23251138	15.8461605	0.00038703	0.02743428	0.02252863	0.05098136
ARVT	0.00922253	0.74493472	0.00002584	0.00166712	0.00138101	0.00435255
TRVT	0.07009791	4.45120973	0.00009454	0.00623864	0.00516674	0.0112084
TCVT	0.02408555	1.95582918	0.0000599	0.00465551	0.00386339	0.00841214
SVT	0.22804291	15.7578716	0.0003969	0.02811988	0.02308495	0.05225423
SW*SW	0.04190074	4.24157626	0.00038909	0.02171281	0.01788506	0.11112342
TWR*SW	-0.0100848	-0.7200767	-0.0000612	-0.0027853	-0.0023034	-0.0150244
TWR*TWR	-0.0058443	-0.2202621	-0.0000622	-0.0007902	-0.0006652	0.00548202
AR*SW	0.17774619	14.3954777	0.00035838	0.02450294	0.02000682	-0.1151283
AR*TWR	-0.0076728	-0.7477548	0.00000238	-0.0016948	-0.0014459	0.01168214
AR*AR	0.14825962	12.2564395	0.00034954	0.02480542	0.02032343	0.08555033
TR*SW	0.01779568	1.51050945	0.0000115	0.00131578	0.00099383	-0.0397695
TR*TWR	0.00597507	0.53850932	-0.0000022	0.00061557	0.00047543	0.00381528
TR*AR	0.0616934	4.85149164	0.00006763	0.00442008	0.00355621	0.10024989
TR*TR	0.00119063	0.10541918	0.00004198	-0.0007267	-0.0002792	0.01048987
TOC(1)*SW	-0.0139531	-1.2165054	0.0000166	0.00058832	0.00053061	0.07070818
TOC(1)*TWR	0.0023984	0.18813071	0.00000944	0.00051628	0.00040169	-0.0035619
TOC(1)*AR	-0.1236874	-9.7887468	-0.0001585	-0.0109364	-0.0089092	-0.1810938
TOC(1)*TR	-0.0301026	-2.3998913	-0.0000386	-0.0027209	-0.0021944	-0.0428774
TOC(1)*TOC(1)	0.0852903	6.80133659	0.0001669	0.01248308	0.01006021	0.08194828
TOC(3)*SW	0.00761318	0.61945458	0.00002538	0.00192185	0.00153392	0.01990585
TOC(3)*TWR	0.00940865	0.81687449	0.00002376	0.00121831	0.00097435	0.00105062

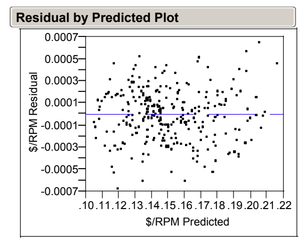
TOC(3)*AR	-0.036918	-2.9535211	-0.0000618	-0.0039008	-0.0031956	-0.0491943
TOC(3)*TR	-0.0087377	-0.6941326	-0.0000078	-0.0007919	-0.000625	-0.0111694
TOC(3)*TOC(1)	0.08760481	7.0118989	0.00020004	0.01432496	0.01173975	0.06203794
TOC(3)*TOC(3)	0.05440775	4.24003241	0.00009478	0.00681266	0.00553586	0.05258224
SWEEP*SW	-0.0301683	-2.4600254	-0.0000806	-0.0056366	-0.0046846	-0.0097067
SWEEP*TWR	0.00195324	0.14314882	0.00000406	0.00015788	0.00012567	0.00149378
SWEEP*AR	-0.0200177	-1.6275903	-0.000052	-0.0040915	-0.0033837	-0.0090655
SWEEP*TR	0.00142238	0.1185152	0.00000503	0.00036703	0.00027477	-0.0008931
SWEEP*TOC(1)	-0.0403142	-3.2772611	-0.0001184	-0.008232	-0.0067964	-0.0161018
SWEEP*TOC(3)	-0.0391747	-3.1883365	-0.0001169	-0.008103	-0.0066922	-0.0149891
SWEEP*SWEEP	0.02937146	2.23207506	0.00000616	0.00279259	0.00208281	0.04915213
ARHT*SW	-0.0015504	-0.1294127	-0.0000074	-0.0003462	-0.0002972	-0.0008411
ARHT*TWR	0.00162951	0.13585269	0.00000198	0.00025487	0.00017178	0.00077915
ARHT*AR	-0.0009911	-0.0783764	-0.0000016	-0.0001726	-0.0001297	-0.0003466
ARHT*TR	-0.0008754	-0.0712259	-0.0000039	-0.0001248	-0.0001199	-0.0004625
ARHT*TOC(1)	0.00096237	0.07750341	-0.0000078	0.00018207	0.00015557	0.00016406
ARHT*TOC(3)	0.00074274	0.0626772	0.00000341	0.00018738	0.00018375	-0.0003719
ARHT*SWEEP	-0.0013656	-0.1094557	-4.05E-07	-0.0001912	-0.0001645	-0.0008624
ARHT*ARHT	0.00084517	0.11295284	-0.0000682	0.00066682	0.00016008	-0.0068442
TRHT*SW	0.0003848	0.03705038	0.00000417	0.00002411	0.00003559	-0.0025042
TRHT*TWR	0.00055663	0.05266456	0.00000152	-0.0000409	-0.0000105	0.00033172
TRHT*AR	-0.0017332	-0.1467285	-0.0000018	-0.0004309	-0.0003335	0.00137406
TRHT*TR	-0.0052604	-0.434534	-0.0000161	-0.0007036	-0.0006361	0.0014821
TRHT*TOC(1)	-0.0021873	-0.1801419	-0.0000067	-0.0003307	-0.0002508	-0.0010355
TRHT*TOC(3)	-0.0015144	-0.1267509	-0.0000034	-0.0002345	-0.0001945	0.0000305
TRHT*SWEEP	0.00149453	0.11979955	-0.000003	0.00026559	0.00025297	0.00184636
TRHT*ARHT	-0.001078	-0.0877533	-0.0000015	-0.0002183	-0.0001778	-0.0003223
TRHT*TRHT	0.01226021	1.06456548	0.0000528	0.00314218	0.00305232	-0.0021599
TCHT*SW	-0.0025448	-0.1917998	-0.0000225	-0.0007337	-0.0005942	-0.0018653
TCHT*TWR	0.00844126	0.73922737	0.00000954	0.00084046	0.00067826	-0.0099041
TCHT*AR	-0.0015939	-0.1287206	-0.0000081	-0.0005191	-0.0004476	0.00025524
TCHT*TR	0.00522621	0.48741885	-0.0000139	0.00064385	0.00052645	-0.0006924
TCHT*TOC(1)	-0.0002792	-0.0231149	-0.0000032	-0.0000708	-0.0000403	-0.0004346
TCHT*TOC(3)	0.00082185	0.0670868	0.000007	0.00014636	0.00013353	0.00026202
TCHT*SWEEP	-0.0002659	-0.0218982	-0.0000015	-0.0000467	-0.0000455	0.00018532
TCHT*ARHT	0.00222552	0.18455011	0.0000096	0.00041097	0.00034774	0.00084378
TCHT*TRHT	0.0011604	0.08525371	6.16E-07	0.00009147	0.00004817	0.00057294
TCHT*TCHT	0.01173399	0.76259924	0.0000048	-0.002203	-0.0019209	0.04989257
SHT*SW	0.00013143	0.05041222	-0.0000119	-0.0008659	-0.0007828	-0.0075459
SHT*TWR	0.00859155	0.77776372	0.00000638	0.00082849	0.00068338	-0.0076275
SHT*AR	-0.0068423	-0.5629881	-0.0000322	-0.0021687	-0.0017501	0.00608278
SHT*TR	0.00253256	0.21020549	0.00001046	0.00029844	0.00026823	0.00308598
SHT*TOC(1)	-0.0038202	-0.3021729	-0.0000053	-0.000372	-0.0002855	-0.0042743
SHT*TOC(3)	-0.0012462	-0.0911183	5.82E-07	-0.0000263	0.00001535	-0.0002592
SHT*SWEEP	0.00165255	0.13457467	0.00000708	0.00033107	0.00032164	0.00008837
SHT*ARHT	0.00301079	0.25208159	0.00000668	0.00070492	0.00057172	-0.0003802
SHT*TRHT	0.01695563	1.1186726	0.00001718	0.00155776	0.00128503	0.00280373
SHT*TCHT	0.00613338	0.4986718	0.00002226	0.00112495	0.00088899	0.00401158

SHT*SHT	0.04675723	3.51229485	0.00001924	0.0010851	0.00105345	0.09872865
ARVT*SW	-0.0015843	-0.1311684	-0.0000063	-0.0003262	-0.0002278	-0.0010133
ARVT*TWR	0.00097302	0.08112049	0.00000466	0.0001614	0.00014685	0.0001524
ARVT*AR	0.0010593	0.0820442	-2.25E-07	0.00002222	-0.0000445	0.00162337
ARVT*TR	-0.0000439	-0.0109263	-0.0000021	-0.0001197	-0.000074	0.00066703
ARVT*TOC(1)	0.00058835	0.04625455	0.00000402	0.00009909	0.00005616	0.00033311
ARVT*TOC(3)	0.00111471	0.09101306	0.00000357	0.0001663	0.00014813	0.0004973
ARVT*SWEEP	-0.0009653	-0.075841	-0.0000047	-0.0001553	-0.0001129	-0.0007315
ARVT*ARHT	-0.000676	-0.0657653	0.00000522	-0.0000033	-0.0000011	-0.0004977
ARVT*TRHT	-0.0004387	-0.0376607	0.00000285	-0.0001112	-0.0000519	0.00033221
ARVT*TCHT	0.00080612	0.06614821	0.00000222	0.00017929	0.00014583	-0.000024
ARVT*SHT	-0.0001976	-0.0170585	0.0000055	-0.0000815	-0.0000489	0.0000778
ARVT*ARVT	-0.020048	-1.5209018	-0.0000848	-0.0024988	-0.0018719	-0.0193204
TRVT*SW	-0.0025187	-0.2031844	-0.000007	-0.0004818	-0.0003928	-0.0023343
TRVT*TWR	0.00229425	0.19643128	0.00000293	0.00026461	0.00021773	0.00122237
TRVT*AR	0.00124747	0.10382216	0.00000459	0.00005069	0.00007164	0.00097862
TRVT*TR	-0.003763	-0.3063025	-0.0000137	-0.0010162	-0.0008392	-0.0036035
TRVT*TOC(1)	0.0009068	0.07517366	-8.43E-07	0.00025142	0.00018281	-0.0009963
TRVT*TOC(3)	0.00143486	0.11675602	0.00000587	0.0002507	0.0002391	-0.0003054
TRVT*SWEEP	-0.0098674	-0.8171206	-0.0000161	-0.0009086	-0.0007153	-0.0136562
TRVT*ARHT	0.00045654	0.03850061	-0.000003	0.00006792	0.00007096	0.00026172
TRVT*TRHT	0.0062878	0.54887975	0.00000423	0.00121722	0.00096873	-0.0016244
TRVT*TCHT	0.00014728	0.01456713	0.00000365	0.00006866	0.00004474	-0.0004003
TRVT*SHT	-0.0013606	-0.0654404	-0.0000051	-0.000226	-0.0001639	-0.0001807
TRVT*ARVT	0.00051351	0.0414507	-0.0000021	0.00006866	0.00004673	0.00037808
TRVT*TRVT	0.0008265	0.05590944	-0.0000095	-0.0004283	-0.0004506	0.0085234
TCVT*SW	-0.003732	-0.2953328	-0.0000064	-0.0006733	-0.0005624	-0.0031796
TCVT*TWR	0.00146285	0.13059476	0.0000099	0.00019889	0.0001663	0.00047878
TCVT*AR	-0.0011191	-0.0905771	-0.0000077	-0.0003182	-0.0002784	0.00066799
TCVT*TR	-0.0007688	-0.0602604	4.87E-07	-0.0000839	-0.0000963	-0.0003482
TCVT*TOC(1)	0.00064606	0.04939262	5.50E-07	0.00014294	0.00008183	-0.0002441
TCVT*TOC(3)	0.0008018	0.06816475	-3.68E-07	0.00015388	0.00010048	0.00034593
TCVT*SWEEP	-0.000341	-0.0275562	0.00000295	-0.0000026	-0.0000544	-0.0002169
TCVT*ARHT	0.00147332	0.1235611	0.00000432	0.00030005	0.00028258	0.00054542
TCVT*TRHT	-0.0010073	-0.0825546	-6.66E-07	-0.0001458	-0.0001013	-0.0007412
TCVT*TCHT	0.00071481	0.05255667	-0.0000016	0.00015547	0.00013749	0.00002648
TCVT*SHT	-0.0006193	-0.0510864	0.00000603	-0.0001383	-0.0000651	0.00004485
TCVT*ARVT	0.00204977	0.16705744	0.00000241	0.00038021	0.00033168	0.0005773
TCVT*TRVT	0.0007779	0.06480622	-5.25E-07	0.00020351	0.00014414	-0.0002135
TCVT*TCVT	-0.0048809	-0.3442899	0.00002151	0.0011186	0.00078633	-0.0186773
SVT*SW	-0.0104194	-0.8258352	-0.0000411	-0.0023085	-0.0019082	-0.0113901
SVT*TWR	0.00585239	0.52772343	0.0000048	0.00058933	0.00049727	0.00127566
SVT*AR	-0.0050024	-0.4144305	-0.0000205	-0.0018228	-0.0014717	0.00627865
SVT*TR	0.00085808	0.07495617	0.00000624	0.00008542	0.00007539	0.00202522
SVT*TOC(1)	-0.0010307	-0.0844829	-0.0000021	0.00009149	0.00002678	-0.0033454
SVT*TOC(3)	0.00126259	0.10600846	0.00001717	0.00026402	0.00023777	0.00014046
SVT*SWEEP	-0.0001409	-0.0087917	-0.0000028	0.00006838	0.00007408	-0.000699
SVT*ARHT	0.00749168	0.61166022	0.00001082	0.00117725	0.00092492	0.00153958

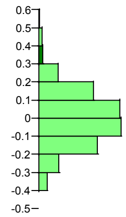
SVT*TRHT	-0.0013643	-0.0645473	-0.0000042	-0.0000999	-0.0000786	-0.0010055
SVT*TCHT	0.00106146	0.08965939	0.00001077	0.00022269	0.00020221	-0.0000256
SVT*SHT	-0.0011671	0.01896414	0.00000335	-0.0000241	-0.0000343	0.00026989
SVT*ARVT	-0.0025303	-0.2152698	-0.0000058	-0.0003567	-0.0002402	0.00050808
SVT*TRVT	0.01947124	1.27298612	0.00002457	0.0018807	0.0014792	0.00248219
SVT*TCVT	0.00825302	0.66974972	0.00002265	0.0016052	0.0013543	0.00274788
SVT*SVT	-0.0147083	-0.9050687	0.00000546	0.00221504	0.00164747	-0.04831
AR*AR*AR	-0.1038088	-7.4538871	-0.0001468	-0.0032578	-0.0036817	-0.2784932
SW*SW*SW	-0.0299695	-1.9725688	0.00015929	-0.0018142	-0.0018623	-0.1322368
TWR*TWR*TWR	-0.0135358	-0.6118202	0.0001201	0.0035483	0.00299844	-0.0882802
TOC(1)*TOC(1)*TOC(1)	0.00551668	-0.1697659	0.00005481	-0.0065345	-0.0038576	0.13221135
TOC(3)*TOC(3)*TOC(3)	-0.040835	-2.9937447	0.00004426	0.00286427	0.00261727	-0.138714
SW*SW*TOC(1)	-0.051414	-4.4549642	-0.0002055	-0.0162208	-0.0140626	0.09485636
SW*SW*TOC(3)	0.00850124	0.93860571	0.00008147	0.00474991	0.00350146	-0.0796386
AR*AR*TOC(1)	0.05609682	4.81530555	0.0001673	0.01945541	0.01617195	-0.127422
AR*AR*TOC(3)	0.02016631	1.34048246	0.00001906	0.00079189	0.00101211	0.09474873
AR*AR*SW	0.03532513	2.61708798	-0.0000855	0.00222724	0.00216052	0.0141944
SW*SW*AR	0.07069982	5.14788448	0.00001761	-0.001478	-0.0010909	0.24224862

APPENDIX D – RSE GOODNESS OF FIT FOR ECONOMIC METRICS





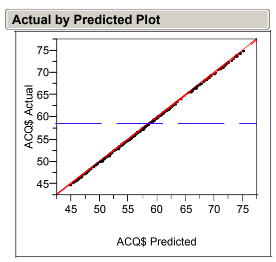
Error Distribution

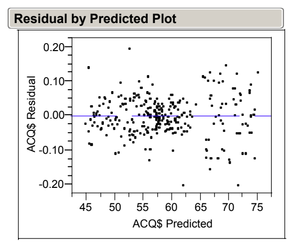


Std. Dev.= 0.157

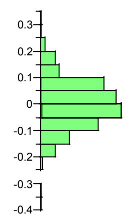
$R^2 = 0.9996$

Figure D1: Measures of "Goodness" for $/RPM Response Surface Equation





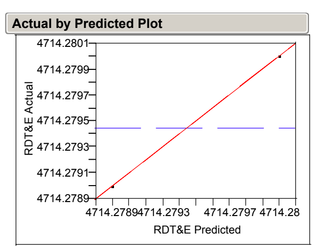
Error Distribution

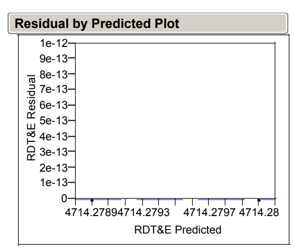


Std. Dev. = 0.094

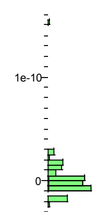
$R^2 = 0.9999$

Figure D2: Measures of "Goodness" for Acquisition Price Response Surface Equation





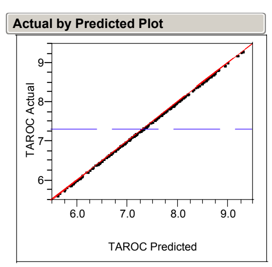
Error Distribution

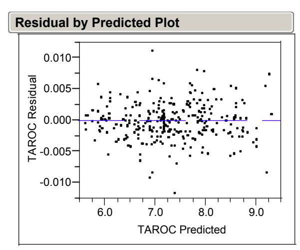


Std. Dev. = 1.45e-11

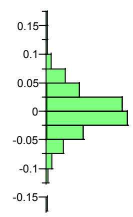
$R^2 = 1$

Figure D3: Measures of "Goodness" for RDT&E Response Surface Equation





Error Distribution



Std. Dev. = 0.04

$R^2 = 0.9999$

Figure D4: Measures of "Goodness" for TAROC Response Surface Equation

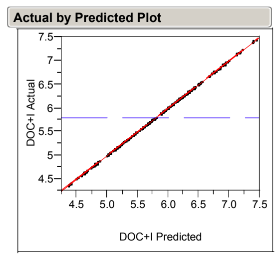
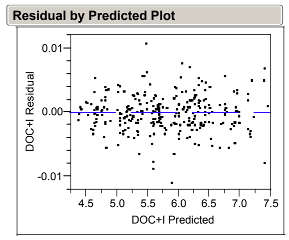
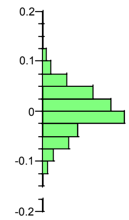
		**Error Distribution**  Std. Dev. = 0.048	$R^2 = 0.9999$

Figure D5: Measures of "Goodness" for DOC+I Response Surface Equation

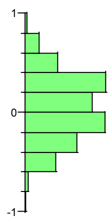
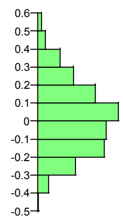
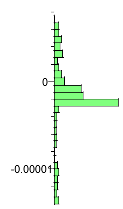
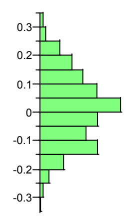
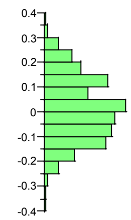
$/RPM Error Distribution	**Acq. Price Error Distribution**	**RDT&E Error Distribution**	**TAROC Error Distribution**	**DOC+I Error Distribution**
				
Std. Dev. = 0.325	Std. Dev. = 0.194	Std. Dev. = 4.4 e-6	Std. Dev. = 1.22	Std. Dev. = 0.131

Figure D6: Error Distributions for Random Economic Data

APPENDIX E – ECONOMIC RSE COEFFICIENTS

	$/RPM	ACQ$	RDT&E	TAROC	DOC+I
Intercept	0.145059	57.3321	4714.279	7.168109	5.686433
Util	-0.00388	-0.00262	-1.13E-11	-0.23481	-0.21939
Prod #	-0.00407	-5.75218	0.0005	-0.25219	-0.23561
CLF	-0.01908	0.003872	7.05E-15	0.028899	0.000186
FLF	-0.00175	0.001818	7.05E-15	0.002574	8.53E-05
ROIA	0.00686	-0.00792	-4.94E-14	-0.00032	-0.00034
ROIM	0.003381	4.734434	-7.05E-15	0.221399	0.206853
Fuel Cost	0.010255	0.00264	0	0.673128	0.628891
Learn1	0.001603	2.288767	0	0.096085	0.089795
Learn2	0.0003	0.457403	7.05E-15	0.01857	0.017399
LearnA1	0.000206	0.28357	7.05E-15	0.011872	0.011097
LearnA2	2.17E-05	0.057798	0	0.00238	0.002248
LearnAS1	0.000164	0.23069	0	0.009729	0.009058
LearnAS2	4.21E-05	0.042101	0	0.001733	0.001581
LearnFE1	0.000747	1.061748	0	0.044593	0.041636
LearnFE2	0.000158	0.215109	0	0.008771	0.008225
SL	-0.00765	-0.00188	0	-0.36465	-0.16781
Util*Util	0.000403	0.011263	-3.70E-12	0.023921	0.022586
Prod #*Util	0.000367	-0.00322	7.11E-15	0.02277	0.021289
Prod #*Prod #	0.000738	1.200763	0.0005	0.051421	0.048586
CLF*Util	0.000654	-0.00138	7.11E-15	-6.6E-05	-8.6E-05
CLF*Prod #	0.000683	-0.00182	-2.20E-13	-7.4E-05	-8.6E-05
CLF*CLF	0.003203	0.011263	-3.70E-12	0.000421	0.000586
FLF*Util	3.8E-05	-0.00356	7.11E-15	-0.00021	-0.00017
FLF*Prod #	8.02E-05	-0.00172	-1.07E-13	-0.00012	-7.8E-05
FLF*CLF	0.000569	-0.00144	-1.07E-13	-0.00032	-0.0003
FLF*FLF	-5.2E-05	0.011263	-3.70E-12	0.000421	0.000586
ROIA*Util	-0.00062	-0.00542	7.11E-15	-0.00018	-0.0002
ROIA*Prod #	-0.00052	0.00773	-4.97E-14	0.000324	0.00032
ROIA*CLF	-0.00099	-0.00122	7.11E-15	-2.7E-05	-5.5E-05
ROIA*FLF	-8.6E-05	0.004566	7.11E-15	0.000191	0.000156
ROIA*ROIA	0.000173	0.011263	-3.70E-12	0.000921	0.000586
ROIM*Util	-0.00028	-0.00548	-7.11E-15	-0.01912	-0.01788
ROIM*Prod #	-0.00055	-0.82261	-7.11E-15	-0.03716	-0.03468
ROIM*CLF	-0.00056	0.003184	7.11E-15	0.000145	0.000117
ROIM*FLF	-4.5E-05	0.004926	7.11E-15	0.000238	0.000219
ROIM*ROIA	0.000266	-0.0064	7.11E-15	-0.00022	-0.0002
ROIM*ROIM	-0.00013	0.016763	-3.70E-12	0.000921	0.000586
Fuel Cost*Util	-5.3E-06	-0.00931	0	-0.00048	-0.00043
Fuel Cost*Prod #	-1.5E-05	-0.00654	0	-0.0003	-0.00029
Fuel Cost*CLF	-0.00173	0.006387	0	0.000254	0.000289
Fuel Cost*FLF	-0.00018	0.001957	0	0.000129	0.000109
Fuel Cost*ROIA	-1.1E-05	0.000348	0	2.73E-05	7.81E-06

Fuel Cost*ROIM	7.23E-06	0.00152	0	7.42E-05	8.59E-05
Fuel Cost*Fuel Cost	5.29E-05	0.011263	-3.70E-12	0.000921	0.000586
Learn1*Util	-0.00015	-0.01645	0	-0.00993	-0.00924
Learn1*Prod #	-6.9E-05	-0.12354	0	-0.00504	-0.00471
Learn1*CLF	-0.00029	-0.00155	0	-5.1E-05	-2.3E-05
Learn1*FLF	-2.4E-05	0.000926	0	7.42E-05	9.38E-05
Learn1*ROIA	0.000253	-0.00242	0	-0.00011	-0.00012
Learn1*ROIM	3.75E-05	0.073051	0	0.002566	0.002398
Learn1*Fuel Cost	-6.8E-06	0.008098	0	0.000363	0.000336
Learn1*Learn1	9.79E-05	0.158763	-3.70E-12	0.006421	0.006086
Learn2*Util	-5.4E-05	0.005332	7.11E-15	-0.00157	-0.00149
Learn2*Prod #	2.79E-05	0.067465	7.11E-15	0.002887	0.002664
Learn2*CLF	-7.1E-05	-0.00308	7.11E-15	-0.00014	-0.00015
Learn2*FLF	-7.2E-05	0.002488	7.11E-15	0.000129	0.000109
Learn2*ROIA	3.77E-05	0.008426	7.11E-15	0.000402	0.000367
Learn2*ROIM	-3.2E-05	-0.01103	-7.11E-15	-0.00074	-0.00071
Learn2*Fuel Cost	-1.17E-07	0.002316	0	8.98E-05	0.000117
Learn2*Learn1	4.04E-05	0.084957	0	0.003488	0.003258
Learn2*Learn2	5.29E-05	0.020763	-3.70E-12	0.000921	0.001086
LearnA1*Util	-2E-05	0.006574	7.11E-15	-0.00081	-0.00075
LearnA1*Prod #	-1.2E-05	-0.01661	7.11E-15	-0.00068	-0.00059
LearnA1*CLF	-1.7E-05	0.002988	-7.11E-15	0.00016	0.000156
LearnA1*FLF	-1.8E-05	0.000715	-7.11E-15	1.95E-05	7.03E-05
LearnA1*ROIA	7.76E-05	0.000387	-7.11E-15	0.003277	0.003063
LearnA1*ROIM	4.83E-05	0.011574	7.11E-15	0.000418	0.000375
LearnA1*Fuel Cost	-1.4E-05	0.006199	0	0.000293	0.000281
LearnA1*Learn1	1.86E-05	-0.00189	0	-5.9E-05	-3.1E-05
LearnA1*Learn2	-7.8E-06	0.001543	7.11E-15	0.000121	9.38E-05
LearnA1*LearnA1	2.87E-06	-0.02674	-3.70E-12	-0.00108	-0.00091
LearnA2*Util	-1.6E-05	-0.00808	0	-0.00061	-0.00056
LearnA2*Prod #	2.63E-05	0.010723	0	0.000457	0.000422
LearnA2*CLF	-6.6E-06	9.77E-05	0	1.17E-05	4.69E-05
LearnA2*FLF	-7.5E-06	-0.00838	0	-0.00038	-0.00035
LearnA2*ROIA	-2.3E-05	0.007762	0	0.000379	0.000313
LearnA2*ROIM	-6.8E-06	-3.5E-05	0	-1.2E-05	-3.1E-05
LearnA2*Fuel Cost	1.97E-05	0.012762	0	0.001098	0.001016
LearnA2*Learn1	9.41E-06	0.001184	0	0.000105	4.69E-05
LearnA2*Learn2	-7.1E-06	-0.00135	0	-7.4E-05	-9.4E-05
LearnA2*LearnA1	2.11E-05	0.013926	0	0.000582	0.000523
LearnA2*LearnA2	5.29E-05	0.012763	-3.70E-12	0.000421	0.000586
LearnAS1*Util	-3.3E-05	-0.00185	0	-0.00102	-0.00093
LearnAS1*Prod #	-3.4E-05	-0.0107	0	-0.00043	-0.00037
LearnAS1*CLF	-4.2E-05	-0.00039	0	-3.5E-05	-5.5E-05
LearnAS1*FLF	4.73E-06	-0.005	0	-0.00011	-9.4E-05
LearnAS1*ROIA	8.74E-05	-0.00114	0	-0.00011	-3.9E-05
LearnAS1*ROIM	1.73E-05	0.008012	0	0.000316	0.000305
LearnAS1*Fuel Cost	1.32E-05	-0.00169	-4.97E-14	-2.7E-05	-7E-05
LearnAS1*Learn1	-3.2E-06	-0.00158	0	-8.2E-05	-0.0001

LearnAS1*Learn2	5.12E-06	0.001934	0	9.77E-05	0.000117
LearnAS1*LearnA1	-2.6E-06	-0.00354	0	-0.00015	-0.00016
LearnAS1*LearnA2	-4.6E-06	0.011645	0	0.000543	0.000469
LearnAS1*LearnAS1	5.29E-05	0.034763	-3.70E-12	0.001421	0.001086
LearnAS2*Util	-6.9E-06	-0.00754	0	-0.0005	-0.00047
LearnAS2*Prod #	-1.8E-05	0.009723	0	0.000387	0.000375
LearnAS2*CLF	2.23E-06	-0.00507	0	-0.00025	-0.00022
LearnAS2*FLF	1.94E-05	-0.00332	0	-0.00017	-0.00015
LearnAS2*ROIA	2.05E-05	0.000371	0	7.42E-05	4.69E-05
LearnAS2*ROIM	6.52E-06	0.008074	0	0.00034	0.000297
LearnAS2*Fuel Cost	-3.6E-06	0.010543	0	0.00048	0.000469
LearnAS2*Learn1	-1.6E-05	-0.00632	-7.11E-15	-0.00029	-0.00027
LearnAS2*Learn2	-1.2E-05	-0.01716	0	-0.00072	-0.00066
LearnAS2*LearnA1	1.07E-05	0.007348	0	0.000277	0.000273
LearnAS2*LearnA2	-2.2E-05	0.000613	0	3.52E-05	3.91E-05
LearnAS2*LearnAS1	2.48E-05	0.007051	0	0.000238	0.000234
LearnAS2*LearnAS2	5.29E-05	0.011763	-3.70E-12	0.000921	0.000586
LearnFE1*Util	-8.4E-05	-0.00689	0	-0.00456	-0.00426
LearnFE1*Prod #	-7.2E-05	-0.05468	0	-0.00224	-0.00209
LearnFE1*CLF	-0.00012	-0.00541	0	-0.0002	-0.00023
LearnFE1*FLF	-9E-06	0.006723	0	0.000254	0.000234
LearnFE1*ROIA	0.000122	-0.0024	0	-0.00013	-0.00013
LearnFE1*ROIM	1.9E-05	0.028941	0	0.001012	0.000898
LearnFE1*Fuel Cost	-1.2E-05	0.008723	0	0.000387	0.000352
LearnFE1*Learn1	4.87E-05	-0.00267	-7.11E-15	-7.4E-05	-3.9E-05
LearnFE1*Learn2	7.77E-06	0.000145	0	8.98E-05	7.03E-05
LearnFE1*LearnA1	3.1E-05	-0.0028	0	-0.00013	-0.00011
LearnFE1*LearnA2	3.63E-06	-0.00158	0	-9E-05	-6.3E-05
LearnFE1*LearnAS1	-8.8E-06	-0.00071	0	-2.7E-05	-2.3E-05
LearnFE1*LearnAS2	-2.5E-05	-0.00025	7.11E-15	1.17E-05	-6.25E-17
LearnFE1*LearnFE1	5.29E-05	0.044263	-3.70E-12	0.001921	0.001586
LearnFE2*Util	-4.9E-05	-0.00154	0	-0.00091	-0.00085
LearnFE2*Prod #	2.56E-05	0.030574	0	0.001285	0.001195
LearnFE2*CLF	-4E-05	0.006652	0	0.000309	0.00032
LearnFE2*FLF	-7.5E-06	-0.00446	0	-0.00016	-0.00013
LearnFE2*ROIA	4.07E-05	0.007582	0	0.000348	0.00032
LearnFE2*ROIM	6.68E-06	-0.00467	0	-0.00031	-0.00032
LearnFE2*Fuel Cost	-1.3E-05	-0.00604	7.11E-15	-0.00032	-0.00027
LearnFE2*Learn1	-1.7E-05	-0.00065	0	-2E-05	-2.3E-05
LearnFE2*Learn2	-6.6E-06	-0.00256	0	-9E-05	-8.6E-05
LearnFE2*LearnA1	-6.5E-06	0.001371	0	9.77E-05	3.13E-05
LearnFE2*LearnA2	2.16E-05	-0.00119	0	-5.1E-05	-4.7E-05
LearnFE2*LearnAS1	4.31E-05	-0.00607	-7.11E-15	-0.00027	-0.00026
LearnFE2*LearnAS2	1.45E-05	0.005465	0	0.000301	0.000266
LearnFE2*LearnFE1	3.87E-06	0.03852	0	0.001582	0.001477
LearnFE2*LearnFE2	5.79E-05	0.016763	-3.70E-12	0.000921	0.000586
SL*Util	4.9E-05	-0.00877	0	0.002668	0.002477
SL*Prod #	7.63E-05	0.003363	0	0.005535	0.00518

SL*CLF	0.000943	0.001207	0	-0.0016	2.34E-05
SL*FLF	7.06E-05	0.006918	0	0.000199	0.000266
SL*ROIA	-8.4E-05	-0.00308	0	-0.00015	-0.00018
SL*ROIM	-7.9E-05	5.86E-05	0	-0.00514	-0.00485
SL*Fuel Cost	1.5E-05	0.011309	0	0.000551	0.000477
SL*Learn1	-3E-05	-0.00107	0	-0.00193	-0.00177
SL*Learn2	-2.2E-05	-0.00402	0	-0.00059	-0.00052
SL*LearnA1	-2.1E-05	-0.00721	0	-0.00056	-0.00056
SL*LearnA2	7.4E-05	0.001223	7.11E-15	2.73E-05	1.56E-05
SL*LearnAS1	6.6E-06	-0.00662	0	-0.0005	-0.00045
SL*LearnAS2	-3.8E-05	-0.00148	0	-0.00015	-0.00013
SL*LearnFE1	-3.7E-05	-0.00061	0	-0.0009	-0.00084
SL*LearnFE2	-1.3E-05	-0.00329	0	-0.0003	-0.00029
SL*SL	0.001513	0.011263	-3.70E-12	0.072921	0.033586

APPENDIX F – TECHNOLOGY IMPACT MATRICES

Table FI: Technology Compatibility for 2006

	T1	T2	T3	T4	T5
TRL=9 Date	2000	2006	2006	2006	2006
T1		1	1	1	1
T2			1	1	1
T3				1	1
T4					1
T5					

Table FII: Technology Compatibility for 2008

	T1	T2	T3	T4	T5	T6	T7
TRL=9 Date	2000	2006	2006	2006	2006	2007	2007
T1		1	1	1	1	1	1
T2			1	1	1	1	1
T3				1	1	1	1
T4					1	1	1
T5						1	1
T6							1
T7							

Table FIII: Technology Compatibility for 2009

	T1	T2	T3	T4	T5	T6	T7	T8	T9	T10	T11
TRL=9 Date	2000	2006	2006	2006	2006	2007	2007	2009	2009	2009	2009
T1		1	1	1	1	1	1	1	1	1	1
T2			1	1	1	1	1	1	1	1	1
T3				1	1	1	1	0	1	1	1
T4					1	1	1	1	1	1	1
T5						1	1	1	0	1	1
T6							1	1	1	1	1
T7								1	1	1	1
T8									1	1	1
T9										1	1
T10											1
T11											

Table FIV: Technology Compatibility for 2010

	T1	T2	T3	T4	T5	T6	T7	T8	T9	T10	T11	T12	T13	T14	T15
TRL=9 Date	2000	2006	2006	2006	2006	2007	2007	2009	2009	2009	2009	2010	2010	2010	2010
T1		1	1	1	1	1	1	1	1	1	1	1	1	1	1
T2			1	1	1	1	1	1	1	1	1	0	1	1	1
T3				1	1	1	1	0	1	1	1	1	0	1	1
T4					1	1	1	1	1	1	1	1	1	0	1
T5						1	1	1	0	1	1	1	1	1	0
T6							1	1	1	1	1	1	1	1	1
T7								1	1	1	1	1	1	1	1
T8									1	1	1	1	0	1	1
T9										1	1	1	1	1	0
T10											1	1	1	1	1
T11												1	1	1	1
T12													1	1	1
T13														1	1
T14															1
T15															

Table FV: Technology Compatibility for 2011 & 2012

	T1	T2	T3	T4	T5	T6	T7	T8	T9	T10	T11	T12	T13	T14	T15	T16	T17	T18	T19	T20
TRL=9 Date	2000	2006	2006	2006	2006	2007	2007	2009	2009	2009	2009	2010	2010	2010	2010	2011	2011	2011	2011	2011
T1		1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
T2			1	1	1	1	1	1	1	1	1	0	1	1	1	1	0	1	1	1
T3				1	1	1	1	0	1	1	1	1	0	1	1	1	1	1	1	1
T4					1	1	1	1	1	1	1	1	1	0	1	1	1	0	1	1
T5						1	1	1	0	1	1	1	1	1	0	1	1	1	1	1
T6							1	1	1	1	1	1	1	1	1	1	1	1	1	1
T7								1	1	1	1	1	1	1	1	1	1	1	1	1
T8									1	1	1	1	0	1	1	1	1	1	1	1
T9										1	1	1	1	1	0	1	1	1	1	1
T10											1	1	1	1	1	1	1	1	1	1
T11												1	1	1	1	1	1	1	1	1
T12													1	1	1	1	0	1	1	1
T13														1	1	1	1	1	1	1
T14															1	1	1	0	1	1
T15																1	1	1	1	1
T16																	1	1	0	1
T17																		1	1	1
T18																			1	1
T19																				1
T20																				

Table FVI: Technology Compatibility for 2013

	T1	T2	T3	T4	T5	T6	T7	T8	T9	T10	T11	T12	T13	T14	T15	T16	T17	T18	T19	T20	T21	T22	T23	T24	T25	T26	T27	T28
TRL=9 Date	2000	2006	2006	2006	2006	2007	2007	2009	2009	2009	2009	2010	2010	2010	2010	2011	2011	2011	2011	2011	2013	2013	2013	2013	2013	2013	2013	2013
T1		1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
T2			1	1	1	1	1	1	1	1	1	0	1	1	1	1	0	1	1	1	1	1	1	1	1	1	1	1
T3				1	1	1	1	0	1	1	1	1	0	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1
T4					1	1	1	1	1	1	1	1	1	0	1	1	1	0	1	1	1	1	1	1	1	1	1	1
T5						1	1	1	0	1	1	1	1	1	0	1	1	1	1	1	1	1	1	0	1	1	1	1
T6							1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
T7								1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
T8									1	1	1	1	0	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1
T9										1	1	1	1	1	0	1	1	1	1	1	1	1	1	0	1	1	1	1
T10											1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
T11												1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
T12													1	1	1	1	0	1	1	1	1	1	1	1	1	1	1	1
T13														1	1	1	1	1	1	1	1	1	0	1	1	1	1	1
T14															1	1	1	0	1	1	1	1	1	1	1	1	1	1
T15																1	1	1	1	1	1	1	1	0	1	1	1	1
T16																	1	1	0	1	1	1	1	1	0	1	1	1
T17																		1	1	1	1	1	1	1	1	1	1	1
T18																			1	1	1	1	1	1	1	1	1	1
T19																				1	1	1	1	1	0	1	1	1
T20																					1	1	1	1	1	1	1	1
T21																						1	1	1	1	1	1	1
T22																							1	1	1	1	1	1
T23																								1	1	1	1	1
T24																									1	1	1	1
T25																										1	1	1
T26																											1	1
T27																												1
T28																												

Table FVII: Technology Compatibility Matrix for 2014

	T1	T2	T3	T4	T5	T6	T7	T8	T9	T10	T11	T12	T13	T14	T15	T16	T17	T18	T19	T20	T21	T22	T23	T24	T25	T26	T27	T28	T29	T30
TRL=9 Date	2000	2006	2006	2006	2006	2007	2007	2009	2009	2009	2009	2010	2010	2010	2010	2011	2011	2011	2011	2011	2013	2013	2013	2013	2013	2013	2013	2013	2014	2014
T1		1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
T2			1	1	1	1	1	1	1	1	1	0	1	1	1	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1
T3				1	1	1	1	0	1	1	1	1	0	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1	1
T4					1	1	1	1	1	1	1	1	1	0	1	1	1	0	1	1	1	1	1	1	1	1	1	1	1	1
T5						1	1	1	0	1	1	1	1	1	0	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1
T6							1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
T7								1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
T8									1	1	1	1	0	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1	1
T9										1	1	1	1	1	0	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1
T10											1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
T11												1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
T12													1	1	1	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1
T13														1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1	1
T14															1	1	1	0	1	1	1	1	1	1	1	1	1	1	1	1
T15																1	1	1	1	1	1	1	1	0	1	1	1	1	1	1
T16																	1	1	0	1	1	1	1	1	0	1	1	1	1	1
T17																		1	1	1	1	1	1	1	1	1	1	1	1	1
T18																			1	1	1	1	1	1	1	1	1	1	1	1
T19																				1	1	1	1	1	0	1	1	1	1	1
T20																					1	1	1	1	1	1	1	1	1	1
T21																						1	1	1	1	1	1	1	1	1
T22																							1	1	1	1	1	1	1	1
T23																								1	1	1	1	1	1	1
T24																									1	1	1	1	1	1
T25																										1	1	1	1	1
T26																											1	1	1	1
T27																												1	1	1
T28																													1	1
T29																														1
T30																														

APPENDIX G – ORIGINAL TECHNOLOGY IMPACT MATRIX

	T1	T2	T3	T4	T5	T6	T7	T8	T9	T10	T11	T12	T13	T14	T15	T16	T17	T18	T19	T20	T21	T22	T23	T24	T25	T26	T27	T28	T29	T30	T31	T32	T33	T34	T35	T36
Technology Impact																																				
Wing Weight (skin or structure)				-0.03	-0.03				-0.2					-0.02	-0.08			-0.03						-0.15				-0.05					-0.35			-0.3
Fuselage Weight (skin or structure)																-0.12			-0.07		-0.11				-0.1						-0.25			-0.21		
HT Weight (skin or structure)		-0.03	-0.13					-0.2				-0.02	-0.08				-0.03						-0.15				-0.05					-0.35			-0.3	
VT Weight (skin or structure)		-0.03	-0.13					-0.2				-0.02	-0.08				-0.03						-0.15				-0.05					-0.35			-0.3	
Cdi	-0.04										-0.01																		-0.01	-0.091						
Cdo						-0.02					-0.01																			-0.091						
Landing Gear Weight																						-0.21							-0.45							
avionics weight																																				
hydraulics weight																										-0.5										
furnishings and equipment weight							-0.02																													
VT area																														-0.15						
HT area																														-0.15						
Engine Weight										0.05										0.05																
Fuel Consumption*																				-0.17																
RDT&E costs*																																				
O&S costs*																																				
Production costs*																																				
Utilization*																																				
Wing Area*																																				
Thrust-to-weight ratio*																																				
* Extra Impact Factors	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36

APPENDIX H – DISCUSSION OF TECHNOLOGY IMPACT ON DESIGN

Impact ID	Technology Impact	Affecting Technology	Degradation or Improvement (%)	Discussion
FRWI	Wing Weight (skin or structure)	T4	-3%	The use of the composite materials, which have lower weight than the current aluminum alloy, will reduce the weight.
		T5	-13%	
		T9	-20%	The reduction in the composite manufacturing cost will enable a more extensive use of composites material, which corresponds to lighter structure.
		T14	-2%	The use of new alloy technology, which is anticipated to have lower density than the current aluminum alloy, will reduce the weight.
		T15	-8%	
		T18	-3%	The superplastic forming process will stretch the superplastic alloys into thin and lighter shapes, thus reducing the weight.
		T24	-15%	The use of new metallic materials, which is anticipated to have lower density than the current aluminum alloy, will reduce the weight.
		T28	-5%	The use of active load alleviation system will enable the materials to have a lower fatigue life characteristics, which enable the structure to be manufactured lighter.
		T33	-30%	The use of biologically inspired material, which is anticipated to have much lower density than the current aluminum alloy, will reduce the weight.
		T36	-30%	The use of BIOSANT material, which is anticipated to have much lower density than the current aluminum alloy, will reduce the weight.
FRFU	Fuselage Weight (skin or structure)	T16	-7%	The superplastic forming process will stretch the superplastic alloys into thin and lighter shapes, thus reducing the weight.
		T19	-7%	The use of the Al-Li alloy materials, which have lower weight than the current aluminum allow, will reduce the weight.
		T21	-11%	The use of new metallic materials, which is anticipated to have lower density than the current aluminum alloy, will reduce the weight.
		T25	-7%	The use of the composite materials, which have lower weight than the current aluminum alloy, will reduce the weight.
		T31	-18%	The use of biologically inspired material, which is anticipated to have much lower density than the current aluminum alloy, will reduce the weight.
		T34	-18%	The use of BIOSANT material, which is anticipated to have much lower density than the current aluminum alloy, will reduce the weight.
FRHT	Horizontal Tail Weight	T2	-3%	The use of the composite materials, which have lower weight than the current aluminum allow, will reduce the weight.

		T3	-13%	The use of the composite materials, which have lower weight than the current aluminum alloy, will reduce the weight.
		T8	-20%	The reduction in the composite manufacturing cost will enable a more extensive use of composites material, which corresponds to lighter structure.
		T12	-2%	The use of new alloy technology, which is anticipated to have lower density than the current aluminum alloy, will reduce the weight.
		T13	-8%	
		T17	-3%	The superplastic forming process will stretch the superplastic alloys into thin and lighter shapes, thus reducing the weight.
		T23	-15%	The use of new metallic materials, which is anticipated to have lower density than the current aluminum alloy, will reduce the weight.
		T27	-5%	The use of active load alleviation system will enable the materials to have a lower fatigue life characteristics, which enable the structure to be manufactured lighter.
		T32	-35%	The use of biologically inspired material, which is anticipated to have much lower density than the current aluminum alloy, will reduce the weight.
		T35	-30%	The use of BIOSANT material, which is anticipated to have much lower density than the current aluminum alloy, will reduce the weight.
FRVT	Vertical Tail Weight (skin or structure)	T2	-3%	The use of the composite materials, which have lower weight than the current aluminum allow, will reduce the weight.
		T3	-13%	The use of the composite materials, which have lower weight than the current aluminum alloy, will reduce the weight.
		T8	-20%	The reduction in the composite manufacturing cost will enable a more extensive use of composites material, which corresponds to lighter structure.
		T12	-2%	The use of new alloy technology, which is anticipated to have lower density than the current aluminum alloy, will reduce the weight.
		T13	-8%	
		T17	-3%	The superplastic forming process will stretch the superplastic alloys into thin and lighter shapes, thus reducing the weight.
		T23	-15%	The use of new metallic materials, which is anticipated to have lower density than the current aluminum alloy, will reduce the weight.
		T27	-5%	The use of active load alleviation system will enable the materials to have a lower fatigue life characteristics, which enable the structure to be manufactured lighter.
		T32	-35%	The use of biologically inspired material, which is anticipated to have much lower density than the current aluminum alloy, will reduce the weight.

		T35	-30%	The use of BIOSANT material, which is anticipated to have much lower density than the current aluminum alloy, will reduce the weight.
FCDI	Induced Drag Coefficient (C_{Di})	T1	-4%	The APO system provide automatic reconfiguration of the control surfaces to achieve a minimum-drag trim condition during flight, thus reduces the drag forces subjected to the aircraft during flight.
		T11	-1%	The optimized configuration between the propulsion system and the airframe will results in a less drag configuration.
		T26	-3%	The adaptability capability of the aircraft to suit the flight condition will reduce the drag forces subjected to it during flight.
		T30	-9.1%	The adaptive capability of the wing to change its shape during flight as to better suit the flight condition will reduce the drag forces subjected to it during flight.
FCDO	Zero-Lift Drag Coefficient	T6	-2%	The advanced computational fluid dynamics (CFD) tools incorporated in the design process will help to produce a less-drag configuration.
		T11	-1%	The optimized configuration between the propulsion system and the airframe will results in a less drag configuration.
		T29	-1%	The elimination of the externally mounted antenna system will result in a less-drag configuration.
		T2	-0.5%	The use of composite materials will enable a much smoother surface and thus, reducing the drag forces subjected to the aircraft.
		T4	-0.5%	
		T30	-9.1%	The adaptive capability of the wing to change its shape during flight as to better suit the flight condition will result in a better less-drag shape for the flight condition.
FRLGM	Landing Gear Weight	T22	-21%	The use of new metallic materials on landing gear, which is anticipated to have lower density than the current aluminum alloy, will reduce the weight.
WAVONC	Avionics Weight	T1	+2%	The implementation of the APO system will include additional electronic devices on board of the aircraft, thus increasing the avionics weight.
		T10	+1%	The implementation of the propulsion system health management will include additional electronic devices on board of the aircraft, thus increasing the avionics weight.
WAVONC	Avionics Weight	T26	+4%	The implementation of various advanced control systems on a living aircraft concept will include many electronic devices on board the aircraft, thus increasing the avionics weight.
		T27	+2%	The implementation of the active load alleviation system will include additional electronic devices on board of the aircraft, thus increasing the avionics weight.
		T28	+2%	

		T29	-45%	The implementation the advanced antenna system is anticipated to reduce the various complicated electronic devices into a more compact, advanced data transfer system. Thus, it will reduce the weight of the avionics.
		T30	+2%	The implementation of the adaptive wing shaping technology will include many electronic devices on board the aircraft for the shaping control, thus increasing the avionics weight.
WHYD	Hydraulics Weight	T26	-50%	The implementation of the living aircraft concept will include the anticipated integration of electronic technology to reduce the hydraulics system equipments or devices, thus reducing the weight.
WFURN	Furnishings & Equipment Weight	T7	-2%	The use of advanced, more stable, fire suppressant agent will enable a much simple fire suppression system, thus eliminating the need for complex equipments.
SVT	Vertical Tail Area	T30	-15%	The implementation of the adaptive wing shaping technology will enable the wing to adapt to the flight condition, thus reducing the dependency on the tail wing.
SHT	Horizontal Tail Area	T30	-15%	The implementation of the adaptive wing shaping technology will enable the wing to adapt to the flight condition, thus reducing the dependency on the tail wing.
WENG	Engine Weight	T10	+2.5%	The implementation of the propulsion system health management technology will include additional devices to be included in the engine design as to allow the operation of the technology.
		T20	+2.5%	The implementation of the adaptive engine control system will include additional devices to be included in the engine design as to allow the operation of the technology.
FACT	Fuel Consumption	T20	-17%	The implementation of the adaptive engine control system will enable the engine to adapt its operating condition to suit the flight condition better to increase its efficiency, and thus reduce the fuel consumption.
AKRDTE	RDT&E Costs	T10	+1%	The inclusion of more complex system implementation onboard the aircraft and increased experimentation efforts on structural compatibility with the technology will increase the RDT&E costs.
		T20	+0.5%	
		T26	+3%	
		T27	+1.5%	
		T28	+1.5%	
		T29	+0.1%	
		T30	+3%	
		T2	+2.5%	The inclusion of more complex processes, higher material costs and more experimentation efforts on structural compatibility with the technology will increase the RDT&E costs.
		T3	+2.5%	
		T4	+2.5%	
		T5	+2.5%	
		T7	+0.1%	
		T8	+3%	
		T9	+3%	
		T12	+3%	

		T13	+3%	
		T14	+3%	
		T15	+3%	
		T16	+3%	
		T17	+3%	
		T18	+3%	
		T19	+1%	
		T21	+3.5%	
		T22	+3.5%	
		T23	+3.5%	
		T24	+3.5%	
		T25	+2%	
		T31	+5%	
		T32	+5%	
		T33	+5%	
		T34	+5%	
		T35	+5%	
		T36	+5%	
		T6	-1.5%	The reduction of expensive experimental efforts, such as the wind tunnel testing, will reduce the RDT&E costs.
		T11	-2%	
AKOANDS	O&S Costs	T2	+0.5%	The lower damage tolerance of the materials will increase the frequency of supportability inspections and thus increases the O&S costs.
		T3	+0.5%	
		T4	+1%	
		T5	+1%	
		T8	+0.5%	
		T9	+1%	
		T25	+2%	
		T1	-3%	The reduction in the drag forces will reduce the amount of force subjected to the system, thus avoiding damage and reducing the number of supportability check frequency. This also will reduce fuel consumption.
		T6	-2%	
		T11	-2%	
		T29	-0.5%	
		T30	-2%	
		T7	+1%	The anticipated high cost of the fire suppressant agent will increase the operational cost since it needs to be replaced after certain number of operations.
		T12	-1%	The higher damage tolerance due to the higher strength of the materials will reduce the frequency of the supportability inspections and thus, the overall O&S costs.
		T13	-1%	
		T14	-1%	
		T15	-1%	
		T16	-1%	
		T17	-1%	
		T18	-1%	
		T19	-2%	
		T21	-1%	
		T22	-1%	
		T23	-0.5%	
		T24	-1%	
		T31	-1%	
		T32	-0.5%	
		T33	-1%	
		T34	-1%	
		T35	-0.5%	

		T36	-1%	
		T10	-3.5%	The reduction in the propulsion system supportability inspections due to the increased life of the propulsion system and also the reduction in the fuel consumption will reduce the overall O&S costs.
		T20	-2%	
		T26	-0.5%	The reduction in the frequency of the supportability inspection due to less damage prone adaptability and the reduction in the fuel consumption will reduce the overall O&S costs.
		T27	-0.5%	The reduction in the frequency of the supportability inspection due to lower subjected fatigue damage will reduce the overall O&S costs.
		T28	-0.5%	
AKPRICE	Production Costs	T2	+0.5%	The increase costs for the materials and processes will increase the overall production costs.
		T3	+0.5%	
		T4	+1%	
		T5	+1%	
		T19	+3%	
		T25	+2.5%	
		T1	+0.5%	The inclusion of high cost systems will drive the production costs to be higher.
		T10	+1%	
		T20	+0.5%	
		T26	+3%	
		T27	+1%	
		T28	+1%	
		T29	+1%	
		T30	+2.5%	
		T7	+0.1%	The use of high cost materials will drive the production costs to be higher.
		T21	+0.5%	
		T22	+0.2%	
		T23	+0.5%	
		T24	+1.5%	
		T31	+3.5%	
		T32	+1.5%	
		T33	+2.5%	
		T34	+3.5%	
		T35	+1.5%	
		T36	+2.5%	
		T12	+0.2%	The high cost of the materials used and processes involved will increase the production costs.
		T13	+0.4%	
		T14	+0.8%	
		T15	+1%	
		T16	+2%	
		T17	+0.5%	
		T18	+1%	
		T8	-1%	Although the use of composite materials will increase the cost of materials, the reduction in manufacturing cost due to the low-cost technique will decrease the overall production costs a bit.
		T9	-2%	
U	Utilization	T10	+3%	The reduction in the supportability inspection frequency will increase the utilization level, and although the time to repair may be longer, it is expected that the difference in the 'grounded' hours will not be much dominant compared to the
		T12	+1%	
		T13	+1%	
		T14	+2%	
		T15	+2%	

		T16	+1%	frequency reduction.
		T17	+2%	
		T18	+1%	The reduction in the supportability inspection frequency will increase the utilization level, and although the time to repair may be longer, it is expected that the difference in the 'grounded' hours will not be much dominant compared to the frequency reduction.
		T19	+1%	
		T20	+2%	
		T21	+2%	
		T22	+2%	
		T23	+1%	
		T24	+2%	
		T27	+1%	
		T28	+1%	
		T31	+1%	
		T32	+1%	
		T33	+1%	
		T34	+2%	
		T35	+2%	
		T36	+2%	
		T2	-1%	The increase in the supportability inspection frequency will reduce the utilization level.
		T3	-1%	
		T4	-2%	
		T5	-2%	
		T8	-2%	
		T9	-3%	
		T25	-4%	
		T26	+1.5%	The adaptability characteristics to various flight mission and reduced frequency for supportability inspection will increase the utilization level, and although the time to repair may be longer, it is expected that the difference in the 'grounded' hours will not be much dominant compared to the frequency reduction.
		T30	+1%	

APPENDIX I – SCRIPTS

The following code was used for creating FLOPS input files based on the DoE created:

```
#!/usr/local/bin/tcl -f
#  the syntax for this loop is as follows:
#  for each line in file 'tech_doe.table' execute the info in between the
#  squiggly brackets starting by assigning the whole line into the
#  character 'line'
for_file line tech_doe.table {
#  for each line that has been assigned into the character string '$line'
#  then assign the elements contained in that character into the following
#  specific variables. For example, the first number contained in the
#  first row of the file 'tech_doe.table' will be assigned to the
#  variable 'a' which is in general the number of cases to be executed in a
#  subsequent script, the second number will be assigned into the variable
#  called 'var1', and so on
lassign $line a var1 var2 var3 var4 var5 var6 var7 var8 var9 var10 var11 var12 var13 var14 var15
var16 var17 var18 var19 var20
#  Now open a file called 'varfile' and make it a writeable ('w') file
set file [open varfile w]
#  in that file, write (puts) on the first line the following:
#  'WTIN FRWI and the current value of var1', then on the second line
#  put 'WTIN FRHT and the current value of var2', and so on.
puts $file "WTIN FRWI $var1 "
puts $file "WTIN FRFU $var2 "
puts $file "WTIN FRHT $var3 "
puts $file "WTIN FRVT $var4 "
puts $file "MISSIN FCDI $var5 "
puts $file "MISSIN FCDO $var6 "
puts $file "WTIN FRLGM $var7 "
puts $file "WTIN FRLGN $var7 "
       puts $file "WTIN WAVONC $var8 "
puts $file "WTIN WHYD $var9 "
puts $file "WTIN WFURN $var10 "
puts $file "WTIN SVT $var11 "
puts $file "WTIN SHT $var12 "
puts $file "WTIN WENG $var13 "
puts $file "MISSIN FACT $var14 "
puts $file "IWGT AKRDTE $var15 "
puts $file "IWGT AKOANDS $var16 "
puts $file "IWGT AKPRICE $var17 "
puts $file "COPER U $var18 "
puts $file "CONFIN SW $var19 "
puts $file "CONFIN TWR $var20 "
#  close the file so that the program 'tsw' can open and read the file 'varfile'
#  just created
close $file
#  Run the program tsw to switch out the variables contained in the file 'varfile'
#  into the appropriate namelists and with the current values from the original
#  file called 'base.in'. If your baseline file is called something else, then
#  modify the file name below that tsw is calling. Then tsw rewrites
#  a new file called case'a' for the given case number 'a'
puts stdout "   Running tsw on case $a "
catch "exec tsw -input input_opt.in -output case$a varfile"
}
#  'puts stdout' is a simple command to print to the screen what is contained
#  between the quotes
puts stdout "TSW file switching is COMPLETE.....CONGRATS!!!!"
exit
```

To run the created input files, the following code was used:

```
# this scripts will execute flops based on the number of cases you
# tell it to run
echo "Running script for execution of the DoE cases"
# set i from the lower bound of the number of cases you are interested in running
#to the max value (ie, 'imax')
i=1
imax=257
# this 'while-do' loop executes the commands contained in the 'do-done'
#as long as the counter 'i' is less than or equal to (ie, '-le')
#the value of imax
while [ $i -le $imax ]
do
        echo "Now running file:  $i"
        flops case$i  case$i.out
        echo "$i completed"
        echo "**********************************************************************"
let i=i+1
done
echo ""
echo "running cases is COMPLETE....CONGRATS!!!"
```

To get the metric values the following code was used:

```
#!/usr/local/bin/tcl -f
#  Set the total number of cases that you will be parsing
set Number_of_Cases 257
# touch the files to see if they exist or not so that you are not appending
# to a file that does not exist. if you were to do that, tcl would crash. also,
# if the file did exist, since you are appending to the end of the file, you
# wouldn't know where the current case results started
exec touch summary_perf
exec rm summary_perf
exec touch summary_econ
exec rm summary_econ
# put headers into output files
exec echo "CASE VAPP DFARLDG DFAROFF BLOCKFUEL NOX TOGW WINGAREA WINGWEIGHT" >> summary_perf
exec echo "CASE ACQ RDTE RPM TAROC DOC+I" >> summary_econ
#  For more information regarding how the program parse98 works, just type parse98
#  at the command line to get more info regarding the flags. The program is pretty
#  straight forward
for {set i 1} { $i <= $Number_of_Cases} { incr i 1} {
puts stdout " ********    parsing case $i    ******* "
set vapp [ exec parse98 -search "DVAPP"-read 3 -occurance 1 -offset 0 case$i.out]
set ldgfl [ exec parse98 -search "DFARLDG"-read 3 -occurance 1 -offset 0 case$i.out]
set tofl [ exec parse98 -search "DFAROFF"-read 3 -occurance 1 -offset 0 case$i.out]
set blockfuel [ exec parse98 -search "     BLOCK FUEL"-read 4 -occurance 1 -offset 0 case$i.out]
set nox [ exec parse98 -search "TOTAL NITROGEN OXIDES"-read 6 -occurance 1 -offset 0 case$i.out]
set togw [ exec parse98 -search "TOGW"-read 3 -occurance 1 -offset 0 case$i.out]
      set acq         [ exec parse98 -search "Final Aircraft Price Mil $"   -read 7 -occurance 1
-offset 0 case$i.out]
      set rdte        [ exec parse98 -search "TOTAL RDT&E COST"             -read 4 -occurance 1
-offset 0 case$i.out]
      set rpm         [ exec parse98 -search "Average Yield/RPM"            -read 4 -occurance 1
-offset 0 case$i.out]
      set taroc       [ exec parse98 -search "Method SubTotal" -read 5 -occurance 2 -offset 0
case$i.out]
      set doci        [ exec parse98 -search "Method SubTotal" -read 4 -occurance 2 -offset 0
case$i.out]
set area[ exec parse98 -search " CALCULATED WING AREA "-read 4 -occurance 1 -offset 0 case$i.out]
set wingwt [ exec parse98 -search "         Aluminum"-read 5 -occurance 1 -offset 0 case$i.out]
# append the parsed data into the summary files
exec echo "$i $vapp $ldgfl $tofl $blockfuel $nox $togw $area $wingwt" >> summary_perf
exec echo "$i $acq $rdte $rpm $taroc $doci " >> summary_econ
}
puts stdout "Parsing is now completed!!"
exit
```

APPENDIX J – TECHNOLOGY RSE COEFFICIENTS

	Vapp	LndgFL	TOFL	CO2/ASM	NOx	TOGW
Intercept	102.99178	4729.3213	4399.4922	0.16406	264.37368	124188.72
FRWI	2.11501	92.93463	168.52997	0.00593	7.41301	4982.3251
FRFU	1.35216	59.96918	107.90861	0.00380	4.85946	3140.7107
FRHT	0.11036	4.78978	8.08358	0.00030	0.33015	265.11764
FRVT	0.08634	3.80095	6.66216	0.00024	0.25461	192.16708
FCDI	0.19735	8.70445	53.34249	0.00789	19.64196	1497.7850
FCDO	0.35134	15.64182	89.10525	0.01318	35.54828	2563.7761
FRLGM	0.47126	20.89645	37.09558	0.00130	1.43021	1100.2946
WAVONC	0.27226	12.14269	22.56673	0.00075	0.95360	630.82420
WHYD	0.19767	8.47337	15.65598	0.00055	0.64549	460.20551
WFURN	0.67356	29.65973	54.14190	0.00187	2.40541	1566.3574
SVT	0.14443	6.51547	21.72560	0.00190	4.78499	536.62204
SHT	0.15569	6.93599	21.06608	0.00193	4.37826	581.78918
WENG	1.68040	74.77395	136.22669	0.00478	6.11616	3935.0460
FACT	0.62649	27.85777	154.42774	0.02243	34.39647	4409.8234
AKRDTE	-0.00115	0.09074	-1.23586	0.00008	0.18610	18.32222
AKOANDS	0.00153	0.09563	1.59617	0.00008	0.04784	17.27685
AKPRICE	-0.00094	-0.15788	-0.23379	-0.00003	-0.01751	-4.15892
U	-0.00592	-0.35860	-2.46998	-0.00006	-0.24262	-13.69545
SW	-9.61385	-423.26541	-807.45954	-0.00371	-4.88655	1336.7120
TWR	0.35839	16.29053	-137.16407	0.00179	-8.33750	956.70277
FRWI*FRWI	0.04699	2.74183	10.05774	0.00030	0.24710	160.24549
FRFU*FRWI	0.00449	1.58955	3.63543	0.00013	0.37921	89.41758
FRFU*FRFU	-0.02865	-1.03473	1.46305	-0.00006	0.11329	-12.98450
FRHT*FRWI	-0.00343	0.14235	2.10871	-0.00001	0.13394	-0.15693
FRHT*FRFU	0.00211	0.33903	1.46386	0.00008	0.46390	15.55311
FRHT*FRHT	-0.00395	0.37341	0.19625	0.00028	0.52026	43.50197
FRVT*FRWI	-0.00440	-0.12625	-0.68937	-0.00004	-0.40394	-1.53784
FRVT*FRFU	0.00016	0.06872	0.99488	-0.00002	-0.11158	1.68392
FRVT*FRHT	-0.00133	-0.09364	0.35156	0.00002	0.04885	4.14323
FRVT*FRVT	-0.02339	-2.37093	-5.61372	-0.00037	-0.36011	-59.26669
FCDI*FRWI	0.02317	0.94403	2.51141	0.00044	1.12247	121.34529
FCDI*FRFU	0.00983	0.44616	1.32701	0.00027	0.74383	60.73105
FCDI*FRHT	-0.00303	-0.02492	-0.88885	-0.00002	-0.19955	-4.37134
FCDI*FRVT	-0.00795	-0.06239	0.29517	0.00000	0.01256	1.05307
FCDI*FCDI	0.00996	1.02889	3.64390	0.00010	1.46525	11.02793
FCDO*FRWI	0.02312	1.23744	2.96602	0.00034	0.35557	122.22463
FCDO*FRFU	-0.00452	-0.19769	1.07932	0.00018	0.22879	34.98053
FCDO*FRHT	-0.00155	0.25215	2.12243	0.00001	0.19185	-1.81465
FCDO*FRVT	-0.00220	-0.18083	-0.38616	0.00007	0.01405	13.98492
FCDO*FCDI	0.00372	-0.32023	2.08633	0.00047	2.13900	79.80871
FCDO*FCDO	0.01682	1.38064	8.03127	0.00042	1.30391	92.98071
FRLGM*FRWI	0.01934	1.12476	1.11074	0.00006	-0.10961	78.18834
FRLGM*FRFU	0.00715	0.48928	1.80130	0.00005	0.10247	34.64321
FRLGM*FRHT	0.00192	0.16117	-1.77928	0.00009	-0.24685	28.27598
FRLGM*FRVT	-0.00014	0.16361	-0.96520	0.00002	-0.22659	8.50413
FRLGM*FCDI	0.00059	0.24734	1.18631	0.00006	0.12860	9.02733
FRLGM*FCDO	-0.007054	-0.408540	0.1901122	9.51E-07	-0.040856	4.2652083
FRLGM*FRLGM	-0.007756	0.3385432	0.5605756	0.0001891	0.2061118	60.982310

WAVONC*FRWI	-0.000535	0.3054728	1.1332072	-0.000010	0.0730727	9.3948496
WAVONC*FRFU	-0.009229	-0.209269	-0.529782	-0.000003	0.1029458	-1.028572
WAVONC*FRHT	-0.004026	-0.012745	-0.682785	-0.000016	-0.018758	-5.266196
WAVONC*FRVT	-0.002868	0.1055142	0.6210260	-0.000068	-0.173305	-21.01573
WAVONC*FCDI	0.0046051	0.2145364	1.3481877	0.0000764	0.0158726	22.164221
WAVONC*FCDO	0.0028275	0.1687066	-0.830373	0.0000635	0.0642533	17.149312
WAVONC*FRLGM	0.0057041	0.1858392	-0.073172	0.0000314	0.2363554	16.182292
WAVONC*WAVONC	0.0199047	1.9492632	11.079102	0.0002575	1.0107962	29.882800
WHYD*FRWI	0.0073249	-0.132230	-1.077401	0.0000010	-0.216960	3.4512192
WHYD*FRFU	-0.001403	-0.156393	-0.191013	-0.000048	-0.102746	-10.84070
WHYD*FRHT	0.0050504	0.3115125	-0.371176	-0.000026	0.2673984	-4.869966
WHYD*FRVT	0.0081244	0.4668203	3.5997076	0.000055	0.5206538	13.809628
WHYD*FCDI	0.0019006	-0.249224	-0.279510	-0.000009	-0.041210	-9.821443
WHYD*FCDO	-0.002389	-0.051155	-1.466752	0.0000421	-0.120067	8.8187627
WHYD*FRLGM	0.0045896	0.2313018	1.8212473	-0.000001	0.0483415	2.8458203
WHYD*WAVONC	-0.003123	-0.272075	-1.640456	0.0000302	-0.301578	3.2019316
WHYD*WHYD	0.0017799	-0.732335	-8.727701	-0.000070	-0.075916	4.3890744
WFURN*FRWI	0.0141054	1.3153063	5.4212169	0.0001282	0.501688	60.940075
WFURN*FRFU	-0.014018	-0.017520	1.7189014	0.0000189	0.3537634	-1.151847
WFURN*FRHT	-0.005948	-0.246339	-0.549108	-0.000006	-0.123573	-4.704512
WFURN*FRVT	0.0002031	0.2528630	1.6403468	-0.000009	-0.037204	-2.743121
WFURN*FCDI	0.0014641	0.0837046	1.6040094	0.0001156	0.5434310	22.662426
WFURN*FCDO	-0.008059	-0.156381	0.3558334	0.0000227	-0.048775	3.0890650
WFURN*FRLGM	0.0033937	-0.023814	-1.398937	0.0000260	-0.143380	14.185689
WFURN*WAVONC	0.0006034	-0.052282	0.1218472	-0.000043	0.1942546	-9.628074
WFURN*WHYD	0.0026170	-0.182710	-0.804255	-0.000033	-0.176430	-6.200818
WFURN*WFURN	0.0194171	0.0027442	-2.623486	0.0000608	0.7057302	14.685005
SVT*FRWI	0.0035994	0.5578271	2.4458495	0.0000716	0.1283634	26.609293
SVT*FRFU	-0.002661	0.0961193	2.4013833	-0.000009	0.1421789	-5.838026
SVT*FRHT	0.0058661	0.3638967	0.7601566	0.0000683	0.4329839	22.049874
SVT*FRVT	0.0263271	0.9778259	0.1715555	0.0001083	0.1289995	66.198150
SVT*FCDI	0.0083301	0.3835340	4.3151801	0.0001678	0.4928896	32.348237
SVT*FCDO	0.0059298	0.5330834	2.0739429	0.0002106	1.0137766	39.551399
SVT*FRLGM	-0.003808	-0.011382	0.2897318	-0.000052	-0.149912	-12.71077
SVT*WAVONC	-0.005758	-0.259883	-2.491059	-0.000057	-0.428540	-7.765010
SVT*WHYD	0.0044576	0.1576441	0.1658233	0.0000447	-0.201403	19.68193
SVT*WFURN	-0.003993	-0.072144	-0.356003	-0.000094	-0.224650	-21.22224
SVT*SVT	0.0027112	1.1080009	2.7628155	0.0001199	0.2780102	51.880540
SHT*FRWI	0.0121500	0.5123916	0.0921389	0.0000245	-0.115589	18.915424
SHT*FRFU	0.0017532	-0.219541	0.4825840	0.0000595	-0.122956	17.281951
SHT*FRHT	0.0247359	1.0401490	3.2083347	0.0000596	0.1691122	51.846818
SHT*FRVT	0.0036022	-0.012939	-0.212115	-0.000027	-0.122062	-6.395369
SHT*FCDI	0.0005101	-0.252151	-1.146059	0.0000029	-0.035123	-4.861076
SHT*FCDO	0.0022248	0.1948566	1.3656590	0.0002506	0.7142330	51.460380
SHT*FRLGM	-0.005639	-0.054611	0.5972966	0.0000501	-0.070741	16.594579
SHT*WAVONC	-0.008470	-0.297825	-0.049791	-0.000060	-0.109148	-9.825075
SHT*WHYD	0.0031906	0.1268481	1.2889980	0.0000509	0.1006950	9.9211267
SHT*WFURN	0.00453	0.00597	0.72073	-0.00008	-0.09678	-18.75671
SHT*SVT	0.00445	0.13135	0.74720	0.00006	0.11273	14.30687
SHT*SHT	0.00731	0.84899	3.27660	0.00005	0.61469	18.32272
WENG*FRWI	0.07568	4.81921	11.65453	0.00043	0.54114	295.10114
WENG*FRFU	0.03056	2.43945	6.34199	0.00021	0.70676	126.92692

WENG*FRHT	0.00310	0.44176	2.43561	0.00001	0.18395	3.98358
WENG*FRVT	-0.00249	-0.01561	-0.23556	0.00001	-0.10839	8.21930
WENG*FCDI	0.03184	1.46277	6.06676	0.00046	1.33632	135.30498
WENG*FCDO	0.03523	1.63104	4.97173	0.00030	0.38742	125.99008
WENG*FRLGM	0.02238	1.33712	1.22676	0.00005	-0.02552	69.75312
WENG*WAVONC	0.00614	0.37752	2.12549	0.00003	-0.12956	24.65734
WENG*WHYD	-0.00051	0.17907	-0.22406	0.00007	0.18467	23.43825
WENG*WFURN	0.01481	1.28162	2.82688	0.00010	0.22501	65.34394
WENG*SVT	0.00847	0.39421	1.25477	0.00007	0.16076	28.12572
WENG*SHT	0.00062	0.16644	1.91839	0.00013	0.18661	38.13397
WENG*WENG	0.02751	2.97321	6.16256	0.00026	0.26635	141.19135
FACT*FRWI	0.05657	2.98981	12.16129	0.00096	1.36869	276.20247
FACT*FRFU	0.00751	0.79497	6.09197	0.00055	1.12820	103.88477
FACT*FRHT	0.00063	-0.09918	-0.81293	0.00005	-0.32216	10.55940
FACT*FRVT	0.00652	0.34685	0.23690	0.00007	0.09300	15.54238
FACT*FCDI	0.02841	1.35801	8.96616	0.00132	2.93668	242.88110
FACT*FCDO	0.04599	2.08020	13.88989	0.00195	4.18382	367.65452
FACT*FRLGM	0.00002	-0.03804	-0.84025	0.00008	-0.23058	25.81158
FACT*WAVONC	-0.00274	0.01826	0.86803	0.00008	0.03591	12.06563
FACT*WHYD	-0.00193	0.17707	-0.78602	0.00007	0.21157	17.85534
FACT*WFURN	0.00671	0.49051	5.04325	0.00030	0.63634	64.14148
FACT*SVT	0.00534	-0.02075	4.01316	0.00026	0.69041	47.35250
FACT*SHT	0.00943	0.69040	2.47774	0.00027	0.36978	58.15556
FACT*WENG	0.07334	3.70725	12.93340	0.00088	1.55685	286.95670
FACT*FACT	-0.01285	0.19405	-1.45021	0.00031	-0.34346	37.49676
AKRDTE*FRWI	-0.00648	-0.28208	-2.38202	-0.00007	-0.23258	-17.60867
AKRDTE*FRFU	-0.00346	0.03940	-1.13543	-0.00005	0.05237	-6.10176
AKRDTE*FRHT	-0.00174	-0.51447	-2.30526	-0.00004	-0.24340	-11.33190
AKRDTE*FRVT	-0.00075	0.16422	3.33907	0.00002	0.05970	6.44796
AKRDTE*FCDI	-0.00326	-0.05166	2.05747	0.00001	0.09087	0.25362
AKRDTE*FCDO	0.00562	0.36979	1.44211	0.00008	-0.07292	21.31863
AKRDTE*FRLGM	0.00008	-0.11049	0.30085	-0.00002	-0.00845	-0.27499
AKRDTE*WAVONC	-0.00850	-0.25613	0.83842	-0.00005	0.06184	-15.27068
AKRDTE*WHYD	-0.00207	0.27080	1.80945	0.00003	0.05749	14.63536
AKRDTE*WFURN	-0.00014	0.00107	-0.12974	-0.00001	-0.04462	1.11975
AKRDTE*SVT	-0.00593	-0.19104	0.05201	-0.00005	-0.24360	-14.35759
AKRDTE*SHT	-0.00125	0.17651	1.16830	0.00004	0.13819	8.25432
AKRDTE*WENG	-0.00230	-0.23820	-2.56291	-0.00001	-0.42478	-0.19103
AKRDTE*FACT	-0.00094	-0.35741	-1.51097	-0.00001	-0.18242	5.71879
AKRDTE*AKRDTE	0.00687	-0.26466	-5.83542	-0.00018	-1.81203	0.12516
AKOANDS*FRWI	0.00544	0.04989	-0.46116	0.00001	-0.09266	3.18577
AKOANDS*FRFU	-0.00318	-0.16533	-0.80828	-0.00005	-0.23120	-10.91628
AKOANDS*FRHT	0.00208	0.03835	-0.60800	-0.00003	-0.09254	-7.53038
AKOANDS*FRVT	0.00017	-0.15272	-1.96855	-0.00002	-0.05698	-1.85478
AKOANDS*FCDI	0.00305	-0.15311	0.06744	-0.00001	-0.01333	-8.14349
AKOANDS*FCDO	0.00234	0.08922	0.36387	0.00005	-0.08349	12.51143
AKOANDS*FRLGM	-0.00260	-0.08538	-0.57112	-0.00003	0.05278	-11.02593
AKOANDS*WAVONC	-0.00071	-0.12336	-0.29603	-0.00001	-0.22670	-3.74923
AKOANDS*WHYD	-0.01568	-0.77485	-3.16218	-0.00009	-0.55475	-26.38300
AKOANDS*WFURN	-0.00059	0.22897	2.19332	0.00000	0.03417	-3.35036
AKOANDS*SVT	-0.00458	-0.18714	-1.62412	-0.00001	-0.14872	1.03293
AKOANDS*SHT	-0.00555	-0.64420	-2.22414	-0.00009	-0.06138	-23.89866

AKOANDS*WENG	0.00290	0.17121	-0.15244	0.00007	0.10015	22.45230
AKOANDS*FACT	0.00230	0.15455	0.19867	-0.00001	0.11626	-2.84652
AKOANDS*AKRDTE	0.00537	0.48560	1.99931	0.00004	0.36890	13.85347
AKOANDS*AKOANDS	-0.00987	-1.37175	-0.15957	-0.00036	-0.20912	-88.02807
AKPRICE*FRWI	0.00178	0.03811	0.37449	-0.00006	0.11596	-10.14927
AKPRICE*FRFU	-0.00355	-0.27597	-4.07838	-0.00012	-0.23670	-16.59906
AKPRICE*FRHT	0.00864	0.73892	3.13003	0.00007	0.15044	18.94917
AKPRICE*FRVT	-0.00033	-0.20184	0.68168	-0.00002	0.10314	-9.12596
AKPRICE*FCDI	0.00078	0.15450	-0.84310	-0.00009	0.00110	-22.04154
AKPRICE*FCDO	-0.00177	0.00594	-0.65139	0.00000	-0.04756	6.58588
AKPRICE*FRLGM	-0.00398	0.05722	0.18630	0.00001	0.00540	1.29025
AKPRICE*WAVONC	-0.00110	0.07059	0.13304	0.00002	0.20510	7.91601
AKPRICE*WHYD	-0.00878	-0.37198	-1.69400	-0.00007	-0.12111	-15.91344
AKPRICE*WFURN	0.00021	0.17630	1.79787	0.00000	-0.27811	0.40148
AKPRICE*SVT	-0.00361	-0.39217	-2.80207	-0.00011	-0.19549	-29.91156
AKPRICE*SHT	-0.00157	-0.43528	-0.48802	-0.00007	-0.29583	-12.63104
AKPRICE*WENG	-0.00714	-0.14991	-0.59792	-0.00008	0.04281	-18.70760
AKPRICE*FACT	0.00028	-0.06084	0.60661	0.00002	-0.24106	-1.26608
AKPRICE*AKRDTE	0.00338	-0.05533	0.11437	-0.00002	0.08152	-6.76382
AKPRICE*AKOANDS	0.00044	0.07367	-0.23575	-0.00005	-0.00221	-11.43587
AKPRICE*AKPRICE	-0.02019	-1.05859	5.15979	-0.00021	0.04798	-59.68775
U*FRWI	-0.00126	-0.12838	-0.83435	-0.00001	-0.09338	-3.12740
U*FRFU	-0.00237	-0.03456	-0.60299	-0.00006	0.00540	-12.40894
U*FRHT	-0.00681	-0.19349	0.54200	-0.00002	0.07380	2.30188
U*FRVT	-0.00009	-0.36408	-1.88542	-0.00003	-0.01061	-8.55448
U*FCDI	-0.00027	0.12115	0.33828	-0.00003	0.30379	-10.30218
U*FCDO	-0.00161	0.01746	-0.69897	-0.00001	-0.21028	2.37322
U*FRLGM	-0.00341	0.16847	-0.28410	0.00000	0.26771	2.06528
U*WAVONC	0.00151	0.13009	0.49467	0.00000	-0.07214	-1.24141
U*WHYD	0.00241	-0.16552	-1.71158	-0.00001	0.02674	2.61977
U*WFURN	0.00219	0.32736	2.57089	0.00013	0.32463	28.67829
U*SVT	0.00032	-0.01470	1.99081	0.00006	-0.06508	18.34884
U*SHT	-0.00374	-0.06067	-0.91488	-0.00003	-0.05781	-3.30046
U*WENG	-0.00086	-0.21022	-0.95490	-0.00001	-0.13863	-6.51684
U*FACT	0.00972	0.32318	0.76434	-0.00002	-0.05660	2.38901
U*AKRDTE	-0.00065	-0.47571	-1.95469	-0.00003	-0.26619	-5.55582
U*AKOANDS	0.00817	0.29939	2.59673	0.00011	0.30261	24.13557
U*AKPRICE	0.00175	0.11673	0.34062	-0.00002	-0.08161	-7.75970
U*U	0.01590	0.77782	-0.30135	-0.00017	-0.34394	-33.70935
SW*FRWI	-0.01189	-9.06732	-31.64143	-0.00022	-0.49819	406.34584
SW*FRFU	-0.15197	-11.91952	-28.92615	-0.00049	-0.73278	-65.96826
SW*FRVT	-0.01129	-0.89389	-3.24301	-0.00001	-0.35306	3.97785
SW*FCDI	-0.03633	-2.23524	-17.30207	-0.00070	-0.96102	-126.05115
SW*FCDO	-0.01609	-2.21580	-20.68923	-0.00008	0.10968	9.61591
SW*FRLGM	-0.03014	-3.11598	-8.40290	-0.00009	-0.03714	26.24941
SW*WAVONC	-0.03099	-2.63400	-8.28813	-0.00008	-0.15644	-10.35648
SW*WHYD	-0.01311	-1.24738	-4.16600	-0.00004	0.04306	16.07956
SW*WFURN	-0.07181	-6.01701	-15.43720	-0.00018	-0.24464	-31.61231
SW*SVT	-0.02150	-1.66237	-6.96283	-0.00027	-0.72162	-52.68385
SW*SHT	-0.02581	-1.71250	-5.67988	-0.00024	-0.82975	-47.59423
SW*WENG	-0.17572	-14.49302	-38.87755	-0.00064	-1.13609	-61.90708
SW*FACT	-0.07628	-5.93356	-45.18427	-0.00098	-1.53174	-143.69899

SW*AKRDTE	0.01031	0.34720	1.58195	0.00007	0.26500	24.35402
SW*AKOANDS	0.00309	-0.15563	-0.12085	0.00000	-0.12051	-2.41810
SW*AKPRICE	0.00413	0.33460	0.45206	0.00000	0.26719	4.02256
SW*U	-0.00271	-0.06277	-1.69748	-0.00001	-0.06486	-2.33910
SW*SW	1.51267	85.77491	199.29445	0.00228	3.81302	392.88472
TWR*FRWI	0.01507	0.84613	-7.99457	0.00009	0.01750	59.68013
TWR*FRFU	0.01194	0.50932	-6.93483	0.00010	-0.02561	37.08989
TWR*FRHT	-0.00213	0.23251	0.31099	0.00002	0.24866	8.84495
TWR*FRVT	0.00797	0.34961	0.24043	0.00005	-0.02221	10.68843
TWR*FCDI	-0.00275	0.08458	-3.67082	0.00004	-0.43288	14.99847
TWR*FCDO	0.00502	0.16857	-6.15391	0.00004	-1.70698	26.51270
TWR*FRLGM	0.00349	0.20697	-1.96371	-0.00003	-0.01498	14.76019
TWR*WAVONC	0.00441	0.26427	-0.32849	0.00005	-0.10386	19.49639
TWR*WHYD	0.00952	0.37566	0.06056	0.00005	-0.00047	11.27816
TWR*WFURN	-0.00137	-0.29482	-5.56816	-0.00010	-0.37497	-14.57733
TWR*SVT	0.00216	-0.04252	-3.02407	0.00001	-0.35109	8.50792
TWR*SHT	-0.00423	-0.23121	-2.11641	-0.00001	-0.38094	-0.05037
TWR*WENG	0.11140	5.15042	1.25655	0.00035	0.35111	279.23385
TWR*FACT	0.01638	0.74157	-6.45221	0.00030	-0.62472	82.46619
TWR*AKRDTE	0.00771	-0.00504	-0.18141	0.00004	-0.02279	10.91575
TWR*AKOANDS	0.00271	-0.13750	-0.45048	0.00000	-0.06698	-5.57174
TWR*AKPRICE	0.00149	-0.13106	-1.06157	-0.00009	0.08875	-13.88888
TWR*U	0.00143	0.18875	-0.17296	-0.00001	-0.09948	2.30711
TWR*SW	-0.03838	-3.29348	39.62050	-0.00022	-0.04494	-25.07170
TWR*TWR	0.02410	1.08376	9.75668	0.00024	0.57227	61.71422

Coefficients of RSEs (cont)

	ACQ$	RDT&E	$/RPM	TAROC	DOC+I	WAWt
Intercept	54.21984	4359.2957	0.12379	6.09912	4.75230	8.84388
FRWI	1.94088	145.48655	0.00216	0.16379	0.13364	2.75012
FRFU	1.30750	91.53849	0.00144	0.10810	0.08872	0.15573
FRHT	0.11468	6.57079	0.00015	0.00706	0.00553	0.01019
FRVT	0.08567	5.25642	0.00021	0.00793	0.00669	0.01120
FCDI	0.22271	18.16399	0.00064	0.04503	0.03733	0.07582
FCDO	0.39736	32.00079	0.00094	0.07412	0.06125	0.12997
FRLGM	0.39287	18.46942	0.00043	0.03506	0.02847	0.05565
WAVONC	0.38182	23.12027	0.00016	0.02581	0.02170	0.03227
WHYD	0.27334	16.13836	0.00042	0.02549	0.02200	0.01918
WFURN	0.48577	27.64508	0.00055	0.04632	0.03711	0.07831
SVT	0.13655	9.32895	0.00014	0.01540	0.01250	0.02805
SHT	0.16655	10.15703	0.00007	0.01800	0.01487	0.02654
WENG	0.68143	56.99989	0.00108	0.07154	0.05441	0.16849
FACT	0.68168	53.99335	0.00182	0.13032	0.10799	0.22377
AKRDTE	3.78964	873.18415	0.00195	0.17519	0.16365	-0.00112
AKOANDS	0.01408	-0.09459	0.02006	1.23920	0.96798	0.00234
AKPRICE	10.84242	-0.19926	0.00509	0.52019	0.48589	0.00162
U	-0.01267	-0.40577	-0.00678	-0.43490	-0.40632	-0.00240
SW	0.91258	69.10760	0.00089	0.05160	0.04203	-0.83771
TWR	0.83751	68.68920	0.00095	0.05308	0.04650	0.04050
FRWI*FRWI	0.02079	3.80267	-0.00049	0.00245	0.00180	0.08805
FRFU*FRWI	0.01890	2.11788	-0.00003	-0.00060	-0.00086	0.04874

FRFU*FRFU	0.04374	-0.21222	-0.00001	-0.01568	-0.01452	-0.00328
FRHT*FRWI	-0.00632	0.13042	-0.00005	-0.00042	-0.00040	0.00662
FRHT*FRFU	0.01131	0.18683	-0.00006	-0.00047	-0.00043	0.00446
FRHT*FRHT	0.03312	-1.14135	0.00028	0.02169	0.01998	0.00274
FRVT*FRWI	0.00148	0.20816	-0.00007	0.00187	0.00167	0.00330
FRVT*FRFU	0.00960	-0.22768	-0.00015	0.00553	0.00503	-0.00047
FRVT*FRHT	0.01414	-0.06763	-0.00009	0.00344	0.00315	-0.00036
FRVT*FRVT	-0.02544	1.23935	-0.00011	-0.01940	-0.01828	-0.01362
FCDI*FRWI	0.02881	2.09272	-0.00005	0.00088	0.00036	0.02535
FCDI*FRFU	-0.00102	0.94503	-0.00003	0.00235	0.00191	0.00389
FCDI*FRHT	0.00481	-0.25090	-0.00003	-0.00143	-0.00131	0.00245
FCDI*FRVT	-0.01586	0.05615	0.00004	0.00234	0.00210	0.00003
FCDI*FCDI	0.00217	-2.62508	-0.00046	-0.00132	-0.00120	-0.00043
FCDO*FRWI	0.02084	2.92430	0.00000	0.00181	0.00133	0.03886
FCDO*FRFU	0.00163	-0.39363	-0.00004	-0.00180	-0.00182	-0.00112
FCDO*FRHT	-0.01167	-0.27468	-0.00014	0.00012	0.00014	0.00108
FCDO*FRVT	0.00181	0.49006	0.00017	-0.00051	-0.00054	-0.00125
FCDO*FCDI	0.00878	0.33639	0.00003	0.00361	0.00308	0.00138
FCDO*FCDO	0.03074	0.41670	0.00033	0.00444	0.00387	0.01265
FRLGM*FRWI	0.03957	1.64850	0.00026	0.00405	0.00347	0.01435
FRLGM*FRFU	0.00494	0.36734	-0.00011	-0.00037	-0.00041	-0.00150
FRLGM*FRHT	-0.01697	0.65014	-0.00018	-0.00098	-0.00097	-0.00441
FRLGM*FRVT	-0.00701	-0.37772	-0.00001	-0.00172	-0.00150	-0.00277
FRLGM*FCDI	-0.00138	-0.37080	-0.00037	-0.00275	-0.00250	-0.00005
FRLGM*FCDO	0.0024977	0.2567293	-0.000277	-0.005250	-0.004847	-0.004074
FRLGM*FRLGM	-0.015394	-0.282705	0.0010548	0.0082832	0.0075682	-0.003307
WAVONC*FRWI	-0.003044	0.4355910	-0.000052	0.0014583	0.0013740	0.0123366
WAVONC*FRFU	-0.007466	-0.633480	0.0000274	-0.000427	-0.000584	-0.002336
WAVONC*FRHT	-0.000251	-0.096614	-0.000014	-0.003048	-0.002850	-0.004156
WAVONC*FRVT	-0.003901	-0.709633	-0.000155	-0.000163	-0.000107	0.0015553
WAVONC*FCDI	0.0161705	0.2375189	-0.000108	-0.001917	-0.001800	0.0024866
WAVONC*FCDO	-0.000230	-0.073647	-0.000030	-0.003857	-0.003679	0.0014160
WAVONC*FRLGM	-0.001672	-0.021081	0.0000672	-0.000861	-0.000916	0.0005755
WAVONC*WAVONC	-0.031004	-1.050453	-0.000541	-0.002815	-0.002483	0.0061900
WHYD*FRWI	0.0155698	0.0223559	-0.000082	0.0003844	0.0003692	0.0030251
WHYD*FRFU	0.0017440	-0.049476	0.0001172	0.0003944	0.0004549	0.0002163
WHYD*FRHT	-0.009551	-0.403306	-0.000024	-0.000149	-0.000054	-0.001443
WHYD*FRVT	0.0034021	0.1943148	0.0000892	0.0004509	0.0003334	0.0053650
WHYD*FCDI	-0.005767	0.1598893	0.0000126	0.0004617	0.0005620	-0.004191
WHYD*FCDO	0.0090920	-0.039835	0.0002964	-0.000534	-0.000365	0.0000958
WHYD*FRLGM	-0.004633	0.5172432	0.0000297	-0.005858	-0.005365	0.0002553
WHYD*WAVONC	0.0007614	0.2647804	6.62E-06	0.0002434	0.0001797	-0.003669
WHYD*WHYD	0.0462092	-0.743413	0.0002157	0.016075	0.0149364	-0.001587
WFURN*FRWI	0.0347649	1.5493489	-0.000255	-0.001982	-0.002029	0.0277631
WFURN*FRFU	-0.014790	-0.030620	-0.000225	-0.004072	-0.003793	0.0017176
WFURN*FRHT	-0.006845	0.0500560	-0.000047	0.0000541	-0.000043	-0.002292
WFURN*FRVT	-0.008078	0.2606511	0.0000550	-0.000536	-0.000414	0.0023848
WFURN*FCDI	-0.006600	-0.270529	0.0000538	0.0024456	0.0021944	0.0003542
WFURN*FCDO	-0.001175	0.2359164	-0.00010	-0.002650	-0.002414	-0.000704
WFURN*FRLGM	0.0185337	0.6124387	0.0000077	-0.002308	-0.002209	0.0005492
WFURN*WAVONC	-0.001923	0.2540009	-0.000128	0.0002645	0.0002571	0.0025092
WFURN*WHYD	-0.003850	0.2241974	-0.000009	-0.000136	-0.000154	-0.004298

WFURN*WFURN	0.0183246	-0.733689	-0.000598	0.0047738	0.0040682	0.0101858
SVT*FRWI	0.0099859	0.2826661	0.0002192	0.0047021	0.0042266	0.0118820
SVT*FRFU	-0.009300	-0.503793	0.0001363	-0.000986	-0.000908	0.0007573
SVT*FRHT	-0.000194	0.5131991	0.0000451	0.0005709	0.0005458	0.0016062
SVT*FRVT	0.0199827	1.9036176	-0.000120	0.0040974	0.0035065	-0.002404
SVT*FCDI	0.0148968	0.2925281	0.0000795	-0.001269	-0.00131	0.0024412
SVT*FCDO	-0.010164	0.4022379	-0.000058	-0.000426	-0.000469	0.0040268
SVT*FRLGM	-0.005081	-0.217562	-0.000171	-0.002639	-0.002456	-0.001400
SVT*WAVONC	-0.010513	-0.084230	0.0001499	0.0003773	0.0003434	-0.002888
SVT*WHYD	0.0040683	-0.106911	0.0000113	0.0000615	0.0000211	0.0005728
SVT*WFURN	-0.013486	-0.541521	0.0000586	-0.002603	-0.002397	-0.004007
SVT*SVT	-0.035741	1.7301785	0.0003921	-0.010774	-0.010413	-0.004337
SHT*FRWI	0.0150293	-0.055064	0.0001659	-0.000295	-0.000244	0.0099470
SHT*FRFU	0.0162630	-0.425722	0.0000311	-0.000124	-0.000247	-0.002838
SHT*FRHT	0.0210196	1.1698517	-0.000023	0.0024872	0.0021973	0.0033280
SHT*FRVT	0.0091107	0.2803833	-0.000188	-0.002877	-0.002558	-0.002494
SHT*FCDI	-0.005944	0.1734736	-0.000068	-0.002726	-0.002492	-0.004059
SHT*FCDO	-0.004966	-0.309486	0.0001667	0.0024566	0.0020738	0.0024148
SHT*FRLGM	0.0092595	0.8010709	-0.000024	-0.005312	-0.004963	-0.001804
SHT*WAVONC	-0.005458	-0.237794	0.0000265	0.0002752	0.0002754	-0.001377
SHT*WHYD	-0.001356	-0.380674	0.0000374	-0.000029	-0.000178	-0.000523
SHT*WFURN	-0.00310	-0.12763	0.00007	-0.00032	-0.00021	-0.00004
SHT*SVT	0.00951	0.62236	0.00003	0.00375	0.00342	0.00348
SHT*SHT	-0.02227	0.14752	0.00021	-0.01225	-0.01140	0.00212
WENG*FRWI	0.07429	4.96309	0.00004	0.00795	0.00645	0.05828
WENG*FRFU	0.00637	1.59892	0.00015	0.00167	0.00112	0.00482
WENG*FRHT	-0.00785	-0.58719	-0.00005	0.00068	0.00079	0.00461
WENG*FRVT	0.00679	0.78356	-0.00019	0.00273	0.00245	-0.00031
WENG*FCDI	-0.00164	1.58115	-0.00006	0.00377	0.00311	0.00496
WENG*FCDO	0.01667	1.87613	0.00009	0.00200	0.00150	0.00160
WENG*FRLGM	0.01003	1.36130	-0.00012	-0.00083	-0.00100	0.00144
WENG*WAVONC	0.00917	0.14585	-0.00006	-0.00234	-0.00236	0.00110
WENG*WHYD	0.00977	0.86832	0.00011	0.00152	0.00148	-0.00171
WENG*WFURN	0.00068	0.32840	-0.00012	-0.00422	-0.00416	0.00354
WENG*SVT	0.00105	-0.34628	0.00004	-0.00427	-0.00404	0.00151
WENG*SHT	0.00819	0.28819	0.00011	0.00313	0.00291	-0.00167
WENG*WENG	0.01678	1.56822	0.00032	0.00863	0.00771	0.01267
FACT*FRWI	0.05945	4.48227	0.00011	0.00735	0.00580	0.07210
FACT*FRFU	0.00308	0.97910	-0.00004	0.00238	0.00197	0.00742
FACT*FRHT	-0.01790	0.61831	0.00007	-0.00014	-0.00007	-0.00320
FACT*FRVT	-0.00743	0.60338	-0.00020	-0.00110	-0.00106	-0.00092
FACT*FCDI	0.03035	2.68269	0.00015	0.00878	0.00743	0.01036
FACT*FCDO	0.03518	4.45723	0.00002	0.00960	0.00783	0.01766
FACT*FRLGM	-0.00037	0.24562	-0.00010	-0.00337	-0.00319	-0.00376
FACT*WAVONC	-0.00475	0.36450	0.00022	0.00479	0.00449	0.00262
FACT*WHYD	-0.00856	0.09255	0.00003	-0.00167	-0.00155	-0.00242
FACT*WFURN	0.01045	1.36348	-0.00003	-0.00130	-0.00143	0.00406
FACT*SVT	0.00387	0.32844	0.00027	0.00073	0.00057	-0.00086
FACT*SHT	0.01897	0.06176	0.00009	0.00696	0.00636	0.00127
FACT*WENG	0.04554	3.81914	0.00011	0.00873	0.00726	0.01499
FACT*FACT	-0.07900	-0.63880	0.00060	-0.00570	-0.00509	-0.01159
AKRDTE*FRWI	0.13345	28.75334	0.00010	0.00468	0.00444	-0.00246

AKRDTE*FRFU	0.08525	17.91908	0.00011	0.00557	0.00538	-0.00089
AKRDTE*FRHT	0.00752	0.95240	0.00011	0.00075	0.00074	-0.00329
AKRDTE*FRVT	0.01047	1.18313	0.00018	0.00137	0.00123	0.00337
AKRDTE*FCDI	-0.00269	3.60721	-0.00002	-0.00417	-0.00388	-0.00195
AKRDTE*FCDO	0.03315	6.78412	0.00002	0.00427	0.00397	0.00089
AKRDTE*FRLGM	0.02346	3.71366	0.00014	0.00412	0.00375	-0.00271
AKRDTE*WAVONC	0.00171	4.54505	0.00013	-0.00034	-0.00034	0.00013
AKRDTE*WHYD	0.03041	3.25600	0.00000	0.00031	0.00038	-0.00118
AKRDTE*WFURN	0.03573	5.16146	0.00006	0.00252	0.00240	0.00039
AKRDTE*SVT	0.00589	1.81460	-0.00014	-0.00222	-0.00204	-0.00020
AKRDTE*SHT	0.00553	1.72765	-0.00008	-0.00286	-0.00258	0.00033
AKRDTE*WENG	0.06618	11.51860	0.00009	0.00640	0.00595	-0.00408
AKRDTE*FACT	0.05323	10.96167	0.00002	0.00489	0.00458	-0.00314
AKRDTE*AKRDTE	-0.01479	-0.06401	0.00005	0.00776	0.00713	-0.01371
AKOANDS*FRWI	0.00295	0.12549	0.00003	0.02991	0.02404	-0.00144
AKOANDS*FRFU	-0.00329	-0.60852	0.00011	0.01779	0.01429	-0.00162
AKOANDS*FRHT	0.00261	0.46400	0.00008	0.00217	0.00200	-0.00104
AKOANDS*FRVT	0.01446	0.09365	0.00012	0.00445	0.00393	-0.00087
AKOANDS*FCDI	0.00663	-0.77436	0.00004	0.00936	0.00785	0.00161
AKOANDS*FCDO	0.00827	-0.12345	0.00031	0.01746	0.01466	0.00116
AKOANDS*FRLGM	0.00343	0.45311	-0.00009	0.00592	0.00477	-0.00256
AKOANDS*WAVONC	0.00298	-0.20347	-0.00020	0.00670	0.00569	0.00031
AKOANDS*WHYD	0.00293	-1.55703	0.00011	0.00433	0.00390	-0.00417
AKOANDS*WFURN	0.00888	-0.34878	-0.00008	0.00699	0.00534	0.00117
AKOANDS*SVT	-0.00821	0.41087	-0.00001	0.00658	0.00570	-0.00155
AKOANDS*SHT	-0.00701	-0.42780	-0.00014	-0.00076	-0.00114	-0.00680
AKOANDS*WENG	-0.01937	0.48133	0.00004	0.01365	0.01015	-0.00172
AKOANDS*FACT	0.00819	0.17721	0.00019	0.02316	0.01896	0.00113
AKOANDS*AKRDTE	0.00303	0.08878	-0.00015	0.03623	0.03380	0.00204
AKOANDS*AKOANDS	-0.02057	-1.48320	-0.00537	0.00924	0.00849	-0.00924
AKPRICE*FRWI	0.38286	0.05057	0.00032	0.01739	0.01639	-0.00123
AKPRICE*FRFU	0.25220	-0.30274	0.00015	0.01247	0.01169	-0.00088
AKPRICE*FRHT	0.03949	0.06487	0.00010	0.00502	0.00462	0.00619
AKPRICE*FRVT	0.02048	-0.29809	0.00007	0.00223	0.00205	0.00028
AKPRICE*FCDI	0.02017	-0.31767	-0.00022	0.00009	0.00023	-0.00085
AKPRICE*FCDO	0.07721	-0.19870	0.00029	0.00109	0.00110	-0.00179
AKPRICE*FRLGM	0.07825	0.03406	-0.00015	0.00473	0.00428	0.00115
AKPRICE*WAVONC	0.08533	0.00709	0.00001	0.00450	0.00425	-0.00266
AKPRICE*WHYD	0.04167	-0.22202	0.00003	0.00329	0.00304	0.00149
AKPRICE*WFURN	0.09772	-0.35793	-0.00013	0.00351	0.00331	0.00169
AKPRICE*SVT	0.02734	-0.29696	-0.00011	-0.00669	-0.00615	-0.00262
AKPRICE*SHT	0.01811	-0.57858	-0.00013	-0.00133	-0.00120	-0.00478
AKPRICE*WENG	0.12796	-0.59921	0.00008	0.00645	0.00609	0.00015
AKPRICE*FACT	0.13848	-0.19380	0.00001	0.00698	0.00653	0.00190
AKPRICE*AKRDTE	0.76654	-0.36133	0.00034	0.03372	0.03155	0.00049
AKPRICE*AKOANDS	0.00958	-0.04419	-0.00206	0.10339	0.09663	0.00200
AKPRICE*AKPRICE	-0.03460	1.01354	-0.00082	-0.01173	-0.01052	0.00889
U*FRWI	0.00375	-0.11310	-0.00042	-0.01615	-0.01507	-0.00141
U*FRFU	0.00104	-0.18757	-0.00014	-0.00888	-0.00824	-0.00007
U*FRHT	0.01296	0.54819	-0.00006	-0.00009	-0.00022	0.00454
U*FRVT	0.00199	-0.53749	0.00036	0.00052	0.00043	0.00034
U*FCDI	0.00797	-0.03435	0.00003	-0.00252	-0.00239	0.00390

U*FCDO	-0.00855	0.79556	0.00024	0.00000	-0.00007	-0.00241
U*FRLGM	0.00269	0.14989	-0.00011	-0.00508	-0.00468	0.00056
U*WAVONC	-0.01181	0.29174	-0.00037	-0.00507	-0.00474	-0.00207
U*WHYD	-0.00751	-0.30991	-0.00014	-0.00325	-0.00307	-0.00199
U*WFURN	0.00314	-0.17458	0.00004	-0.00421	-0.00394	0.00063
U*SVT	0.02136	0.21503	0.00002	-0.00145	-0.00142	0.00207
U*SHT	-0.00917	0.03395	-0.00014	0.00006	0.00005	-0.00078
U*WENG	0.00134	-0.21918	-0.00002	-0.00339	-0.00323	-0.00031
U*FACT	-0.01168	-0.03988	-0.00014	-0.00595	-0.00568	-0.00089
U*AKRDTE	-0.00213	-0.43376	-0.00011	-0.02668	-0.02489	-0.00142
U*AKOANDS	0.01128	0.63812	-0.00111	-0.08328	-0.07790	-0.00124
U*AKPRICE	0.00830	-0.04309	-0.00145	-0.08512	-0.07958	0.00168
U*U	-0.03234	1.53167	0.00143	0.08386	0.07832	-0.00534
SW*FRWI	0.18056	15.37966	0.00015	0.00755	0.00535	-0.24416
SW*FRFU	0.01473	-0.20024	-0.00005	0.00390	0.00393	-0.01834
SW*FRVT	-0.00346	0.53465	0.00002	0.00303	0.00277	-0.00449
SW*FCDI	-0.02271	-0.80778	-0.00020	-0.00199	-0.00146	-0.01382
SW*FCDO	-0.00401	0.12171	-0.00011	-0.00465	-0.00438	-0.01100
SW*FRLGM	0.03056	0.47076	0.00003	0.00186	0.00148	-0.00331
SW*WAVONC	0.00431	-0.00537	0.00014	-0.00020	-0.00014	-0.00645
SW*WHYD	-0.00137	1.11174	-0.00009	-0.00318	-0.00295	0.00015
SW*WFURN	0.00745	-0.25802	-0.00021	-0.00222	-0.00191	-0.01381
SW*SVT	-0.00130	-0.51493	0.00006	-0.00620	-0.00559	-0.00651
SW*SHT	-0.01262	-0.65113	-0.00009	-0.00514	-0.00464	-0.00531
SW*WENG	-0.00037	0.03339	-0.00005	-0.00403	-0.00359	-0.02506
SW*FACT	-0.00836	-0.55504	0.00000	-0.00704	-0.00616	-0.03528
SW*AKRDTE	0.07762	13.78031	0.00006	0.00272	0.00252	0.00354
SW*AKOANDS	0.00244	-0.21671	0.00023	0.01256	0.01049	-0.00141
SW*AKPRICE	0.18540	0.07418	0.00016	0.00929	0.00871	0.00185
SW*U	-0.00280	0.53959	-0.00005	-0.00870	-0.00800	-0.00056
SW*SW	0.08001	3.75178	0.00049	-0.00221	-0.00308	0.17900
TWR*FRWI	0.02793	2.34284	-0.00012	0.00382	0.00332	0.01442
TWR*FRFU	-0.00019	1.40786	0.00005	-0.00241	-0.00232	0.00097
TWR*FRHT	0.00531	0.45216	-0.00002	-0.00012	-0.00018	0.00144
TWR*FRVT	-0.01016	0.45614	-0.00005	-0.00466	-0.00431	-0.00001
TWR*FCDI	0.00021	1.02670	0.00018	-0.00085	-0.00092	0.00013
TWR*FCDO	0.01248	1.09012	-0.00018	0.00171	0.00143	-0.00202
TWR*FRLGM	0.00480	0.88460	-0.00007	-0.00240	-0.00224	0.00159
TWR*WAVONC	0.00656	-0.50720	-0.00024	-0.00149	-0.00138	0.00100
TWR*WHYD	0.02408	0.23043	-0.00002	0.00539	0.00508	-0.00045
TWR*WFURN	-0.00868	0.21953	-0.00024	-0.00674	-0.00632	-0.00194
TWR*SVT	0.02286	0.27800	-0.00005	0.00164	0.00158	0.00163
TWR*SHT	0.00484	0.52785	-0.00004	0.00058	0.00062	-0.00229
TWR*WENG	0.06997	5.34291	0.00025	0.00818	0.00673	0.00930
TWR*FACT	0.02771	2.09088	0.00011	-0.00017	-0.00038	-0.00028
TWR*AKRDTE	0.07125	13.95654	0.00021	0.00380	0.00344	-0.00163
TWR*AKOANDS	-0.00176	-0.02141	0.00025	0.00874	0.00758	-0.00177
TWR*AKPRICE	0.15625	-0.12072	-0.00001	0.00476	0.00445	-0.00247
TWR*U	-0.00891	0.04268	0.00000	-0.00694	-0.00644	-0.00016
TWR*SW	-0.00335	0.29322	0.00005	0.00334	0.00319	-0.00608
TWR*TWR	-0.01611	1.18814	0.00022	0.00398	0.00367	0.00267

APPENDIX K – RSE GOODNESS OF FIT FOR K-FACTORS

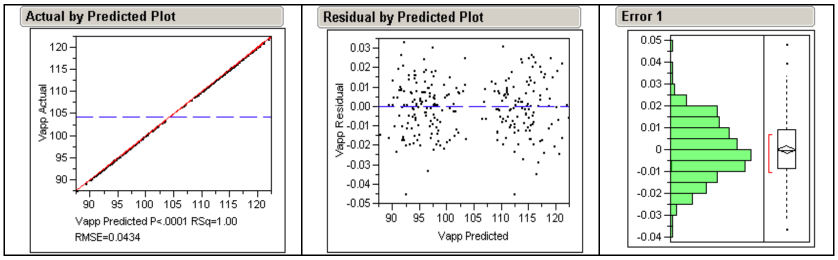


Figure K1: Fit Analysis of Approach Speed

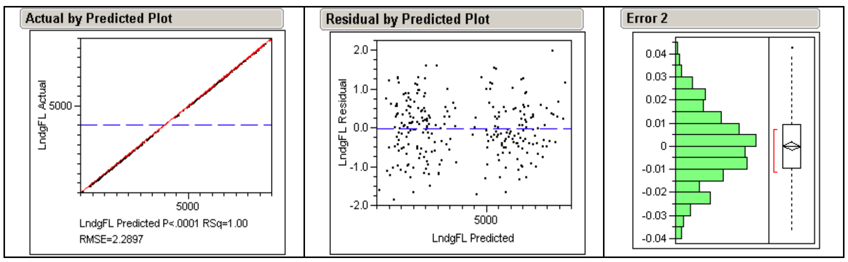


Figure K2: Fit Analysis of Landing Field Length

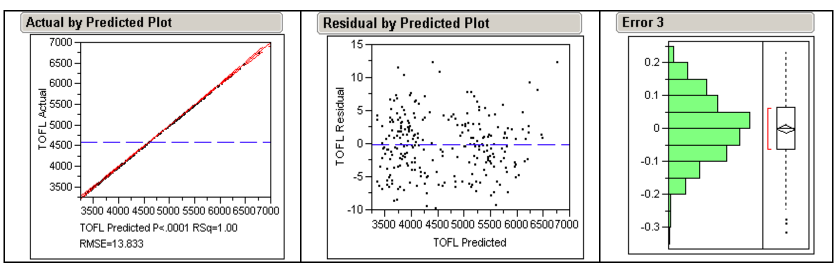


Figure K3: Fit Analysis of Takeoff Field Length

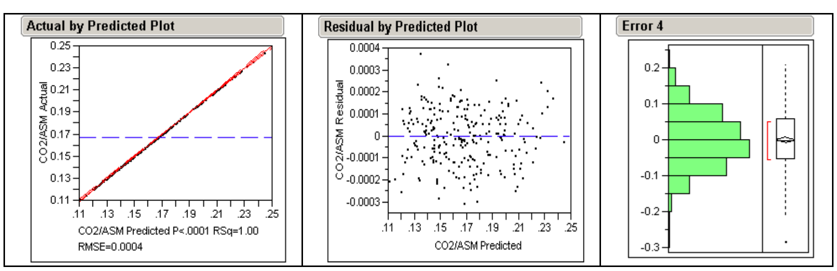


Figure K4: Fit Analysis of CO2/ASM

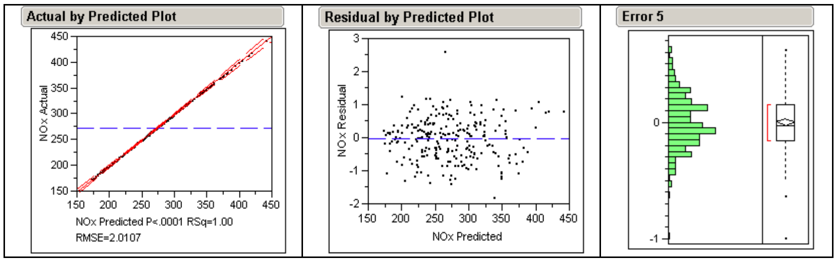


Figure K5: Fit Analysis of NOx

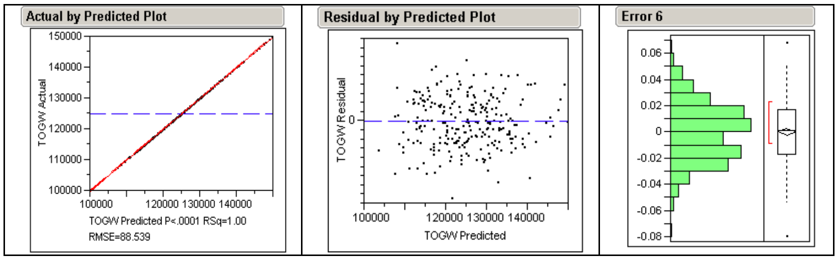


Figure K6: Fit Analysis of Takeoff Gross Weight

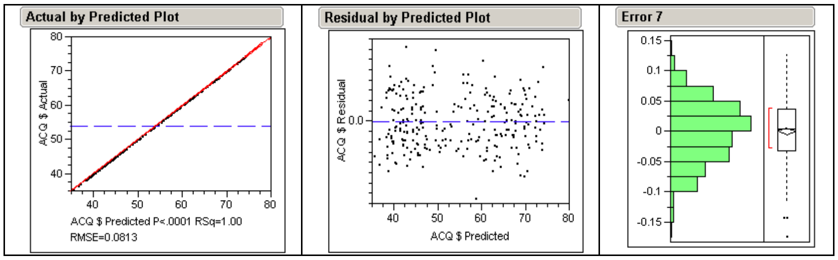


Figure K7: Fit Analysis of Acquisition Cost

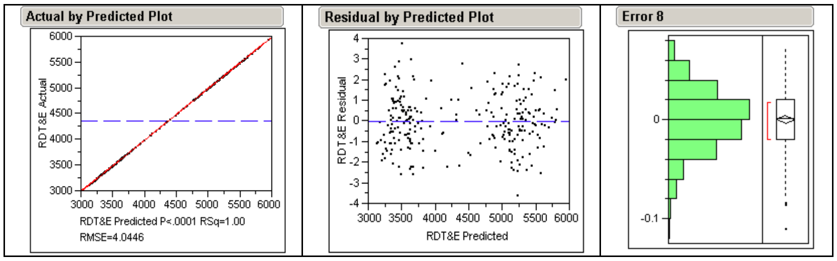


Figure K8: Fit Analysis of RDT&E Cost

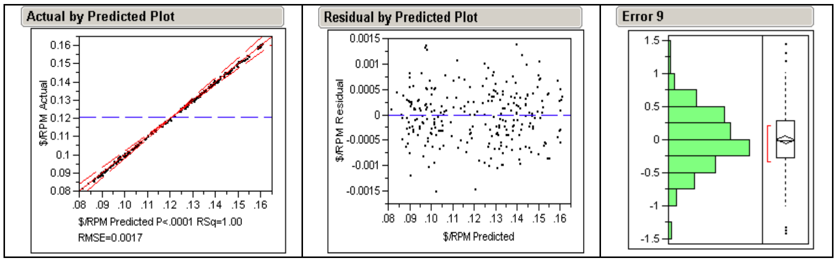


Figure K9: Fit Analysis of Required Yield per RPM

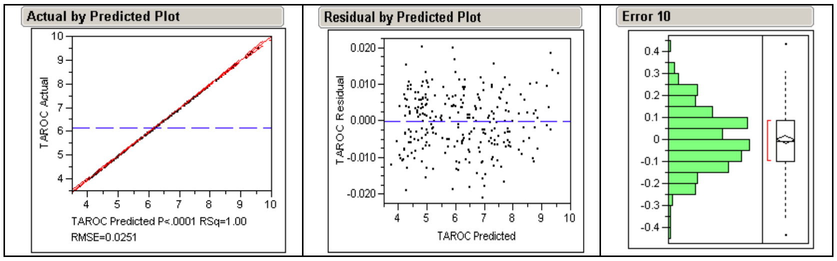


Figure K10: Fit Analysis of Total Airplane Related Operating Costs

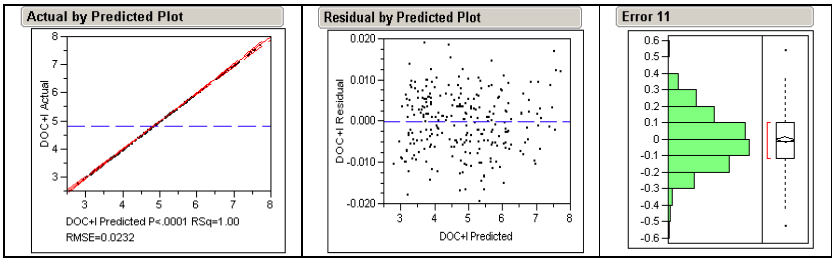


Figure K11: Fit Analysis of Direct Operating Costs Plus Interest

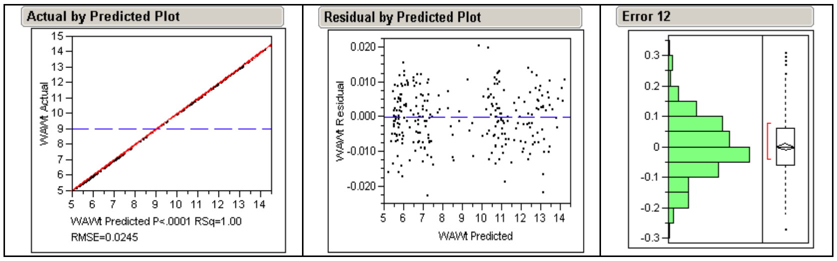


Figure K12: Fit Analysis of Wing Aerial Weight

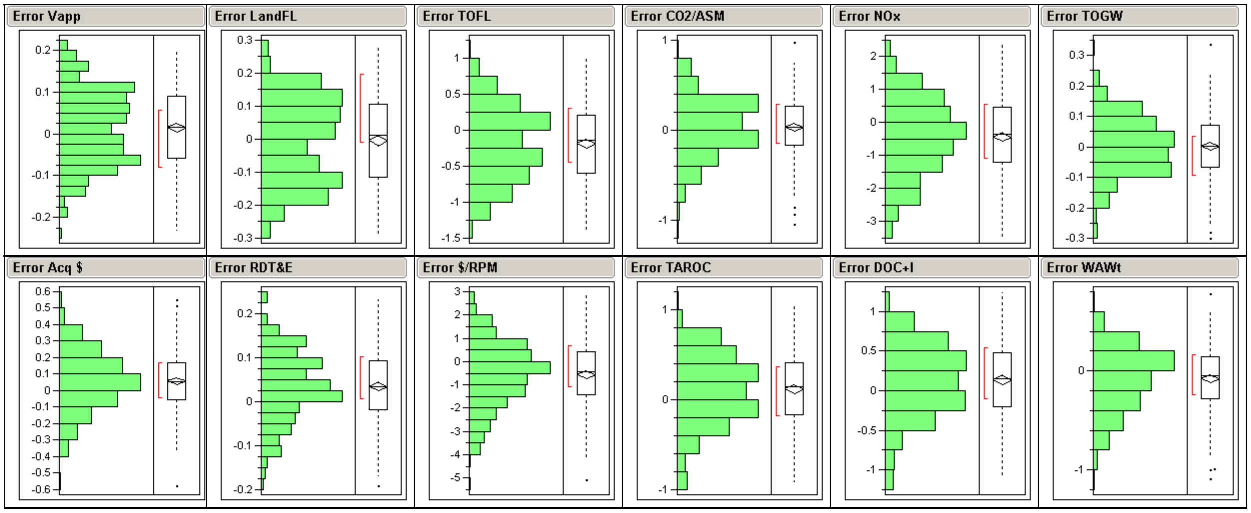


Figure K13: Error Analysis of Random Cases for the Response Surface Equations

APPENDIX L – ANNUAL TECHNOLOGY ENVIRONMENTS

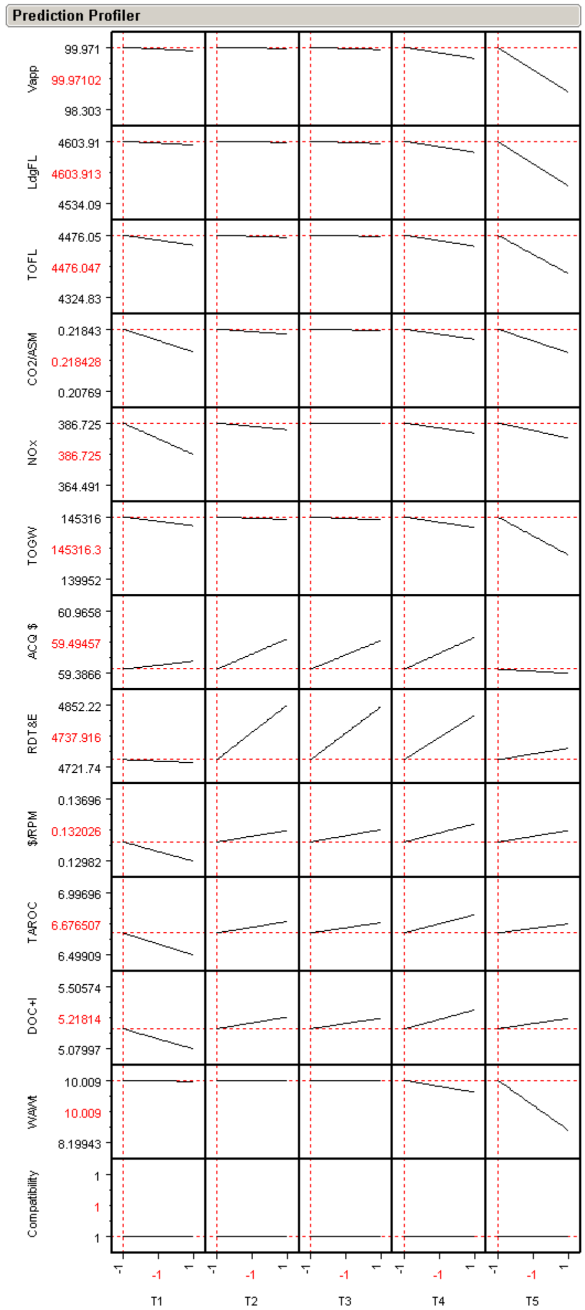


Figure L1: Prediction Profile for 2006

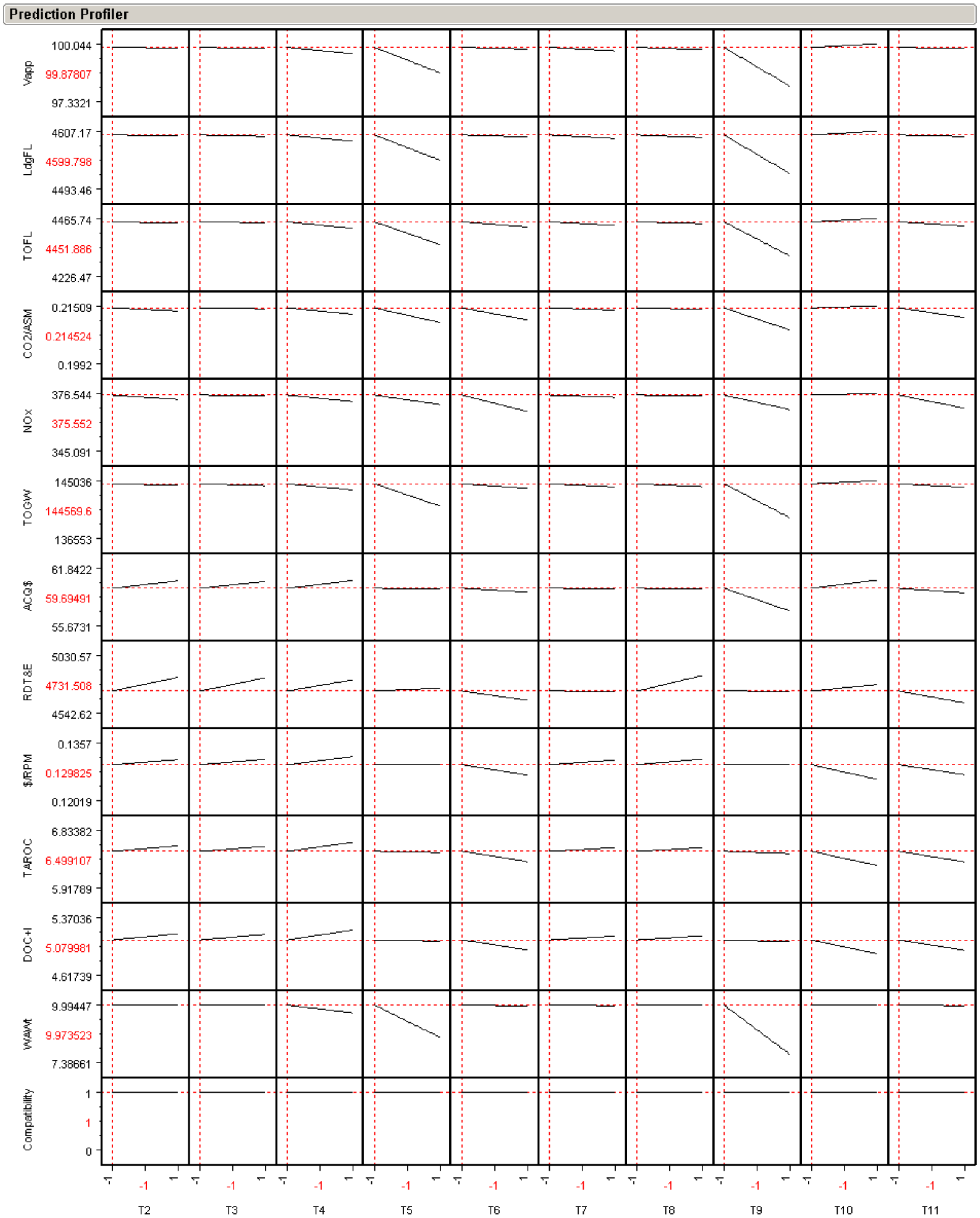


Figure L2: Prediction Profile for 2009

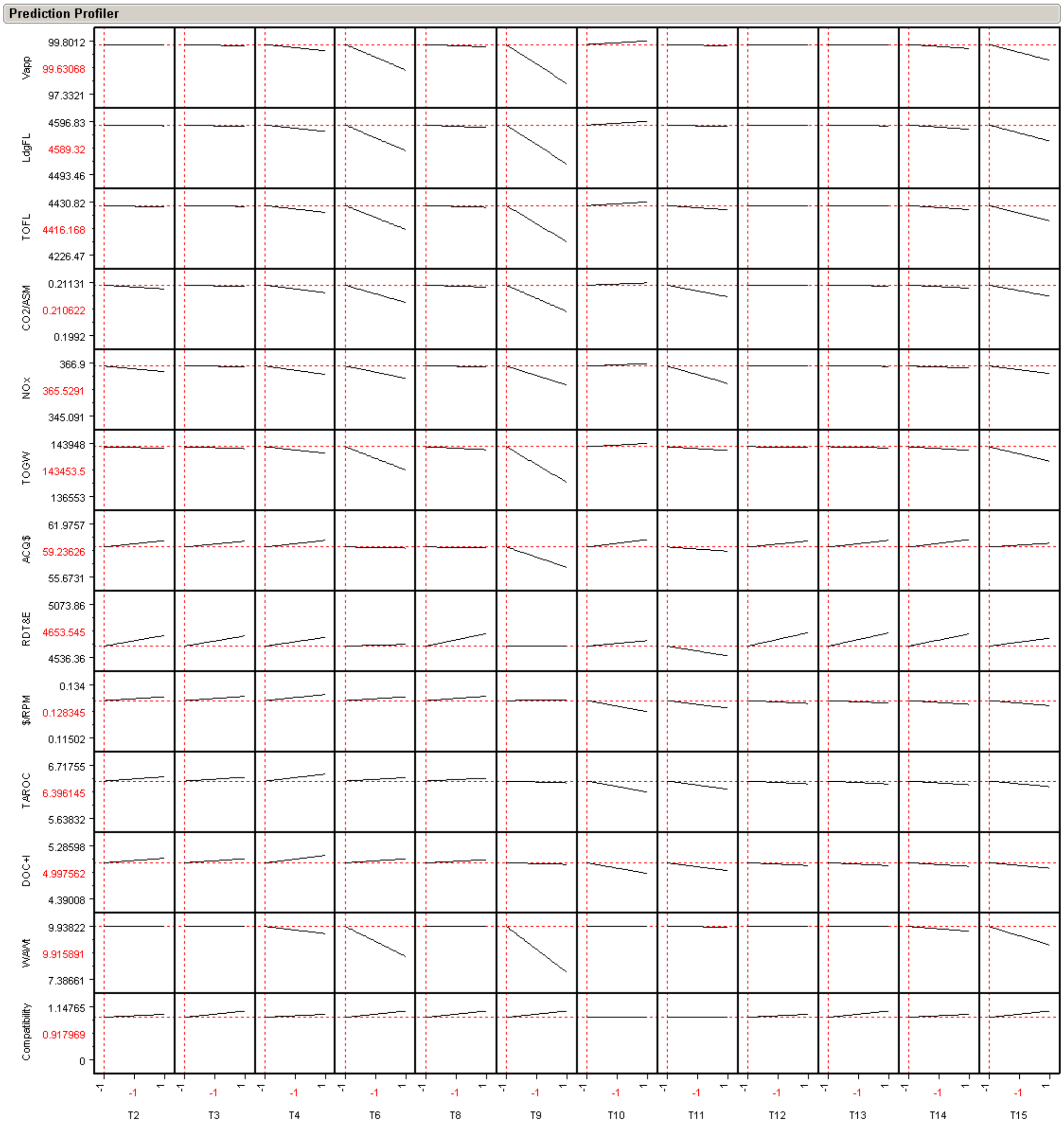


Figure L3: Prediction Profile for 2010

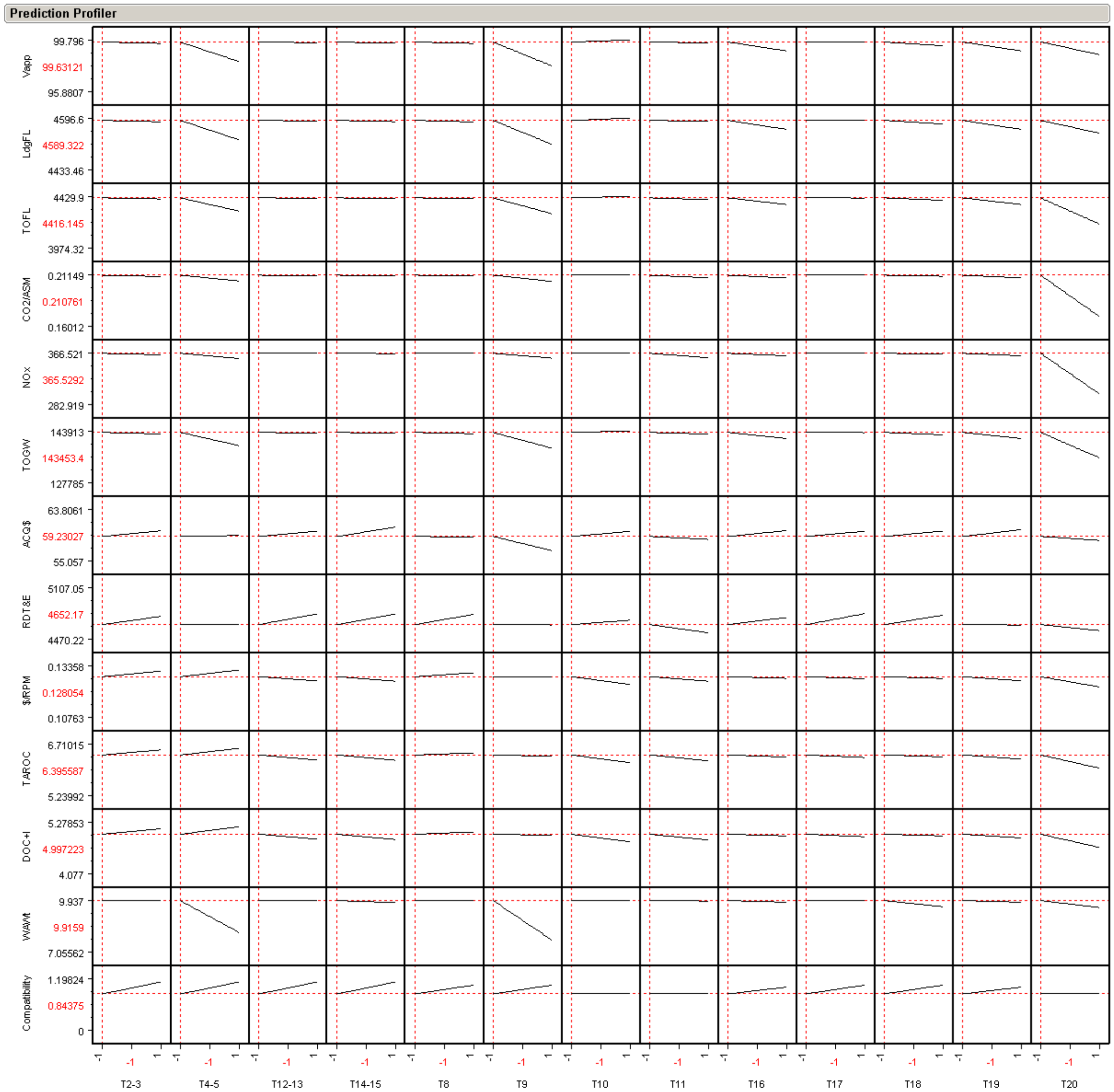


Figure L4: Prediction Profile for 2011-2012

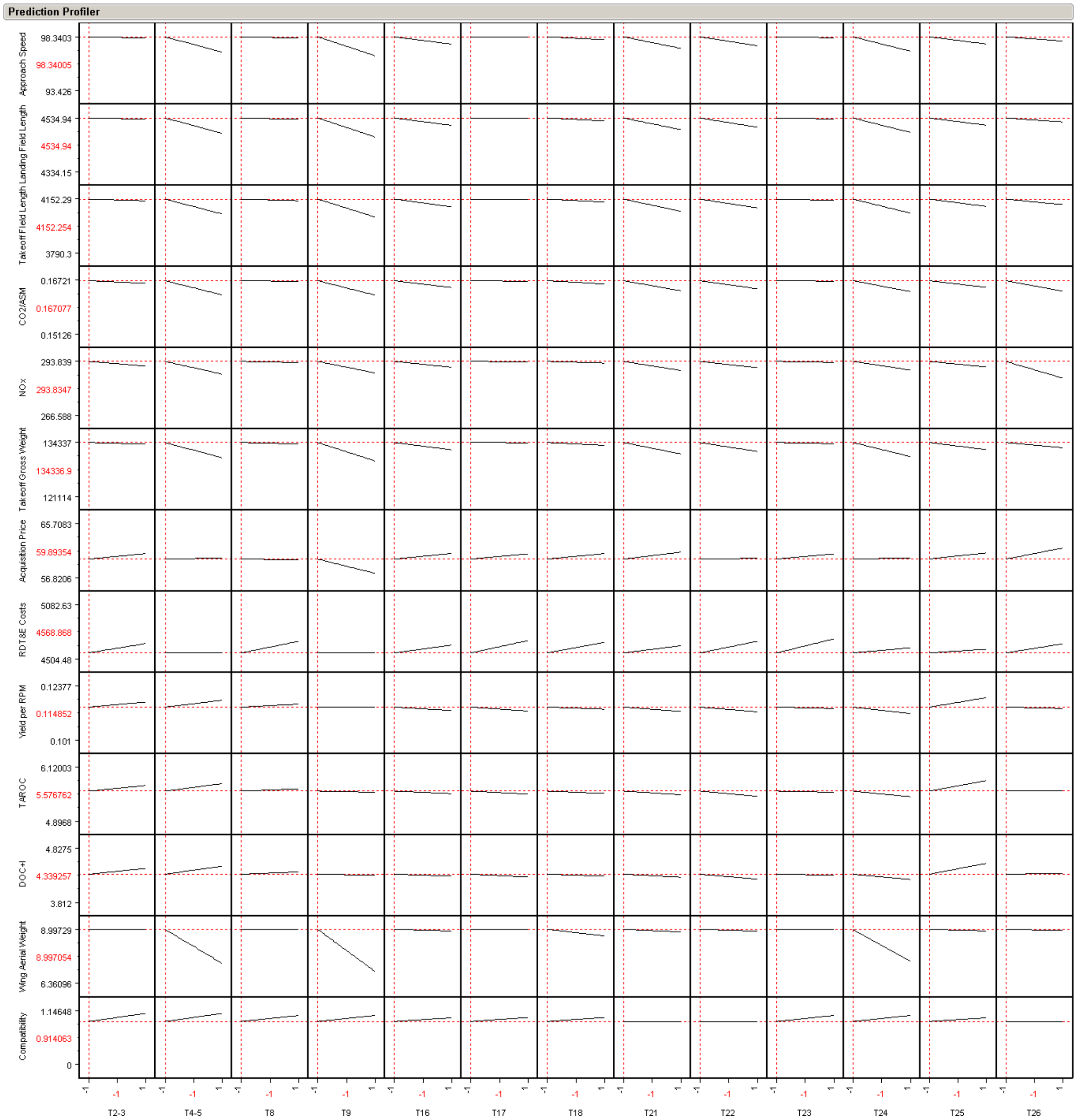


Figure L5: Prediction Profile for 2013

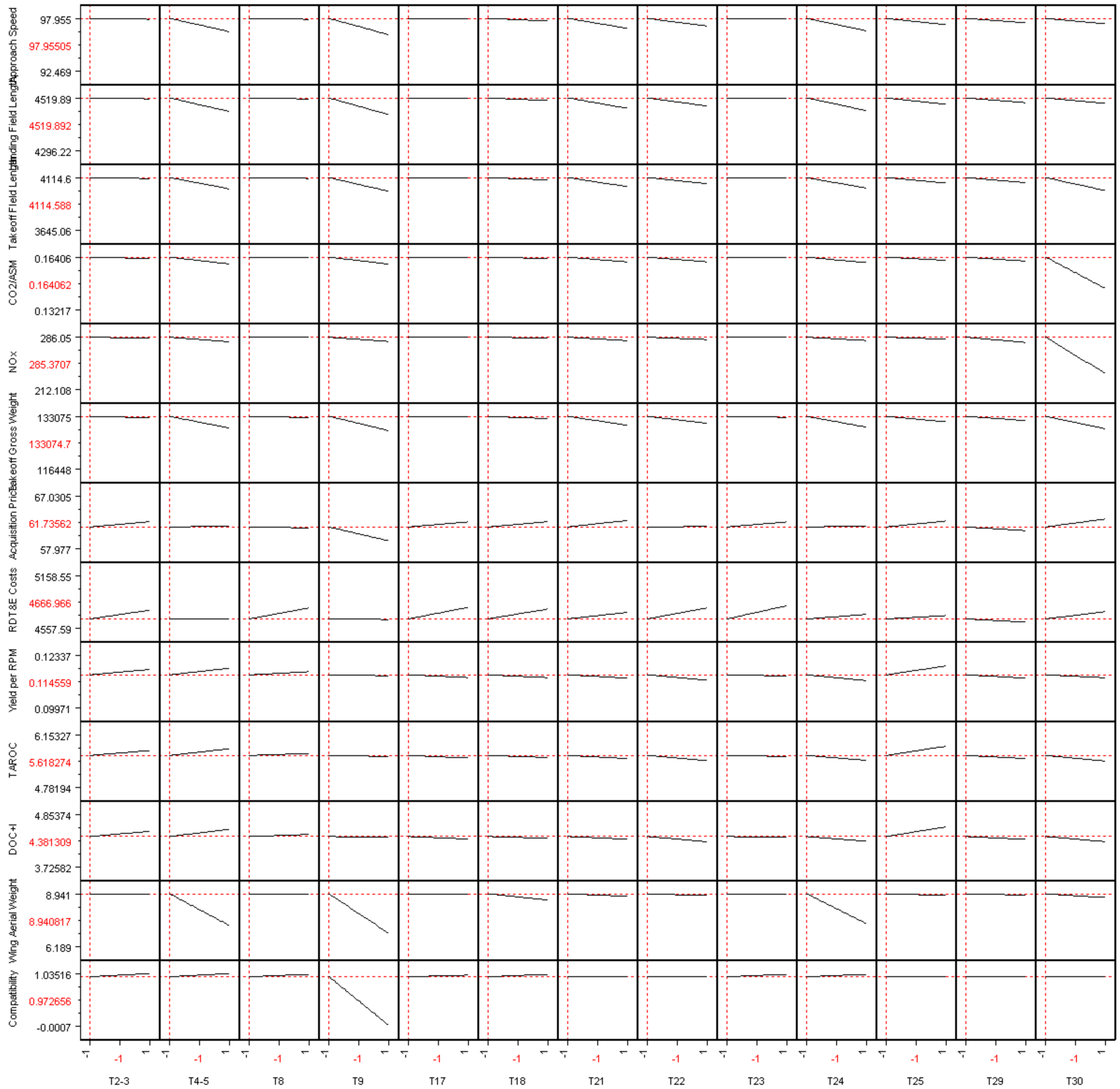


Figure L6: Prediction Profile for 2014

APPENDIX M – ANNUAL TOPSIS SCENARIOS

Table MI: Top Ten Rankings of the Technology Mixes for Year 2006

Rankings	Technology Mix	Technologies
1	18	T1+T5
2	26	T1+T2+T5
3	22	T1+T3+T5
4	17	T1
5	20	T1+T4+T5
6	30	T1+T2+T3+T5
7	25	T1+T2
8	21	T1+T3
9	28	T1+T2+T4+T5
10	24	T1+T3+T4+T5

Table MII: Top Ten Rankings of the Technology Mixes for Year 2008

Rankings	Technology Mix	Technologies
1	71	T1+T5+T6
2	103	T1+T2+T5+T6
3	72	T1+T5+T6+T7
4	87	T1+T3+T5+T6
5	67	T1+T6
6	79	T1+T4+T5+T6
7	68	T1+T6+T7
8	104	T1+T2+T5+T6+T7
9	88	T1+T3+T5+T6+T7
10	119	T1+T2+T3+T5+T6

Table MIII: Top Ten Rankings of the Technology Mixes for Year 2009

Rankings	Technology Mix	Technologies
1	612	T2+T5+T6+T10+T11
2	552	T2+T6+T9+T10+T11
3	868	T2+T3+T5+T6+T10+T11
4	548	T2+T6+T10+T11
5	628	T2+T5+T6+T7+T10+T11
6	560	T2+T6+T8+T9+T10+T11
7	808	T2+T3+T6+T9+T10+T11
8	620	T2+T5+T6+T8+T10+T11
9	568	T2+T6+T7+T9+T10+T11
10	484	T3+T4+T5+T6+T10+T11
Baseline Technology : T1		

Table MIV: Top Ten Rankings of the Technology Mixes for Year 2010

Rankings	Technology Mix	Technologies
1	1084	T3+T10+T11+T12+T14+T15
2	2104	T2+T10+T11+T13+T14+T15
3	1076	T3+T10+T11+T14+T15
4	2100	T2+T10+T11+T14+T15
5	1082	T3+T10+T11+T12+T15
6	2102	T2+T10+T11+T13+T15
7	1147	T3+T9+T10+T11+T12+T14
8	2167	T2+T9+T10+T11+T13+T14
9	1083	T3+T10+T11+T12+T14
10	3124	T2+T3+T10+T11+T14+T15
Baseline Technologies: T1, T6, T7		

Table MV: Top Ten Rankings of the Technology Mixes for Year 2011-2012

Rankings	Technology Mix	Technologies
1	1636	T12-13+T14-15+ T10+T11+T19+T20
2	1650	T12-13+T14-15+T10+T11+T16+T20
3	1634	T12-13+T14-15+T10+T11+T20
4	1256	T12-13+T9+T10+T11+T18+T19+T20
5	620	T14-15+T10+T11+T17+T19+T20
6	1270	T12-13+T9+T10+T11+T16+T18+T20
7	1252	T12-13+T9+T10+T11+T19+T20
8	1128	T12-13+T10+T11+T18+T19+T20
9	634	T14-15+T10+T11+T16+T17+T20
10	612	T14-15+T10+T11+T19+T20
Baseline Technologies: T1, T6, T7		

Table MVI: Top Ten Rankings of the Technology Mixes for Year 2013

Rankings	Technology Mix	Technologies
1	509	T16+T17+T18+T21+T22+T23+T24
2	510	T16+T17+T18+T21+T22+T23+T24+T26
3	501	T16+T17+T18+T21+T22+T24
4	502	T16+T17+T18+T21+T22+T24+T26
5	445	T16+T17+T21+T22+T23+T24
6	446	T16+T17+T21+T22+T23+T24+T26
7	381	T16+T18+T21+T22+T23+T24
8	382	T16+T18+T21+T22+T23+T24+T26
9	1525	T8+T16+T17+T18+T21+T22+T24
10	1526	T8+T16+T17+T18+T21+T22+T24+T26
Baseline Technologies: T1, T6, T7, T10, T11, T20, T27, T28		

Table MVII: Top Ten Rankings of the Technology Mixes for Year 2014

Rankings	Technology Mix	Technologies
1	508	T17+T18+T21+T22+T23+T24+T29+T30
2	492	T17+T18+T21+T22+T24+T29+T30
3	380	T17+T21+T22+T23+T24+T29+T30
4	506	T17+T18+T21+T22+T23+T24+T30
5	444	T17+T18+T22+T23+T24+T29+T30
6	1516	T8+T17+T18+T21+T22+T24+T29+T30
7	364	T17+T21+T22+T24+T29+T30
8	490	T17+T18+T21+T22+T24+T30
9	507	T17+T18+T21+T22+T23+T24+T29
10	500	T17+T18+T21+T22+T23+T29+T30
Baseline Technologies: T1, T6, T7, T10, T11, T20, T26, T27, T28		

Table MVIII: Top Ten Rankings of the Technology Mixes for Year 2015

Rankings	Technology Mix	Technologies
1	72	T30+T34+T35+T36
2	121	T30+T31+T32+T33
3	70	T30+T34+T36
4	86	T30+T32+T34+T36
5	79	T30+T33+T34+T35
6	100	T30+T31+T35+T36
7	93	T30+T32+T33+T34
8	114	T30+T31+T32+T36
9	107	T30+T31+T33+T35
10	105	T30+T31+T33
Baseline Technologies: T1, T6, T7, T10, T11, T20, T27, T28, T29		

APPENDIX N – TECHNOLOGY FRONT FOR 2011-2012 AND 2014

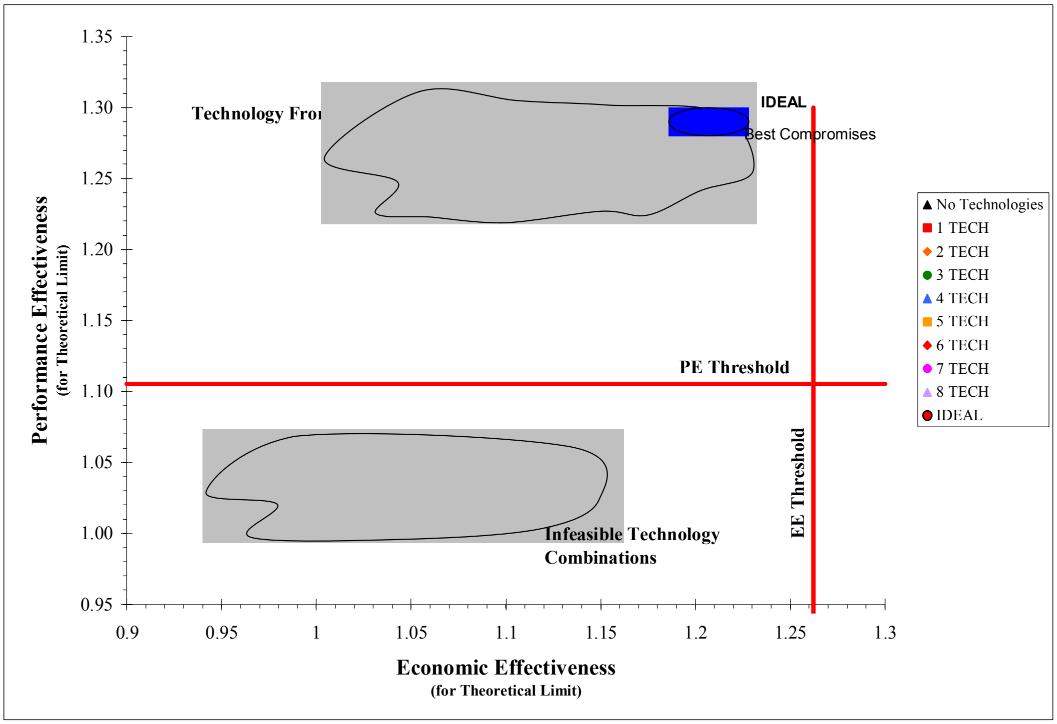


Figure N1: Tech Front 2011

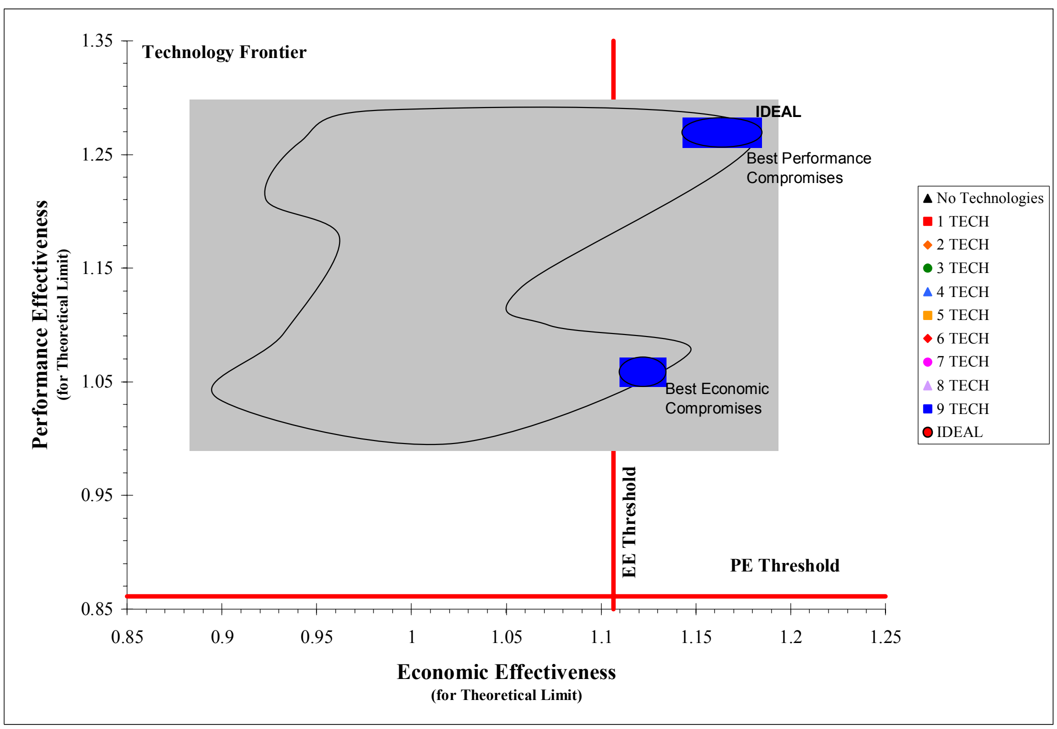


Figure N2: Tech Front 2014

APPENDIX O – TECHNOLOGY SENSITIVITIES

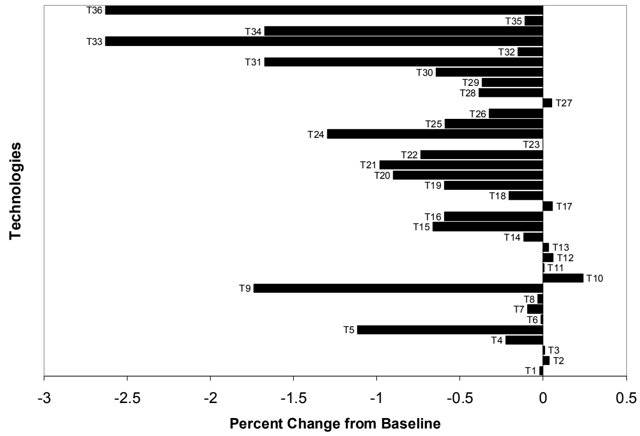


Figure O1: Technology Sensitivity for Approach Speed

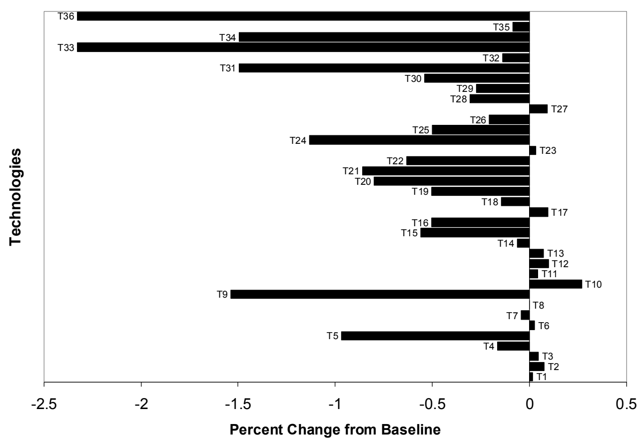


Figure O2: Technology Sensitivity for Landing Field Length

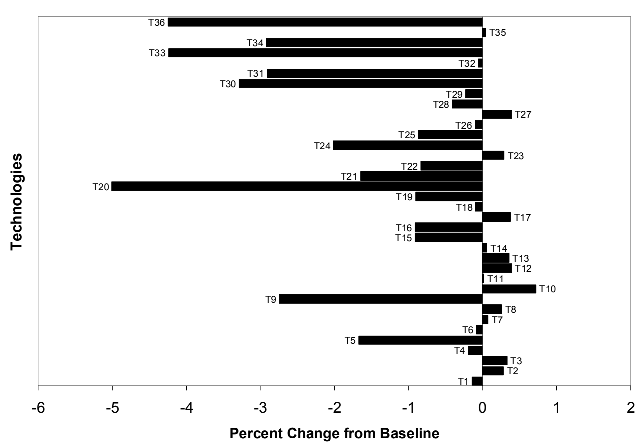


Figure O3: Technology Sensitivity for Takeoff Field Length

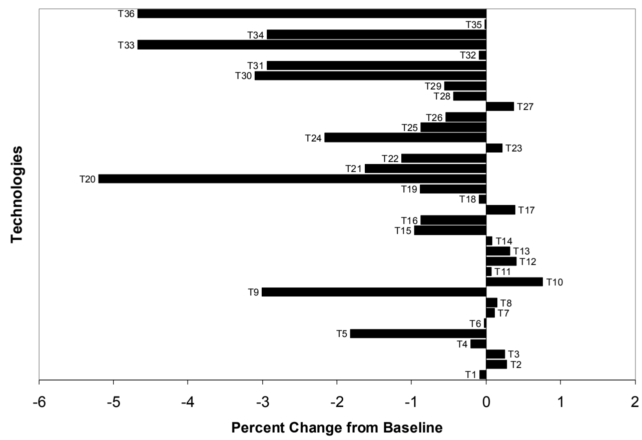


Figure O4: Technology Sensitivity for Takeoff Gross Weight

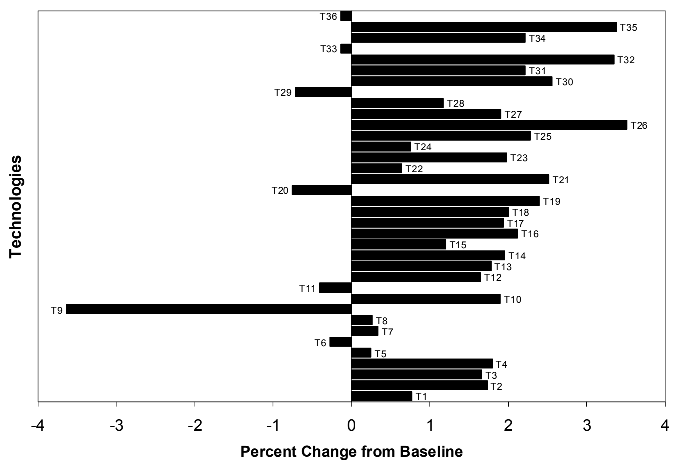


Figure O5: Technology Sensitivity for Acquisition Price

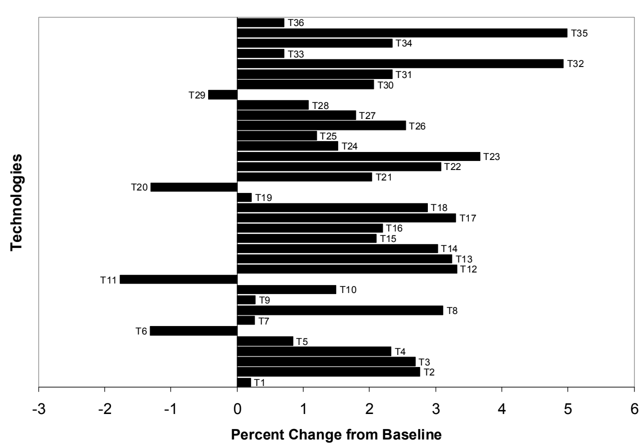


Figure O6: Technology Sensitivity for RDT&E

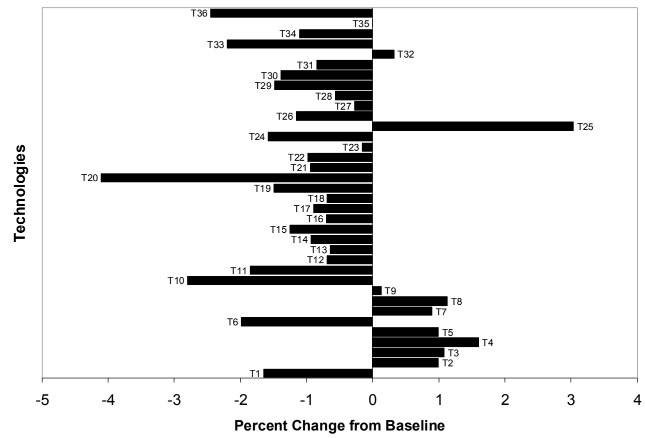


Figure O7: Technology Sensitivity for $/RPM

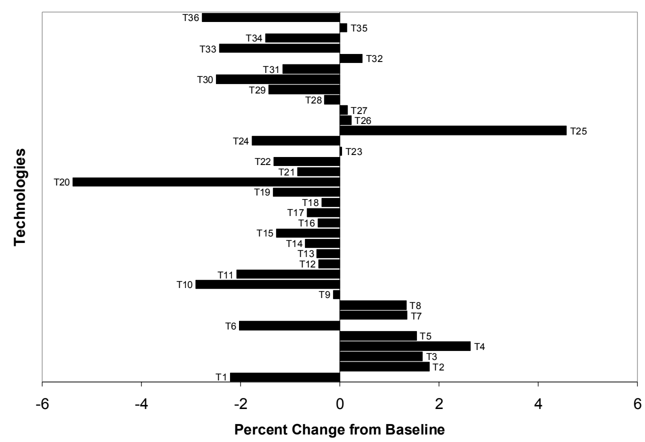


Figure O8: Technology Sensitivity for TAROC

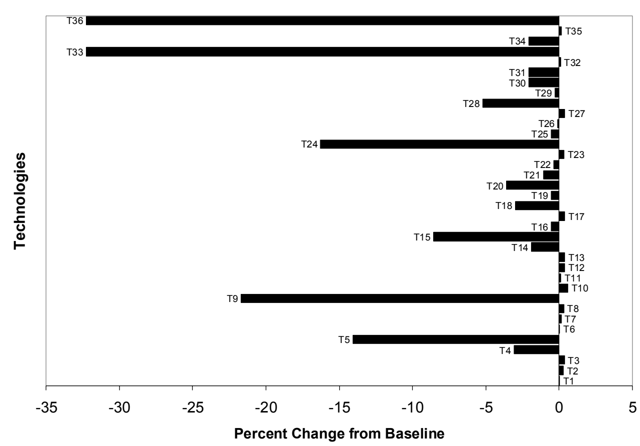


Figure O9: Technology Sensitivity for Wing Aerial Weight

APPENDIX P – EFFECTS OF TECHNOLOGIES ON THE METRICS

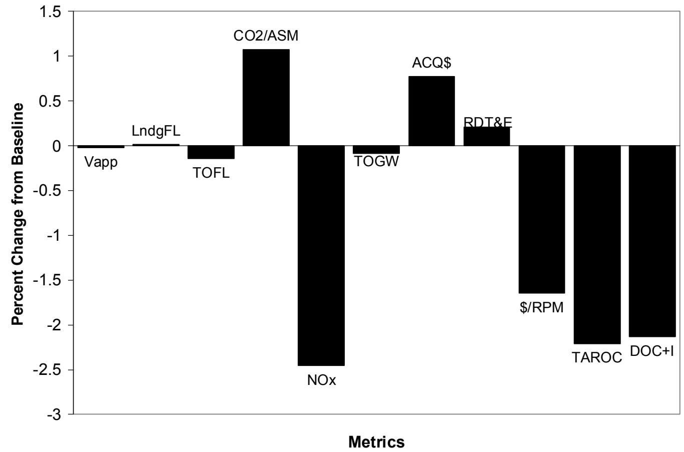


Figure P1: Effects of Technology 1

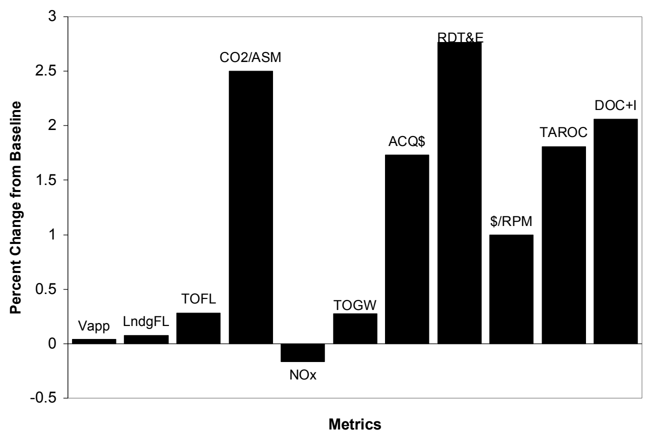


Figure P2: Effects of Technology 2

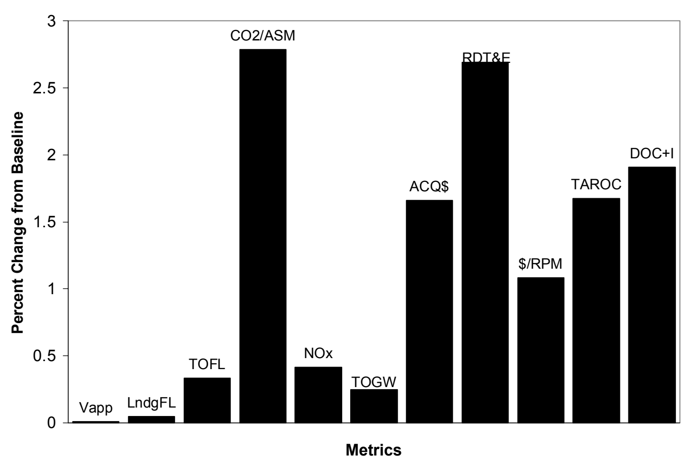


Figure P3: Effects of Technology 3

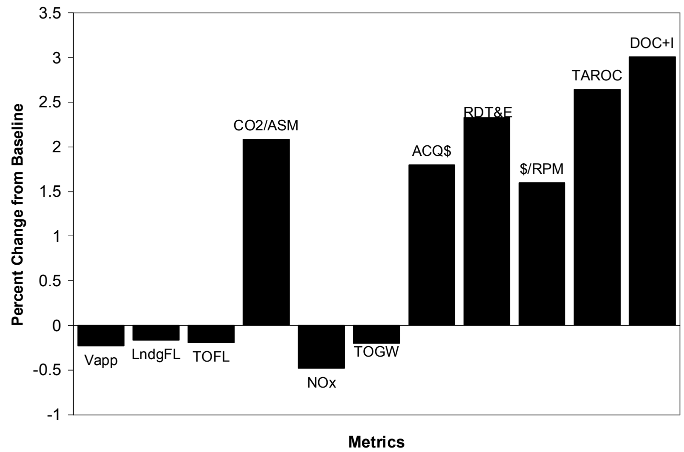


Figure P4: Effects of Technology 4

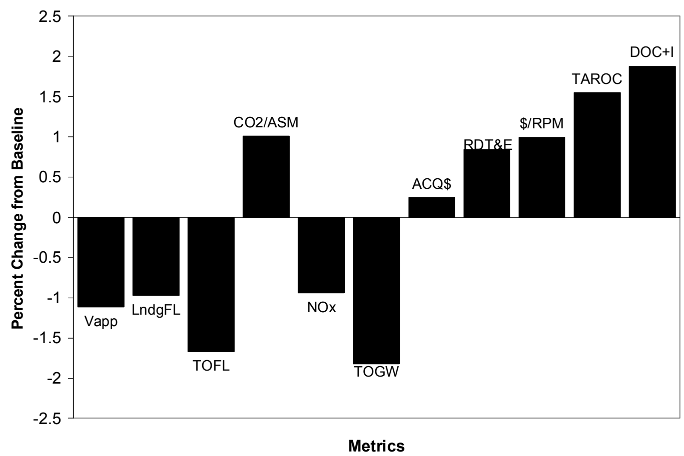


Figure P5: Effects of Technology 5

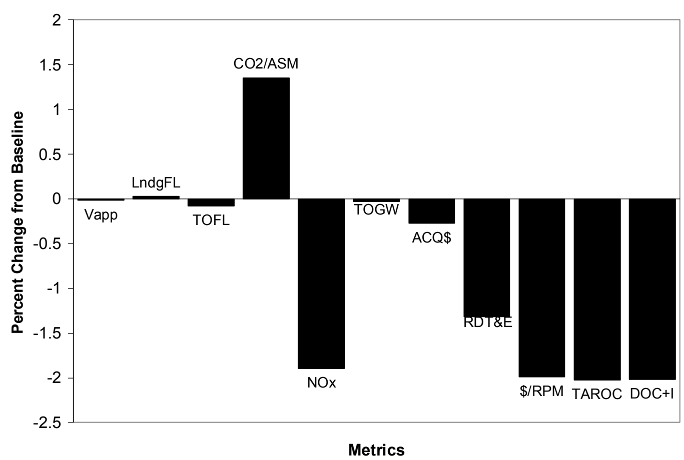


Figure P6: Effects of Technology 6

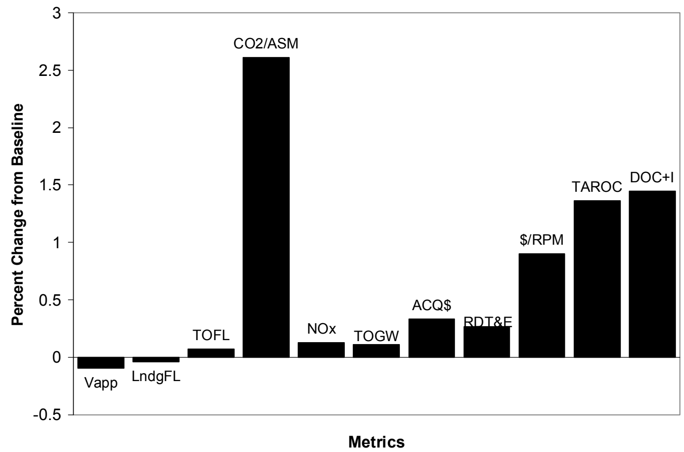


Figure P7: Effects of Technology 7

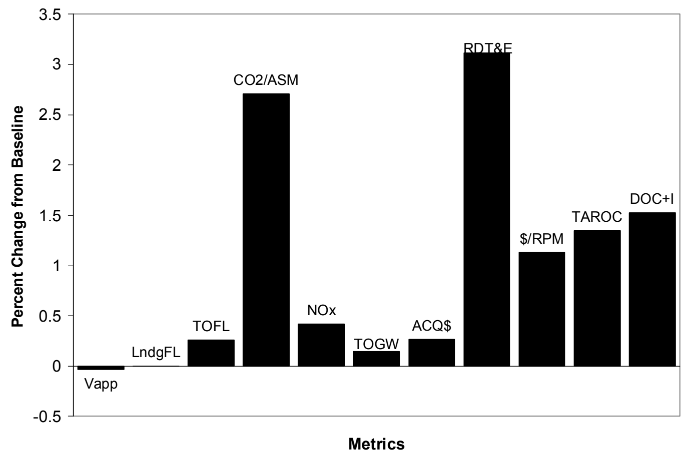


Figure P8: Effects of Technology 8

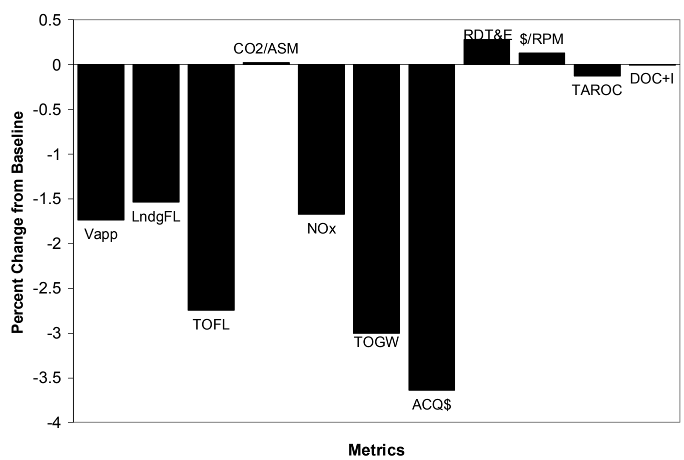


Figure P9: Effects of Technology 9

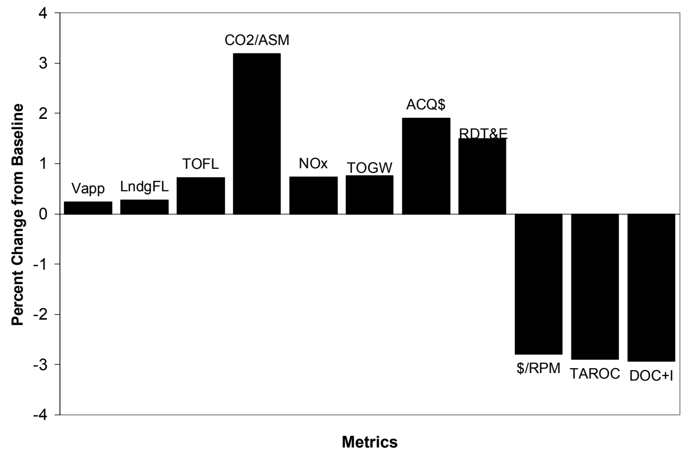


Figure P10: Effects of Technology 10

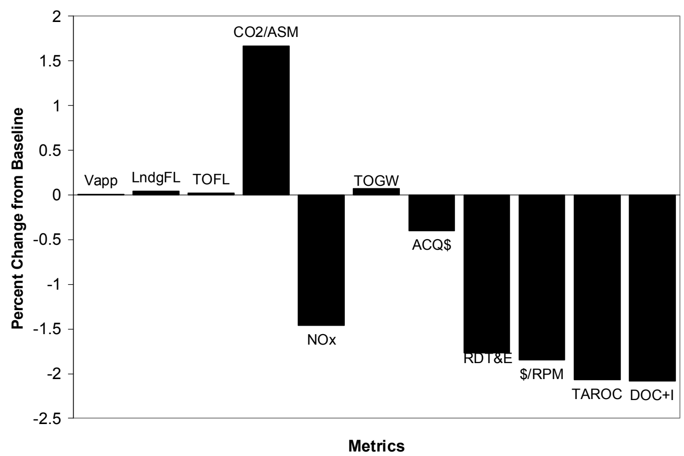


Figure P11: Effects of Technology 11

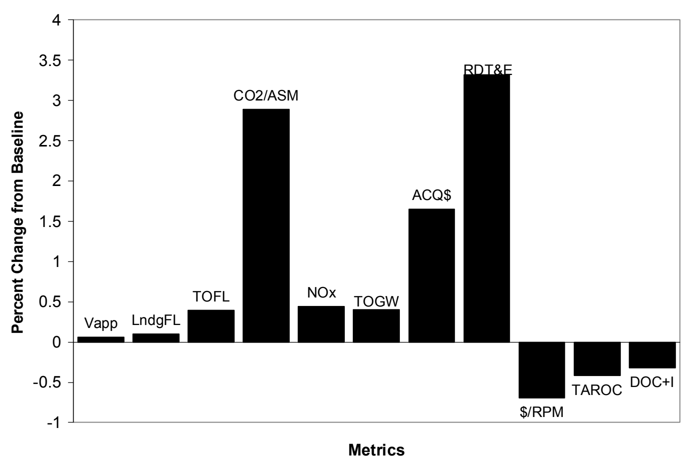


Figure P12: Effects of Technology 12

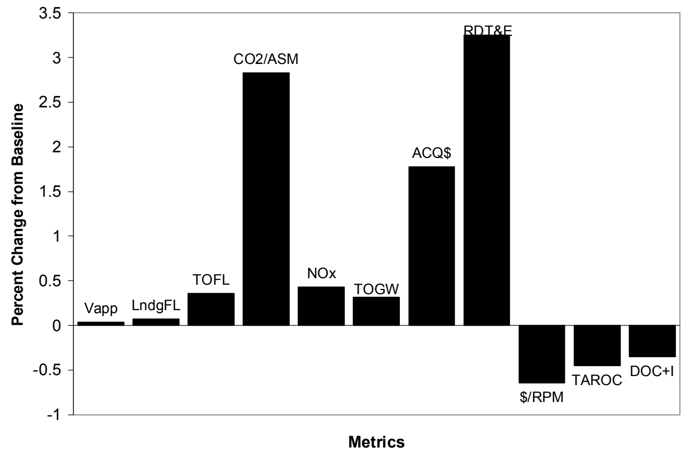


Figure P13: Effects of Technology 13

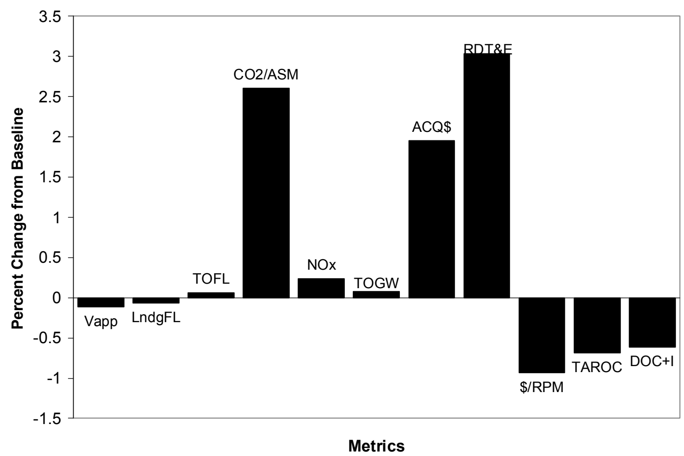


Figure P14: Effects of Technology 14

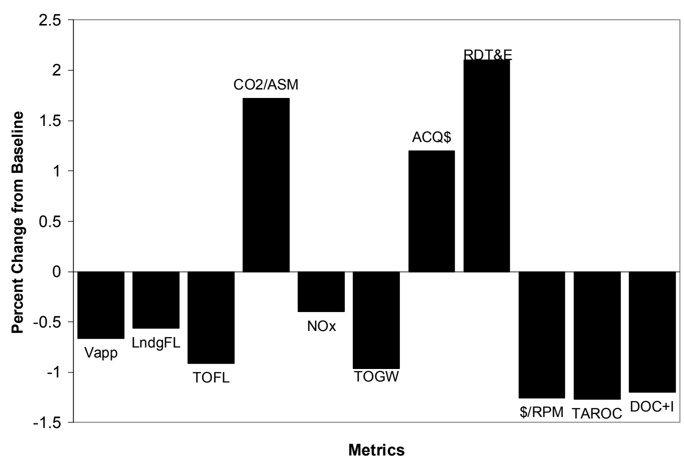


Figure P15: Effects of Technology 15

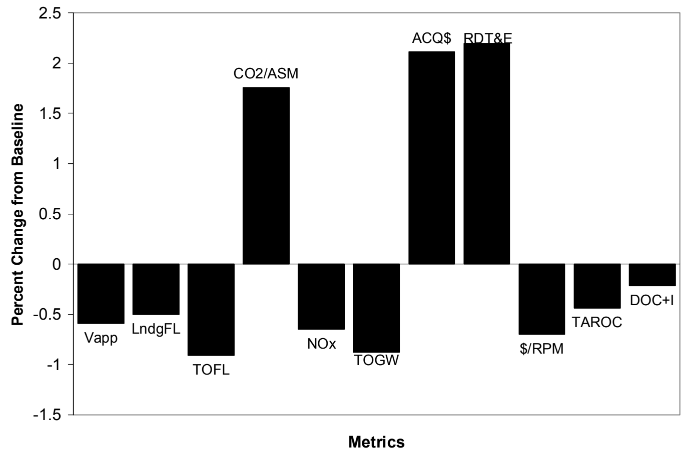


Figure P16: Effects of Technology 16

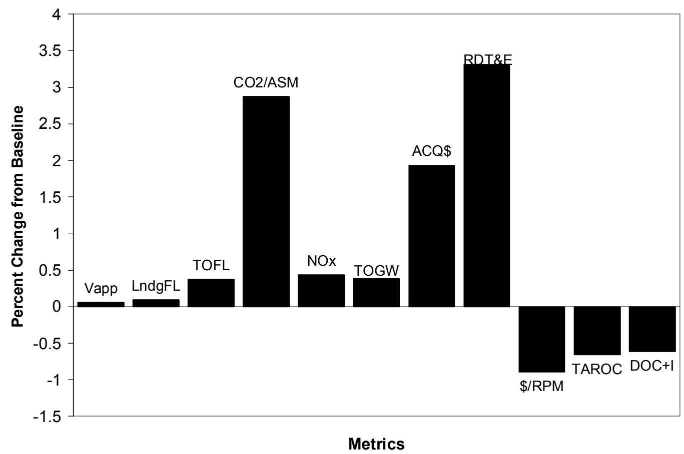


Figure P17: Effects of Technology 17

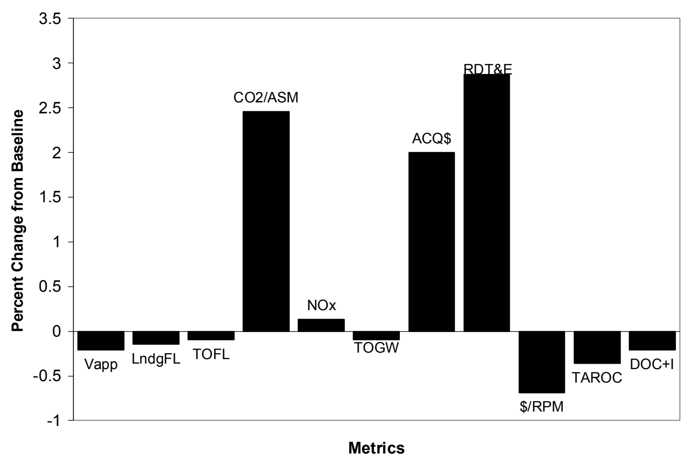


Figure P18: Effects of Technology 18

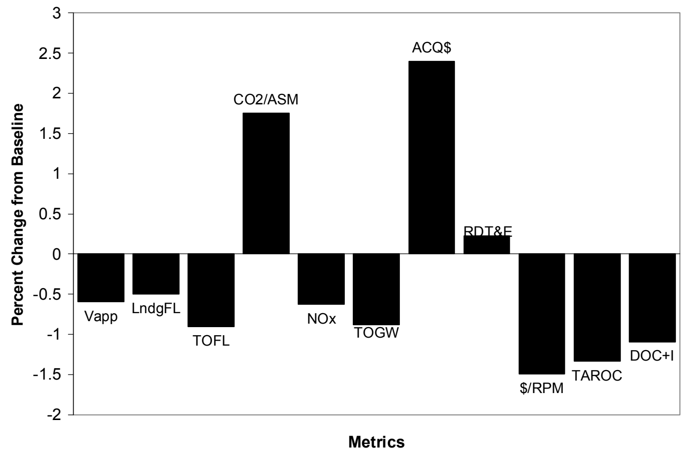


Figure P19: Effects of Technology 19

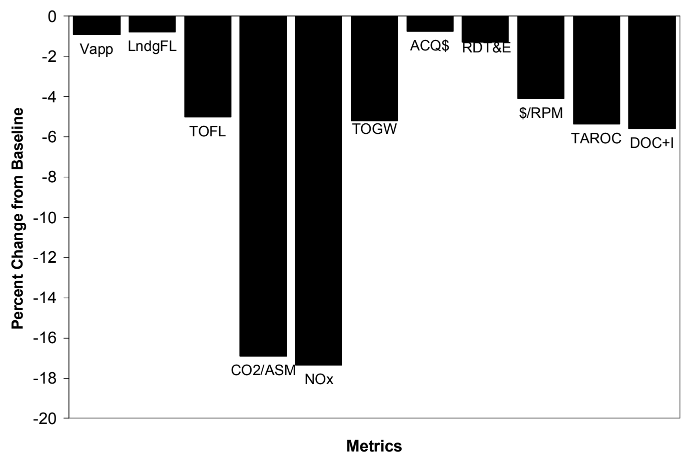


Figure P20: Effects of Technology 20

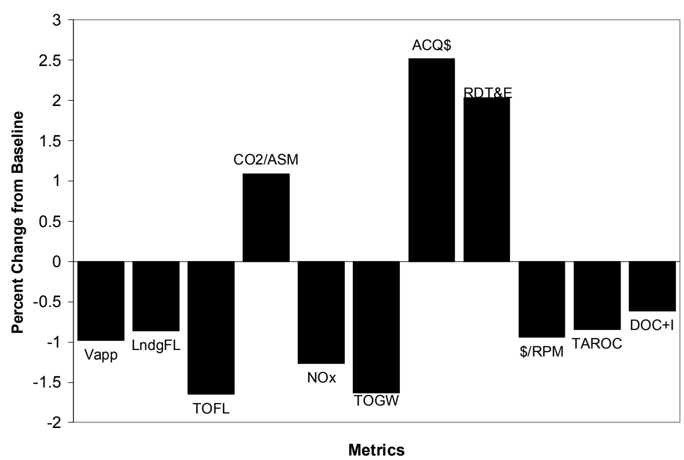


Figure P21: Effects of Technology 21

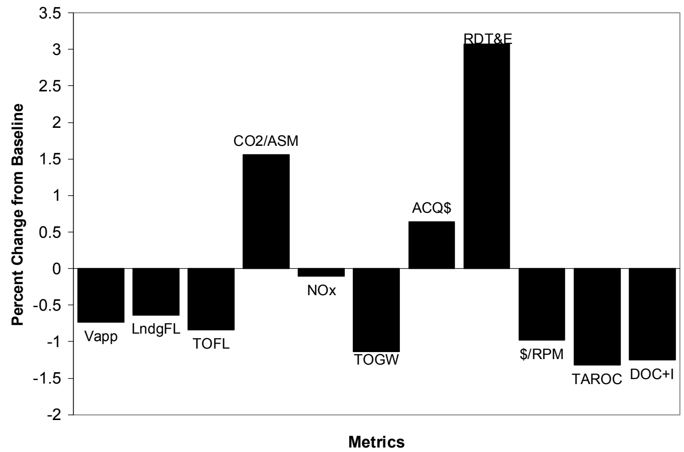


Figure P22: Effects of Technology 22

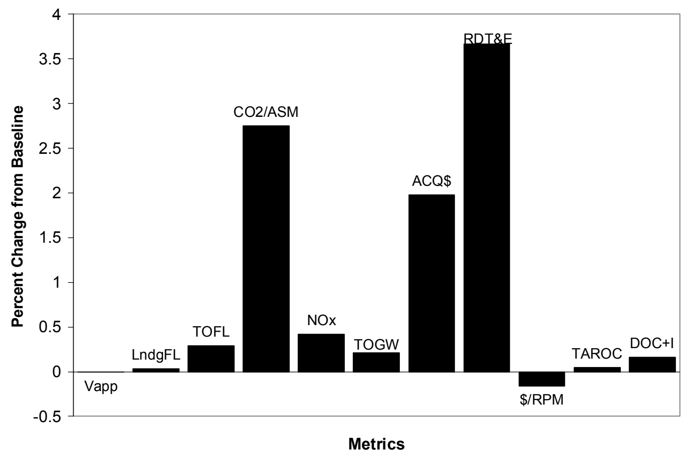


Figure P23: Effects of Technology 23

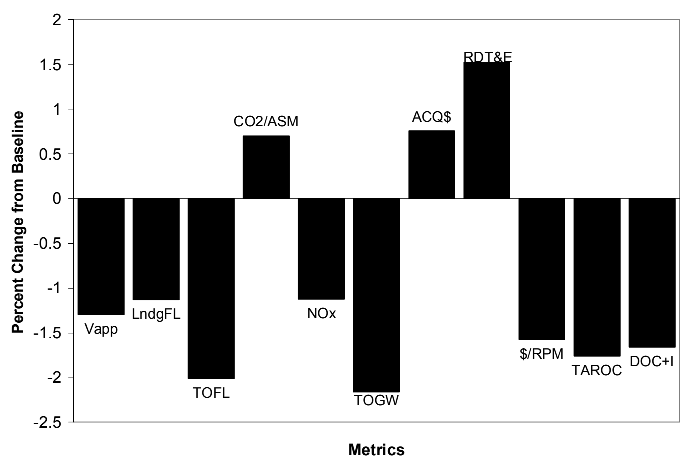


Figure P24: Effects of Technology 24

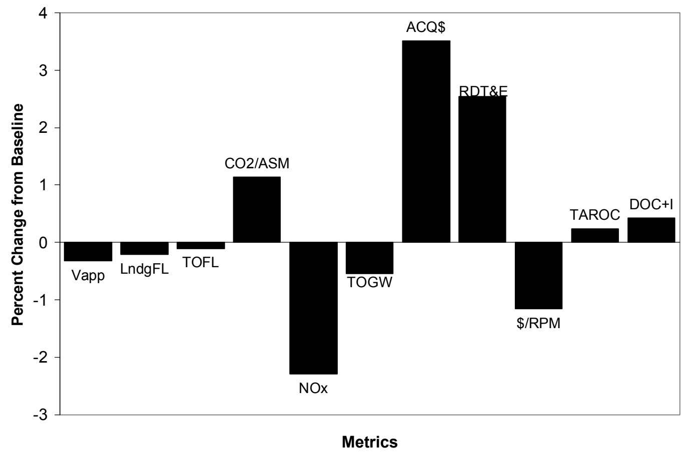


Figure P25: Effects of Technology 25

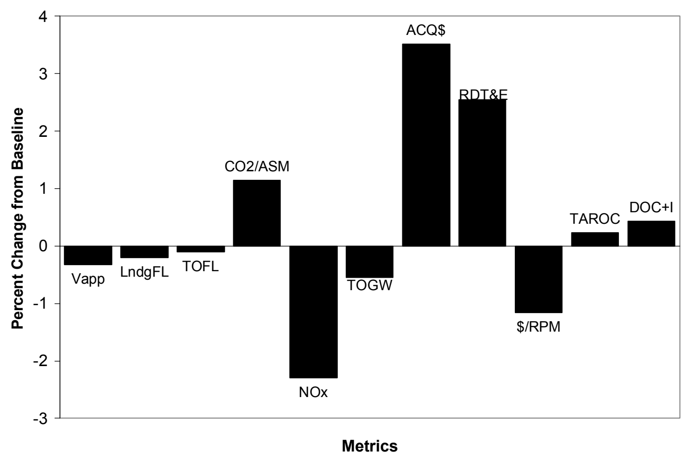


Figure P26: Effects of Technology 26

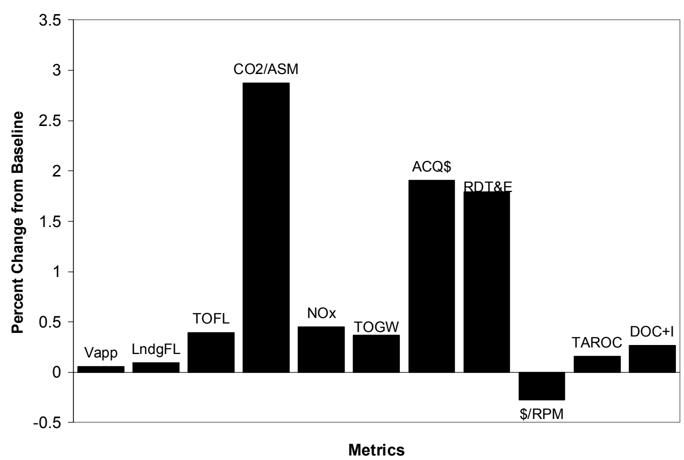


Figure P27: Effects of Technology 27

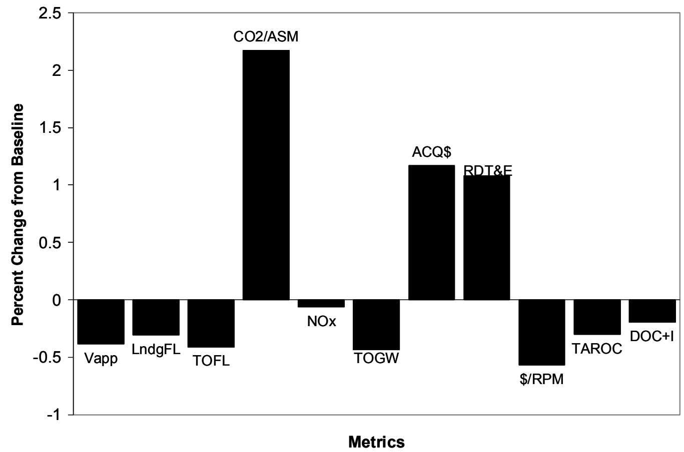


Figure P28: Effects of Technology 28

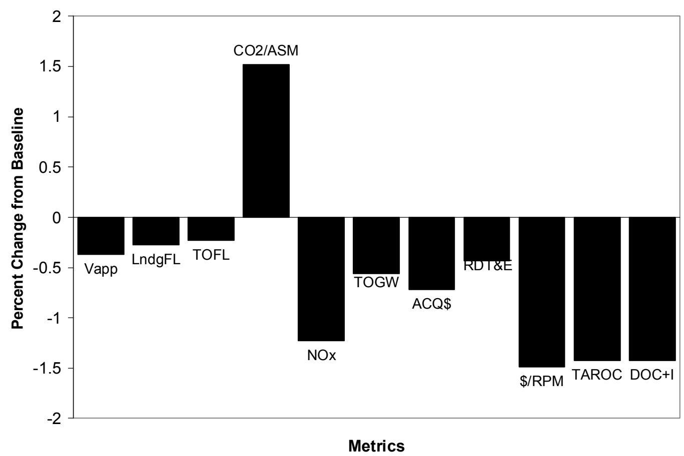


Figure P29: Effects of Technology 29

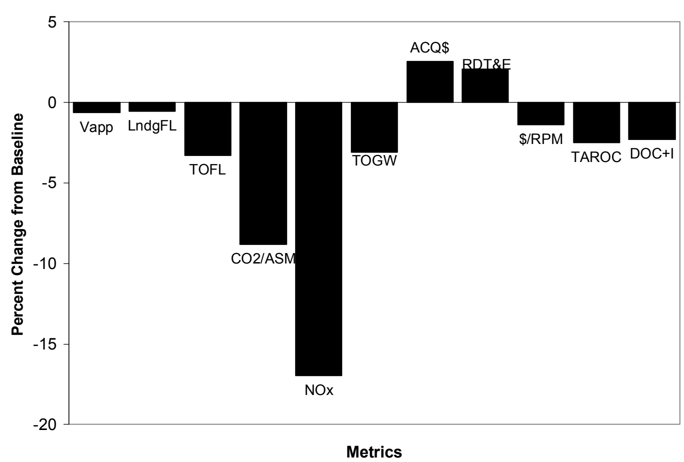


Figure P30: Effects of Technology 30

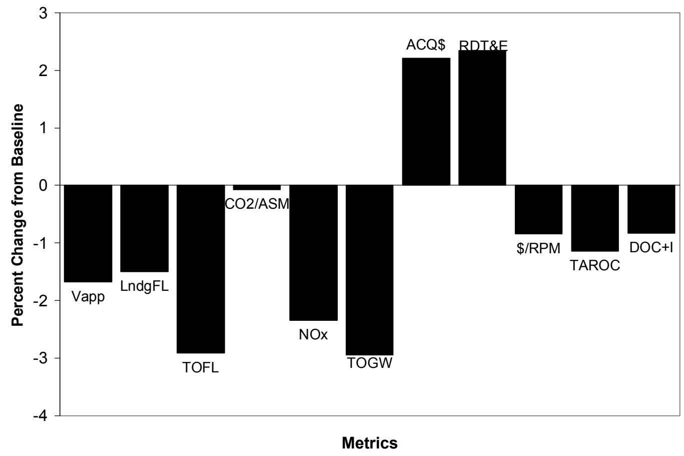


Figure P31: Effects of Technology 31

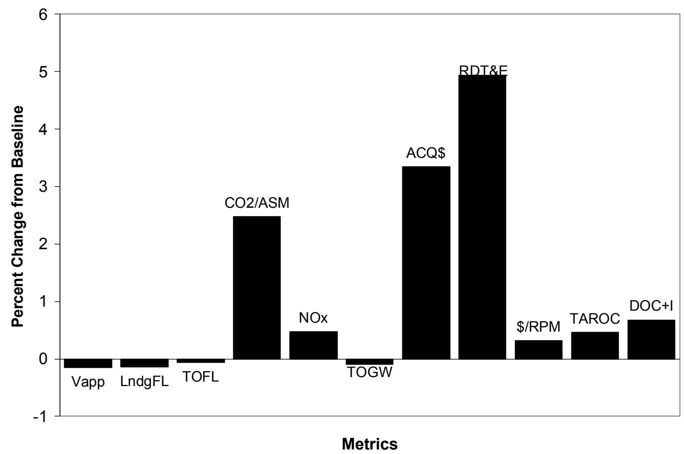


Figure P32: Effects of Technology 32

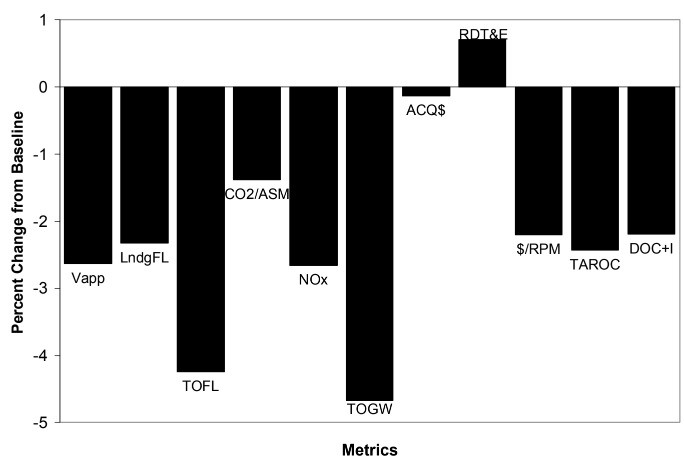


Figure P33: Effects of Technology 33

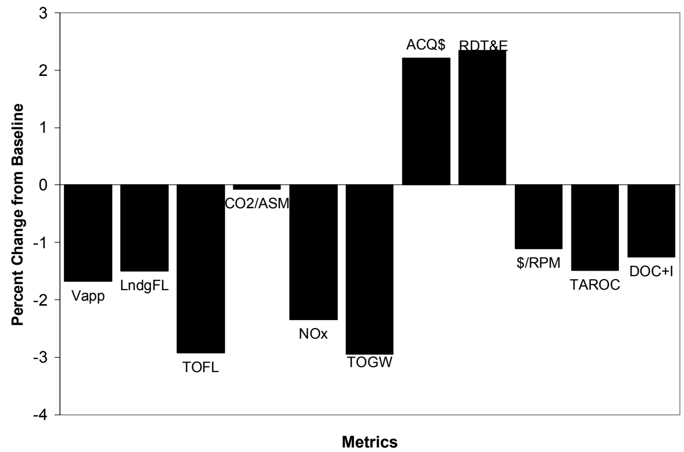


Figure P34: Effects of Technology 34

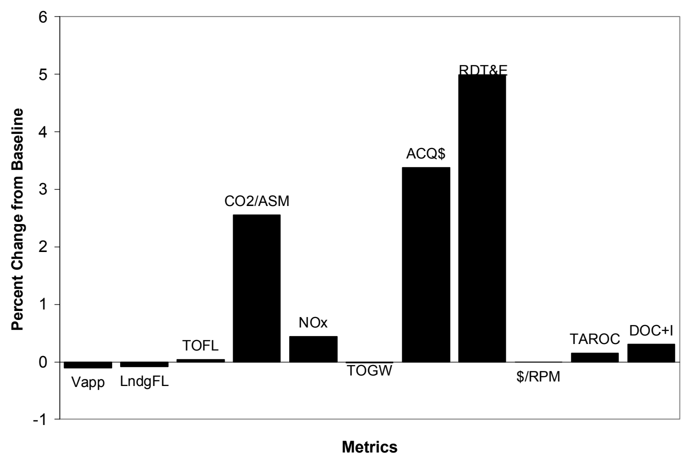


Figure P35: Effects of Technology 35

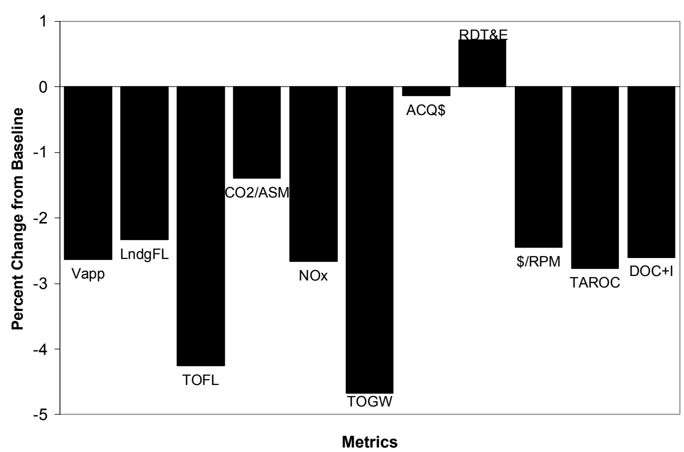


Figure P36: Effects of Technology 36

APPENDIX Q – CLOSING THE LOOP RSE COEFFICIENTS

	Vapp	Landing Length	TO Length	CO2/ASM	NOX	TOGW
Intercept	101.482479	4666.05482	4306.42766	0.14386892	235.580782	118421.674
SW	-9.6658915	-419.67442	-854.87984	-0.0034851	-6.3372093	965.49845
TWR	0.45426357	19.7829457	-144.32171	0.00179294	-7.5	1107.52481
AR	0.36899225	15.7790698	-329.71705	-0.0122707	-33.217054	-1022.2961
TR	0.13604651	5.99612403	12.9806202	0.00066619	1.34883721	358.579457
TOC(1)	-0.122093	-5.3643411	10.251938	0.00344916	10.1589147	254.767054
TOC(3)	0.05271318	2.29457364	24.4418605	0.0038711	10.6162791	650.954264
SWEEP	-0.0007752	0.02713178	-1.6550388	-0.0005323	-2.5116279	-84.359302
ARHT	0.00155039	0.2248062	1.58527132	0.00020648	0.57751938	39.8337209
TRHT	0.04069767	1.86046512	3.73255814	0.00012077	0.1627907	97.025969
TCHT	0.01705426	0.7248062	4.3875969	0.00057457	1.60077519	113.025194
SHT	0.14147287	6.19379845	20.0426357	0.00168126	4.51162791	506.394186
ARVT	0.00620155	0.21705426	1.35271318	0.00016884	0.48449612	34.0403101
TRVT	0.04069767	1.79844961	3.63953488	0.00012487	0.17829457	94.4472868
TCVT	0.01395349	0.58527132	3.58527132	0.00045928	1.30232558	90.3089147
SVT	0.13333333	5.80232558	19.9263566	0.00180278	4.75193798	508.722868
SW*SW	1.51814692	84.9432213	196.628491	0.00222136	-0.0658099	387.0197
TWR*SW	-0.0554688	-4.125	45.2851563	-0.0002266	-0.2421875	-40.157813
TWR*TWR	0.01814692	-0.0567787	9.62849108	0.00001041	0.93419007	13.0196998
AR*SW	0.0703125	1.5859375	144.191406	0.00215664	4.0078125	520.714063
AR*TWR	0.01171875	0.4140625	32.7304688	-0.0001605	1.046875	-4.6382812
AR*AR	0.11814692	4.4432213	99.6284911	0.0031868	5.43419007	653.2197
TR*SW	-0.0054688	-0.796875	-2.9492188	-0.0000238	-0.0859375	14.95625
TR*TWR	8.3267e-16	0.140625	-0.0195313	0.00002626	-0.015625	8.88671875
TR*AR	0.03828125	1.6328125	0.82421875	-0.0000115	-0.1875	71.0929688
TR*TR	-0.0318531	0.4432213	1.62849108	-0.0000439	0.43419007	-6.1303002
TOC(1)*SW	0.00234375	0.4375	-2.8554688	0.00021513	0.828125	2.47421875
TOC(1)*TWR	0.00625	0.109375	-0.6601563	0.00000426	-0.4609375	4.259375
TOC(1)*AR	-0.0539063	-2.3984375	-5.3789063	0.00001231	-0.5546875	-107.03125
TOC(1)*TR	-0.0140625	-0.65625	-1.0507813	-0.000017	0.0234375	-31.579687
TOC(1)*TOC(1)	0.06814692	1.9432213	7.62849108	0.00061407	1.93419007	176.9697
TOC(3)*SW	-0.0023437	-0.5078125	-5.8632813	0.00018525	0.7421875	25.5445312
TOC(3)*TWR	0.003125	0.2265625	-1.2460938	0.00001366	-0.46875	10.9
TOC(3)*AR	-0.0054687	-0.234375	-3.7148438	0.00006539	-0.53125	-3.928125
TOC(3)*TR	2.1649e-15	-0.1484375	-0.1210938	0.00001022	-0.015625	-5.334375
TOC(3)*TOC(1)	0.04375	1.9921875	10.6601563	0.00124988	3.3046875	265.460156
TOC(3)*TOC(3)	0.01814692	0.9432213	5.12849108	0.00055237	1.93419007	115.3197
SWEEP*SW	-0.021875	-0.9140625	-3.4101563	-0.0004678	-1.6171875	-108.34297
SWEEP*TWR	0.00390625	0.2734375	0.51953125	0.00001527	-0.25	13.071875
SWEEP*AR	-0.00625	-0.34375	-3.2929688	-0.0005056	-1.140625	-90.953125
SWEEP*TR	-0.0007812	-0.0234375	-0.0742188	-1.3414e-7	-0.078125	-0.9
SWEEP*TOC(1)	-0.0210938	-0.8359375	-6.2460938	-0.0009143	-2.3671875	-165.80234
SWEEP*TOC(3)	-0.0179687	-0.828125	-6.2382813	-0.0009149	-2.421875	-165.74297
SWEEP*SWEEP	0.01814692	0.4432213	4.62849108	0.00042617	1.43419007	87.8696998
ARHT*SW	-0.0023438	-0.0703125	-0.5742188	-0.0000219	-0.015625	-2.9429687
ARHT*TWR	-3.886e-16	0.0546875	-0.0664063	-0.0000019	-0.1796875	1.5578125
ARHT*AR	0.00390625	-0.03125	-0.4726563	-0.0000199	-0.1484375	-3.6171875

ARHT*TR	-5.551e-17	-0.0234375	-0.0507813	-0.0000019	0.0078125	-1.084375
ARHT*TOC(1)	7.2164e-16	-0.0390625	-0.0820313	-0.0000013	-0.03125	-0.8570313
ARHT*TOC(3)	-0.0015625	-0.046875	-0.0742188	6.27184e-7	-0.0078125	-1.4960937
ARHT*SWEEP	0.00234375	0.015625	0.03515625	-0.0000042	-0.1484375	-0.1164062
ARHT*ARHT	0.01814692	-0.0567787	1.62849108	-0.0000369	-0.0658099	-0.2303002
TRHT*SW	-0.0054687	-0.40625	-1.2382813	-0.0000202	-0.0234375	-4.8257813
TRHT*TWR	-0.0015625	-0.015625	-0.2148438	0.00000227	0.015625	0.2828125
TRHT*AR	-0.0007813	0.0078125	-0.5898438	-0.0000181	-0.09375	-1.50625
TRHT*TR	0.0046875	0.28125	2.20703125	0.00007751	0	15.5234375
TRHT*TOC(1)	-8.327e-16	0.03125	0.06640625	-0.0000011	-0.0234375	0.72421875
TRHT*TOC(3)	0.0015625	0.0390625	0.04296875	0.00000108	-0.015625	0.59609375
TRHT*SWEEP	-0.0007813	-0.0234375	-0.0507813	-0.0000042	-0.015625	-2.3007813
TRHT*ARHT	-0.0015625	-0.0078125	-0.0742188	-0.0000073	-0.0078125	-2.1429687
TRHT*TRHT	-0.0318531	-0.0567787	1.62849108	-0.0000204	0.43419007	-0.0303002
TCHT*SW	-0.0023437	-0.1640625	-1.5351563	-0.0000581	-0.1640625	-9.9101563
TCHT*TWR	4.3854e-15	-0.1953125	0.08203125	-0.0000125	-0.03125	4.8390625
TCHT*AR	0.00078125	-0.0625	-0.6992188	-0.0000466	-0.1875	-6.5375
TCHT*TR	-0.0046875	-0.1953125	-16.464844	0.00001679	-0.234375	-1.2390625
TCHT*TOC(1)	-5.551e-17	0.0078125	-0.1835938	-0.0000103	-0.0390625	-0.8976563
TCHT*TOC(3)	-0.0015625	0.015625	0.10546875	0.00000434	-0.03125	1.17578125
TCHT*SWEEP	-0.0039062	-0.046875	-0.0195313	0.00000317	-0.046875	-0.2148437
TCHT*ARHT	8.3267e-16	0	0.12890625	0.00002658	0.1328125	4.07421875
TCHT*TRHT	-5.551e-17	-0.0546875	-0.0820313	-0.0000016	0.140625	-2.4710937
TCHT*TCHT	0.01814692	0.4432213	2.12849108	-0.0000155	-0.0658099	0.96969979
SHT*SW	-0.021875	-1.5234375	-7.4804688	-0.0001656	-0.6875	-36.263281
SHT*TWR	-0.0070313	-0.4140625	-4.7070313	-0.0001213	-0.3203125	-18.607812
SHT*AR	-1.388e-15	0.03125	-3.8945313	-0.0001574	-0.6015625	-21.96875
SHT*TR	0.00234375	0.0390625	0.19921875	0.00000799	-0.0234375	3.703125
SHT*TOC(1)	-0.0039063	-0.1796875	0.46484375	0.000011	0.15625	-3.7382813
SHT*TOC(3)	-0.0054688	-0.09375	0.31640625	0.0000138	0.1484375	-2.1726563
SHT*SWEEP	0.00625	0.34375	0.44140625	0.00001809	-0.1640625	11.7945312
SHT*ARHT	0.00234375	0.125	2.66796875	0.00009461	0.1875	17.9148438
SHT*TRHT	0.00859375	0.4765625	1.08203125	0.00003272	0.0546875	25.8054687
SHT*TCHT	0.00546875	0.234375	1.08203125	0.00013325	0.3671875	27.9304687
SHT*SHT	-0.0318531	-0.0567787	1.62849108	-0.0000422	0.43419007	-3.8303002
ARVT*SW	-0.0007812	-0.09375	-0.4960938	-0.0000121	0	-3.0976563
ARVT*TWR	-0.0015625	-0.046875	-0.1289063	-0.0000016	0.0390625	-0.6390625
ARVT*AR	-0.0007812	0.0390625	-0.2851563	-0.0000208	-0.0703125	-2.24375
ARVT*TR	-0.0015625	0.046875	0.05859375	-1.8897e-7	0.0078125	1.178125
ARVT*TOC(1)	0.003125	0.03125	0.08984375	0.00000233	-0.0625	1.23828125
ARVT*TOC(3)	0.003125	-0.0078125	0.01953125	-0.0000014	-0.0390625	0.23671875
ARVT*SWEEP	-0.0023438	-0.0234375	-0.0273438	-0.0000039	0.1171875	-2.2601562
ARVT*ARHT	-0.003125	-0.1640625	-0.1601563	-0.0000322	-0.34375	-8.5476562
ARVT*TRHT	-1.665e-16	0.03125	0.03515625	0.00000388	-0.0078125	1.64296875
ARVT*TCHT	-0.0015625	0.0390625	0.08203125	-2.7617e-9	-0.0234375	0.76015625
ARVT*SHT	0.00234375	0.0703125	0.02734375	-0.0000021	0.140625	0.53671875
ARVT*ARVT	0.01814692	-0.0567787	1.62849108	-0.0000317	-0.0658099	0.81969979
TRVT*SW	-0.0054687	-0.390625	-1.0976563	-0.0000156	-0.0859375	-1.7265625
TRVT*TWR	-0.0015625	0.0625	-0.2617188	0.00000117	0	2.58515625
TRVT*AR	-0.0007813	-0.0703125	-0.8554688	-0.0000248	-0.0625	-4.7382813
TRVT*TR	-0.0046875	-0.109375	-0.4335938	-0.0002252	-0.34375	-36.977344
TRVT*TOC(1)	-0.003125	-0.03125	-0.0273438	-0.0000015	-0.0234375	-1.34375

TRVT*TOC(3)	0.0015625	0.0078125	0.01171875	0.00000287	0.015625	-0.2171875
TRVT*SWEEP	-0.0054688	-0.1796875	-0.1132813	-7.6958e-7	0.015625	-7.44375
TRVT*ARHT	-0.0015625	0.0078125	0.03515625	-2.492e-7	-0.0078125	0.8296875
TRVT*TRHT	-0.003125	-0.203125	0.48046875	-0.0000379	0.359375	-9.3921875
TRVT*TCHT	0.003125	0.1015625	-0.0195313	0.00000458	-0.109375	4.1078125
TRVT*SHT	-0.0007812	-0.0546875	-0.0429688	-0.0000048	-0.0078125	-1.5984375
TRVT*ARVT	-0.0015625	-0.015625	-0.1367188	-0.0000087	-0.0390625	-2.421875
TRVT*TRVT	-0.0318531	-0.0567787	1.62849108	-0.0000222	0.43419007	-0.3803002
TCVT*SW	-0.0023437	-0.1953125	-1.3398438	-0.0000489	-0.1796875	-9.6132812
TCVT*TWR	0.0015625	-0.0234375	-0.2851563	-0.0000046	-0.09375	-1.1109375
TCVT*AR	-0.0023437	0.015625	-0.7539063	-0.0000357	-0.15625	-4.9921875
TCVT*TR	0.0015625	0.0390625	0.08984375	0.00000142	0.015625	2.1078125
TCVT*TOC(1)	0.0015625	0.0078125	0.04296875	0.00000308	-0.0078125	1.26015625
TCVT*TOC(3)	-2.776e-16	0.03125	0.08203125	0.00000421	-0.015625	1.44765625
TCVT*SWEEP	0.00390625	-0.015625	-0.0429688	0.00000374	-0.015625	0.04453125
TCVT*ARHT	-0.003125	-0.015625	-0.0039063	-0.0000014	0.0390625	-1.1507812
TCVT*TRHT	-2.776e-16	0.0234375	0.00390625	-0.0000017	-0.125	0.18515625
TCVT*TCHT	-2.776e-16	-0.015625	0.03515625	0.00000241	0.0625	0.46015625
TCVT*SHT	0.00078125	0.0625	0.08984375	0.00000454	0.0078125	1.98203125
TCVT*ARVT	0.0015625	0.0859375	0.16796875	0.00002886	0.0390625	6.14140625
TCVT*TRVT	5.5511e-17	-0.0078125	-0.0585938	-0.0000024	-0.15625	-1.5109375
TCVT*TCVT	0.01814692	0.4432213	1.62849108	-0.0000152	0.43419007	1.06969979
SVT*SW	-0.0140625	-1.2890625	-6.8789063	-0.0001918	-0.6796875	-34.044531
SVT*TWR	-0.0007812	0.0859375	-1.2929688	-0.0000077	-0.25	1.8703125
SVT*AR	-5.551e-17	-0.0625	-4.1992188	-0.0001768	-0.59375	-27.410937
SVT*TR	0.00078125	0.0546875	0.17578125	0.00000436	0.0625	2.7015625
SVT*TOC(1)	-0.0007813	-0.0234375	0.05078125	0.00000784	0.0390625	0.04453125
SVT*TOC(3)	0.00234375	0.03125	0.23046875	0.00001874	0.015625	4.14296875
SVT*SWEEP	-0.003125	-0.015625	0.05859375	0.00000919	-0.078125	1.52421875
SVT*ARHT	-0.0007813	-0.15625	1.97265625	0.00004084	-0.0859375	-0.8210937
SVT*TRHT	-0.0007813	0.0078125	0.07421875	0.00000168	0.03125	1.01484375
SVT*TCHT	0.00078125	0.0625	0.12109375	0.00000396	0.03125	1.70234375
SVT*SHT	-0.003125	0.046875	0.37890625	0.00000814	0.0703125	2.87578125
SVT*ARVT	0.00859375	0.3984375	1.31640625	0.00014531	0.2109375	34.6460938
SVT*TRVT	0.00859375	0.4921875	0.99609375	0.00003743	0.078125	26.4859375
SVT*TCVT	0.00546875	0.21875	1.14453125	0.00014275	0.390625	28.9929687
SVT*SVT	0.01814692	0.4432213	1.62849108	-0.0000541	0.43419007	-10.0303

Coefficients of RSEs (cont)

	ACQ$	RDT&E	$/RPM	TAROC	DOC+I	WAWt
Intercept	62.7373111	4618.93782	0.10237776	4.97680556	3.88794637	6.20937738
SW	0.9054031	60.8330039	0.0004855	0.0335814	0.02762791	-0.6046877
TWR	0.9550155	77.0280659	0.00065857	0.04663566	0.04054264	0.03597302
AR	0.29817054	15.1486705	-0.0002552	-0.0200233	-0.0171047	0.72133003
TR	0.15367829	10.3123798	0.00013457	0.00974031	0.00798837	0.16818326
TOC(1)	-0.1298023	-7.1046163	0.0000431	0.00359302	0.00303876	-0.2933261
TOC(3)	0.06320155	5.69757364	0.00019395	0.01465891	0.01210853	-0.0750486
SWEEP	-0.0104147	-0.9272674	-0.0000291	-0.0021085	-0.0017558	-0.0026438
ARHT	0.00727519	0.53289535	0.00002124	0.00099225	0.00078295	0.00147452
TRHT	0.04353488	2.67532171	0.00003837	0.00258915	0.00212791	0.00367457
TCHT	0.02084496	1.50203488	0.00003705	0.00271705	0.00226357	0.00412879

SHT	0.16148837	10.1085078	0.0001786	0.01304651	0.01074419	0.01891881
ARVT	0.00626357	0.44955814	0.00000977	0.0008062	0.00067054	0.00126419
TRVT	0.04077519	2.61856589	0.00003248	0.00248837	0.00197287	0.00340636
TCVT	0.01492248	1.19767829	0.0000269	0.00212403	0.00173643	0.0033754
SVT	0.15320155	9.76327132	0.00018667	0.01300775	0.01069767	0.01893256
SW*SW	0.00242784	3.77093634	0.0001516	0.00727282	0.00612697	0.12058914
TWR*SW	-0.0054961	-0.0607539	-0.0000152	-0.0009375	-0.0007344	-0.0059813
TWR*TWR	-0.0505722	0.16393634	-0.0000234	-0.0017272	-0.001873	0.00059914
AR*SW	0.13055078	9.20452734	0.00017906	0.01295312	0.01065625	-0.0651849
AR*TWR	-0.0060195	-0.2072852	-0.0000051	-0.0006172	-0.0005547	0.00553932
AR*AR	0.07942784	9.48293634	0.0001666	0.01427282	0.01162697	0.04347914
TR*SW	0.01147266	0.70451172	-8.5938e-7	0.00046875	0.00039062	-0.0193109
TR*TWR	0.00518359	0.28993359	9.375e-7	0.00025781	0.00028906	0.00149505
TR*AR	0.03943359	2.66998047	0.00003125	0.00200781	0.00158594	0.04873255
TR*TR	0.06192784	-0.1275637	0.0000516	0.00177282	0.00162697	-0.0016809
TOC(1)*SW	-0.005957	-0.7832852	0.00000562	0.00023437	0.00020312	0.03455729
TOC(1)*TWR	0.00269141	0.07383984	0.00000555	0.00010156	0.00010156	-0.0018576
TOC(1)*AR	-0.067418	-4.5596445	-0.000051	-0.0034141	-0.0027891	-0.0877503
TOC(1)*TR	-0.018168	-1.1205039	-0.0000142	-0.0009453	-0.0007734	-0.0197013
TOC(1)*TOC(1)	0.00692784	3.75493634	0.0000516	0.00277282	0.00212697	0.04375914
TOC(3)*SW	0.00767578	0.21016016	0.00000898	0.00084375	0.00071094	0.00957005
TOC(3)*TWR	0.00576172	0.34378516	-7.8125e-7	0.00030469	0.00023438	-0.0002062
TOC(3)*AR	-0.0141602	-0.9519961	-0.0000047	-0.0005078	-0.0004531	-0.023999
TOC(3)*TR	-0.0059102	-0.2846523	-0.0000048	-0.0002266	-0.0001875	-0.005501
TOC(3)*TOC(1)	0.05319141	4.12659766	0.00009016	0.00641406	0.00526562	0.027375
TOC(3)*TOC(3)	-0.0235722	1.72943634	0.0000516	0.00127282	0.00112697	0.00979914
SWEEP*SW	-0.0219023	-1.4517383	-0.000034	-0.0024922	-0.0020547	-0.0037323
SWEEP*TWR	0.00054297	0.14826172	-0.0000028	0.00014062	0.00004688	0.00066016
SWEEP*AR	-0.0164102	-1.197207	-0.0000255	-0.0022969	-0.0019063	-0.0035753
SWEEP*TR	-0.0019883	-0.0150352	0.00000102	-0.0000781	-0.0000781	-0.0001862
SWEEP*TOC(1)	-0.0285586	-2.1939883	-0.0000533	-0.0040938	-0.0034219	-0.0061211
SWEEP*TOC(3)	-0.0285508	-2.1934336	-0.0000593	-0.0040937	-0.0034141	-0.0061073
SWEEP*SWEEP	0.08092784	1.20393634	0.0000516	0.00427282	0.00362697	0.00339914
ARHT*SW	-0.0075273	-0.0366914	-0.0000054	-0.0003438	-0.0002891	-0.0002771
ARHT*TWR	-0.0031289	0.03337109	-0.0000053	-0.0001016	-0.0000781	0.00011068
ARHT*AR	0.00485547	-0.0316602	0.00000516	0.00007031	0.00010937	0.0001263
ARHT*TR	-0.0001445	-0.0095039	-0.0000015	-0.0000391	-0.0000313	0.00001328
ARHT*TOC(1)	-0.0001992	-0.0118789	-0.0000011	-0.0000234	1.0408e-17	-0.0001461
ARHT*TOC(3)	-0.000332	-0.0189961	-0.000002	-0.0000234	-0.0000234	-0.000112
ARHT*SWEEP	-0.0000664	-0.0051914	-0.0000015	-2.429e-17	-0.0000078	-0.0000065
ARHT*ARHT	0.06392784	0.00193634	-0.0000184	0.00227282	0.00212697	0.00023914
TRHT*SW	-0.002582	-0.0530742	-0.0000044	-0.0001563	-0.0001328	-0.0008445
TRHT*TWR	-0.004918	0.04231641	2.34375e-7	-0.0001328	-0.0001406	-0.0000057
TRHT*AR	0.00709766	0.00062891	0.00000492	0.00014844	0.00017188	0.00060781
TRHT*TR	0.00100391	0.19336328	0.00000437	0.00035156	0.00021875	0.00149583
TRHT*TOC(1)	0.00169922	-0.0020742	0.00000445	0.00002344	0.00007812	-0.0001604
TRHT*TOC(3)	0.00167578	-0.0040039	-0.0000025	0.00005469	0.00005469	-0.0001878
TRHT*SWEEP	0.00111328	-0.0443555	0.00000781	0.00001562	0.00002344	0.00062708
TRHT*ARHT	-0.0002148	-0.025043	1.5625e-7	-0.0000547	-0.0000391	-0.0000786
TRHT*TRHT	-0.0485722	0.00393634	-0.0000184	-0.0017272	-0.001373	0.00023914
TCHT*SW	-0.0011914	-0.073832	-0.0000067	-0.0001953	-0.0001641	-0.000463
TCHT*TWR	0.00358203	0.27582422	0.00000367	0.00015625	0.00014062	-0.005144

TCHT*AR	-0.0024336	-0.0535195	-0.0000035	-0.0002188	-0.0001875	0.00019036
TCHT*TR	-0.0020586	0.16985547	-0.0000056	-0.0000312	3.8164e-17	-0.0008497
TCHT*TOC(1)	-0.0002695	-0.0192227	5.46875e-7	-0.0000313	-0.0000312	-0.0001471
TCHT*TOC(3)	0.00003516	0.00562891	-0.0000014	0.00003125	0.00003906	-0.0000807
TCHT*SWEEP	-0.0034961	0.00013672	-1.5625e-7	-0.0001484	-0.0001016	-0.0000237
TCHT*ARHT	0.00248828	0.05712109	-0.0000044	0.00014063	0.00013281	0.00014245
TCHT*TRHT	-0.0006289	-0.048293	0.00000539	-0.0000469	0.00000781	-0.0000526
TCHT*TCHT	0.06442784	0.01693634	0.0000516	0.00177282	0.00212697	0.00027914
SHT*SW	-0.0033398	-0.3177773	-0.0000152	-0.0006953	-0.0005937	-0.0036174
SHT*TWR	-0.0025977	0.00961328	-0.0000141	-0.0004531	-0.0003672	-0.0042469
SHT*AR	0.00152734	-0.1636523	3.90625e-7	-0.0004219	-0.0003828	0.00260677
SHT*TR	-0.0007852	0.06645703	-0.0000016	0.00001562	-0.0000078	0.00080417
SHT*TOC(1)	-0.0031211	-0.0974336	0.00000164	-0.0001094	-0.0000547	-0.001425
SHT*TOC(3)	-0.002582	-0.057332	-0.0000073	-0.0000469	-0.0000313	-0.0002029
SHT*SWEEP	0.00416797	0.16901953	0.00000125	0.00022656	0.0001875	0.00062344
SHT*ARHT	0.00680859	0.23597266	0.00000344	0.00053125	0.00045313	0.00015365
SHT*TRHT	0.01755078	0.68651172	0.00000883	0.00090625	0.00073437	0.00097005
SHT*TCHT	0.00534766	0.38330078	0.00000898	0.00064844	0.00053125	0.00150521
SHT*SHT	-0.0495722	-0.0480637	-0.0000184	-0.0017272	-0.001873	0.00007914
ARVT*SW	-0.0004883	-0.0337539	-2.3437e-7	-0.0000625	-0.0000547	-0.0002656
ARVT*TWR	0.00005078	0.00613672	0.000005	0.00000781	0.00003125	-0.0000206
ARVT*AR	-0.002043	-0.0234883	-0.000005	-0.0001172	-0.0001094	0.00013516
ARVT*TR	0.00362891	0.01390234	-7.8125e-8	0.00014844	0.00010938	0.00010443
ARVT*TOC(1)	0.00015234	0.01044922	0.00000109	0.00000781	0.00001562	-0.0000091
ARVT*TOC(3)	0.00000391	-0.001543	-0.0000041	-0.0000234	-0.0000078	-0.0000078
ARVT*SWEEP	-0.004043	-0.0282539	0.00000211	-0.0001406	-0.0001484	-0.0001034
ARVT*ARHT	-0.0002305	-0.1478789	-0.000004	-0.0001328	-0.0001328	-0.0004289
ARVT*TRHT	0.00026172	0.01898828	-0.0000025	0.00002344	0.00003906	0.00005729
ARVT*TCHT	0.00182422	0.00673047	-0.0000014	0.0000625	0.00003906	0.0000362
ARVT*SHT	0.00005078	0.00394141	0.00000359	-0.0000156	0.00003125	0.00003958
ARVT*ARVT	0.06442784	0.01543634	-0.0000184	0.00227282	0.00162697	0.00027914
TRVT*SW	-0.0002383	-0.010457	6.25e-7	-0.0000547	-0.0000547	-0.0004648
TRVT*TWR	-0.0027148	0.07379297	-0.0000041	-0.0000781	-0.0000625	0.00025469
TRVT*AR	0.00483203	-0.0338945	-0.0000032	0.00009375	0.00009375	0.0002276
TRVT*TR	-0.0071211	-0.5144102	-0.0000116	-0.0010156	-0.0008281	-0.0020271
TRVT*TOC(1)	-0.0003789	-0.0277539	0.0000018	-0.0000156	-0.0000156	-0.0004266
TRVT*TOC(3)	-0.000043	-0.0050586	0.00000141	2.0817e-17	-0.0000078	-0.0001898
TRVT*SWEEP	-0.0041992	-0.2998633	-0.0000056	-0.0001953	-0.0002109	-0.0055646
TRVT*ARHT	0.00194141	0.00812109	-7.8125e-7	0.00007813	0.00003906	0.00005156
TRVT*TRHT	0.00524609	-0.1113711	-0.0000024	0.00004687	0.00011719	-0.0014622
TRVT*TCHT	0.00265234	0.06583984	0.00000352	0.00008594	0.00013281	0.00021719
TRVT*SHT	0.00292578	-0.0164492	0.00000289	0.00008594	0.00004687	-0.0000846
TRVT*ARVT	0.00130859	-0.0292383	-0.0000019	1.0408e-17	0.00003906	-0.0001135
TRVT*TRVT	-0.0485722	-0.0005637	-0.0000184	-0.0017272	-0.001373	0.00023914
TCVT*SW	0.00013672	-0.1128398	0.00000187	-0.0001484	-0.0001328	-0.0007667
TCVT*TWR	0.00183203	0.01884766	0.00000164	0.00009375	0.00004687	-0.0000565
TCVT*AR	-0.0006055	-0.0453086	0.00000148	-0.0001406	-0.0001094	0.00040807
TCVT*TR	-0.0047461	0.02895703	0.00000234	-0.0001719	-0.0001563	0.0002138
TCVT*TOC(1)	-0.0016445	0.00501953	5.46875e-7	-0.0000469	-0.0000156	-0.0001794
TCVT*TOC(3)	-0.0015742	0.01332422	0.00000234	-0.0000469	-0.0000234	-0.0000224
TCVT*SWEEP	-0.0018242	0.00381641	0.00000156	-0.0000547	-0.0000391	-0.0000122
TCVT*ARHT	-0.0002461	-0.0174492	-0.0000045	-0.0000313	-0.0000234	0.00013776

TCVT*TRHT	-0.001707	-0.000332	0.00000117	-0.0000625	-0.0000547	0.00000365
TCVT*TCHT	-0.0035977	-0.0084805	-0.0000034	-0.0001172	-0.0001016	-0.0002914
TCVT*SHT	-0.0014336	0.02115234	-0.0000013	-0.0000234	-0.0000156	0.00006771
TCVT*ARVT	0.00462109	0.07787891	0.00000766	0.00025	0.00022656	0.00023568
TCVT*TRVT	-0.0002539	-0.0174023	7.8125e-8	-0.0000547	0.00000781	-0.0000667
TCVT*TCVT	0.06442784	0.01793634	-0.0000184	0.00227282	0.00212697	0.00027914
SVT*SW	-0.0036445	-0.3738867	-0.0000158	-0.0007188	-0.000625	-0.003507
SVT*TWR	0.00028516	0.21097266	7.8125e-8	-0.0000078	0.00000781	0.00000365
SVT*AR	0.00048828	-0.2344492	-0.0000021	-0.0005703	-0.0004453	0.00229115
SVT*TR	-0.0009336	0.05491016	-0.0000025	-0.0000078	-0.0000078	0.00077135
SVT*TOC(1)	-0.0024727	-0.0529805	0.0000018	-0.0000547	-0.0000547	-0.0013177
SVT*TOC(3)	-0.0012773	0.03099609	-0.0000069	0.00002344	0.00001562	-0.0002831
SVT*SWEEP	0.00203516	0.02472266	0.0000025	0.00009375	0.0000625	0.00005885
SVT*ARHT	0.00336328	-0.0004336	-0.0000019	0.00019531	0.0001875	-0.0005839
SVT*TRHT	0.00507422	0.01057422	-7.8125e-8	0.00019531	0.00017187	0.00004557
SVT*TCHT	0.00026172	0.01701953	-0.0000034	0.00001562	0.00001563	0.00002292
SVT*SHT	0.00133203	0.03226172	-0.0000055	0.00009375	0.00007031	0.00005286
SVT*ARVT	0.00644922	0.46239453	0.00001594	0.00074219	0.000625	0.00165885
SVT*TRVT	0.01712109	0.74586328	0.00001492	0.00092188	0.00071875	0.00097318
SVT*TCVT	0.00352734	0.37780859	0.00000633	0.00060937	0.00054687	0.0010151
SVT*SVT	-0.0525722	-0.2055637	-0.0000184	-0.0017272	-0.001873	-0.0001209

APPENDIX R – RSE GOODNESS OF FIT FOR CLOSING THE LOOP

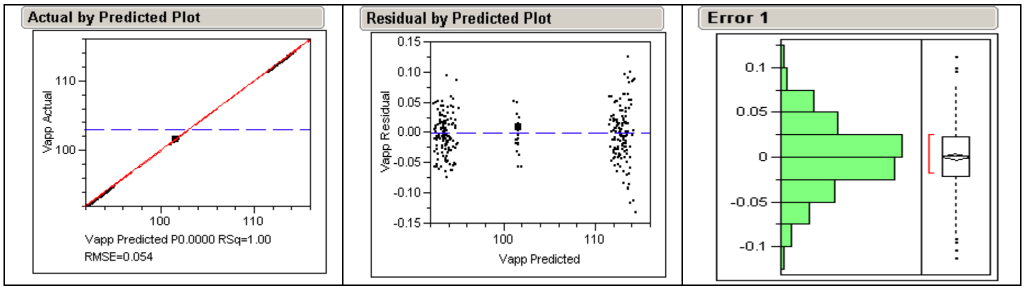


Figure R1: Fit Analysis for Approach Speed

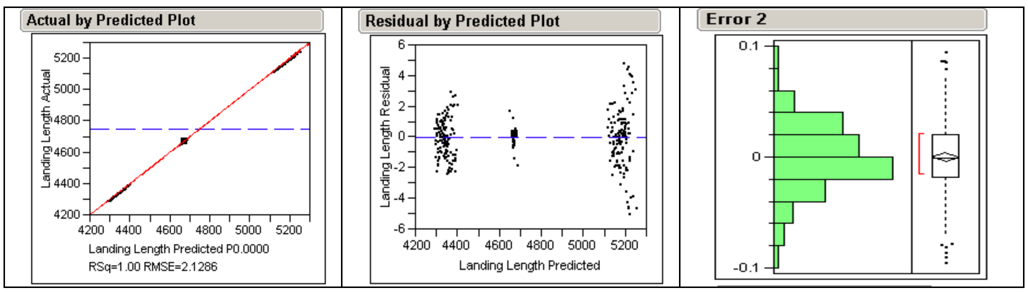


Figure R2: Fit analysis for Landing Field Length

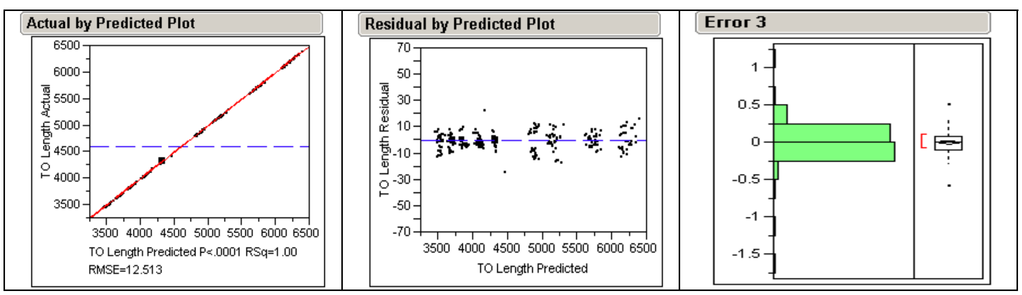


Figure R3: Fit Analysis for Takeoff Field Length

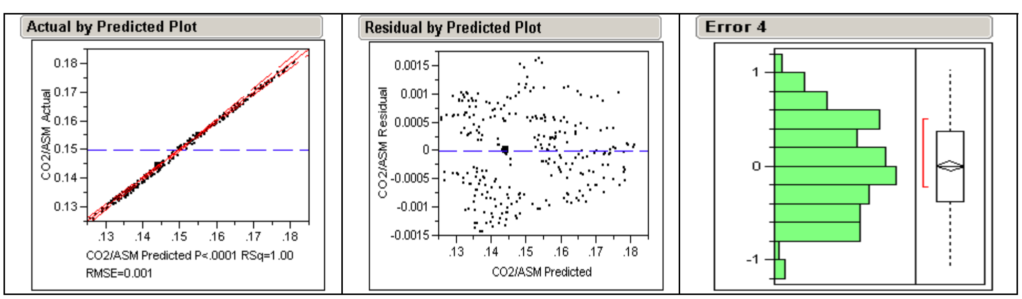


Figure R4: Fit Analysis for CO_2/ASM

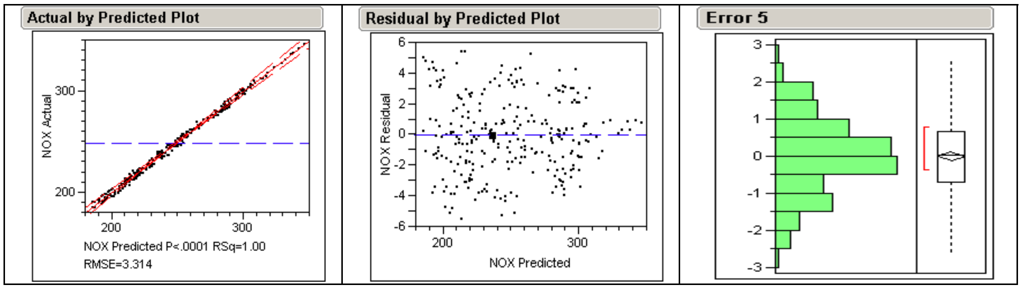


Figure R5: Fit Analysis for NOx

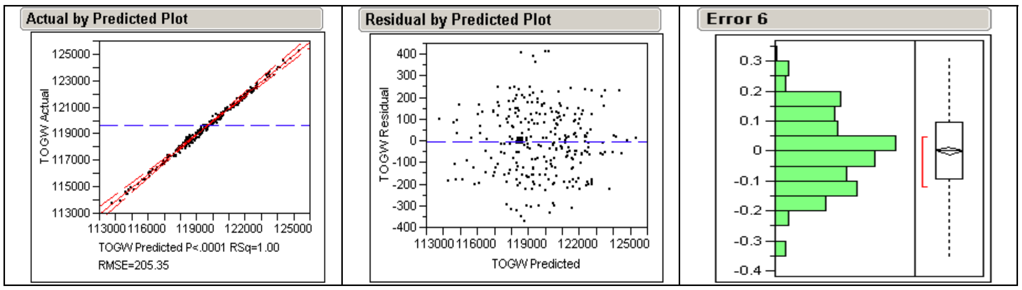


Figure R6: Fit Analysis for Takeoff Gross Weight

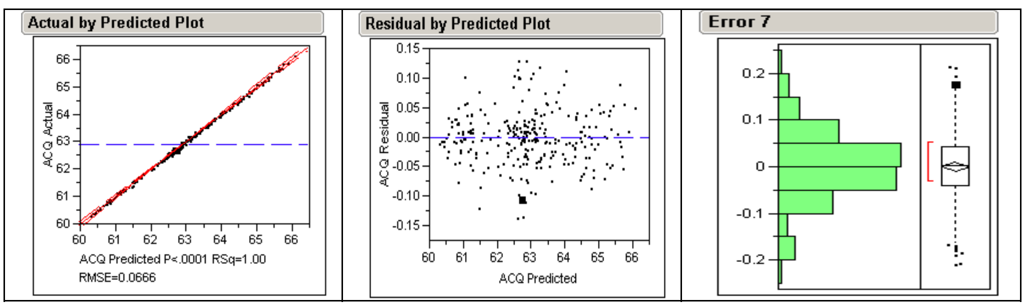


Figure R7: Fit Analysis for Acquisition Price

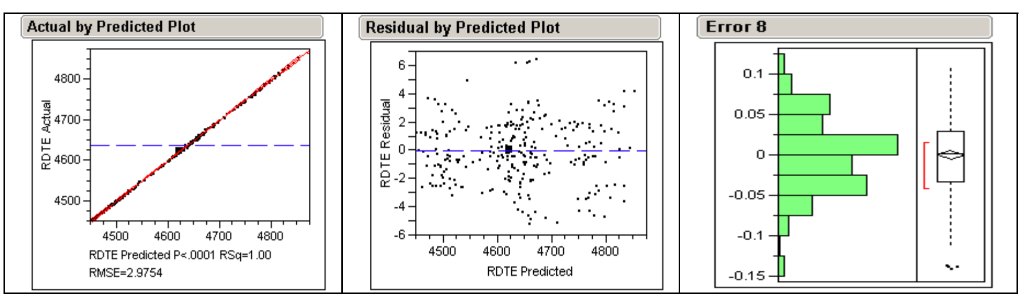


Figure R8: Fit Analysis for RDT&E Cost

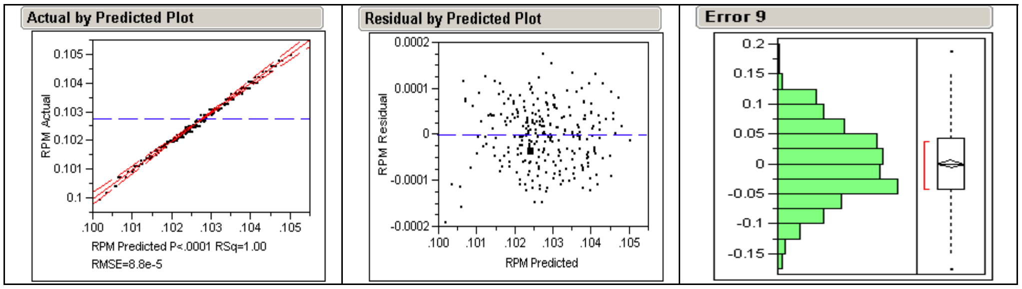


Figure R9: Fit Analysis for Required Yield per RPM

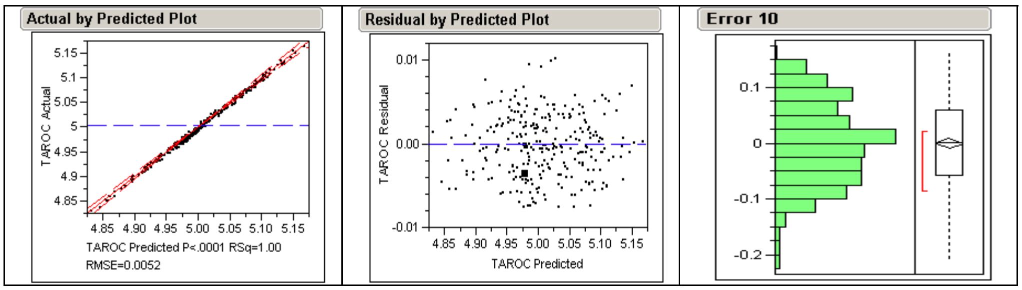


Figure R10: Fit Analysis for Total Airplane Related Operating Costs

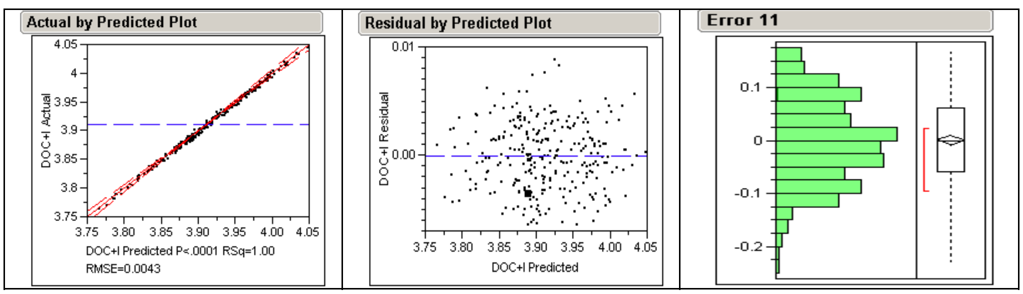


Figure R11: Fit Analysis for Direct Operating Costs Plus Interest

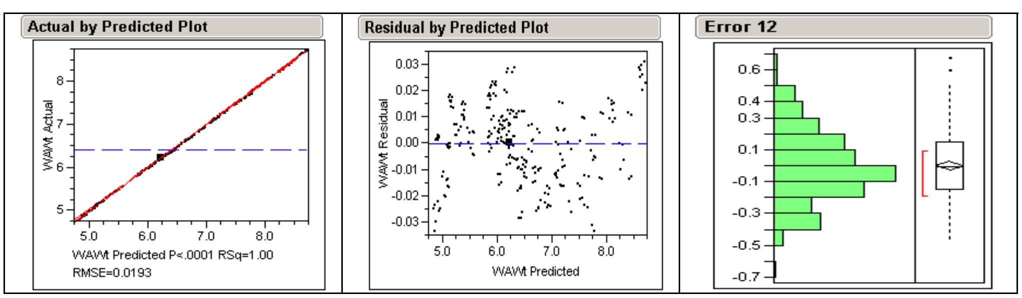


Figure R12: Fit Analysis for Wing Aerial Weight

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