ADM I Course Project Report

Fall 2023 AE-6373-A/Q
Advanced Design Methods I
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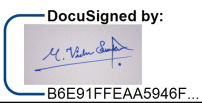
Team: 13
Aircraft size: 210PAX

Honor Code Page

We certify that we have abided by the Honor Code of the Georgia Institute of Technology and followed the collaboration guidelines as specified in the project description for this assignment.



Manivasakan, Vishnu Sankar

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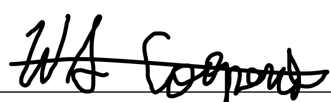

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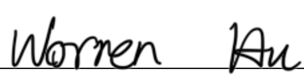

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Executive Summary

Commercial Aviation is a decisive and vital component of the global commercial infrastructure and social fabric. The capabilities provided by commercial air travel and aerial cargo transportation have resulted in a sharp increase in consumer demand for aviation services. In order to meet this steep demand in aircraft production, aircraft manufacturers must be able to deliver a competitive product. Narrow Body Aircraft are a class of aircraft that rest at the peak of this demand. We aim to design a proposed replacement NBA along operationalized performance improvements. Using the TIES method, this process at endstate will produce a viable technology alternative. For this first submission, we completed TIES Steps 1-3. These are enumerated as Problem Definition, Baseline and Alternative Concepts Identification, and Modeling and Simulation. In step one, we defined our problem scope and outlined how we will define success for our proposed NBA design. In step two, we explored the comprehensive solution space through the development of a morphological matrix and selected the viable solution space that represents our baseline aircraft. In step 3, we used EDS to model and simulate our baseline single aisle NBA to assess the current state of performance, and identify the metrics upon which we aim to improve.

1 Problem definition

1.1 Defining the Need

Commercial Aviation is a decisive and vital component of the global commercial infrastructure and social fabric. The capabilities provided by commercial air travel and aerial cargo transportation have resulted in a sharp increase in consumer demand for aviation services. The growth of the air transport industry is projected to balloon to 1.5 trillion per annum of the global Gross Domestic Product (GDP) by as early as 2036.[1] With more planes than ever taking to the skies, this consumer demand for an increase in aviation necessitates streamlining aircraft manufacturing and improving airspace deconfliction and air traffic control through individual aircraft performance improvements. However, simply saturating the market with comparable aircraft to the current structure is insufficient. All future aircraft must also meet stringent emission standards. This will require a technological paradigm shift in how we build aircraft.

1.2 Defining the Market

Narrow Body Aircraft (NBA), be it either large single-aisle aircraft or small twin aisle aircraft, is an aircraft class of unmatched versatility. NBAs have the capacity to move 150-300 personnel and are the aircraft of choice for domestic flights and short haul international flights.[2] Modified NBA passenger aircrafts can also execute domestic cargo flights with a capacity up to 30,000 pounds.[3] Boeing predicts that a total of 29,530 new NBAs will have to enter production within the next 20 years in order to meet the present market demand.[4] With a clearly defined market and demand increase, aircraft manufactures must improve upon present narrow body aircraft design in order to remain competitive.

1.3 Request for Proposal – RFP

Through this analysis, we as the Research and Development Team have taken on a Request for Proposal (RFP) from the aircraft manufacturer.

An optimally designed narrow body aircraft with concrete performance improvements compared to the present narrow body fleet will dominate this demanding market. Consequently, we will operationalize success by designing a proposed replacement narrow body aircraft with the following performance improvements:

Additionally, these aircraft performance improvements translate into outputs of tangible, qualitative significance that cannot be ignored. These qualitative translations will arm decision-makers at echelon and will enable a more cohesive understanding of the outputs of our improved design.

Parameter	Target
Approach Speed	Decreased by 15%
Balanced Take-off Field Length	Decreased by 15%
Operating Empty Weight	Decreased by 25%
Wing Span	Constrained
Nitrogen Oxide Emissions	Decreased by 20%
Nitrogen Oxide Certification Limit	Constrained
Acquisition Price with Spares	Decreased by 15%
Research, Development, Testing, and Evaluation Cost	Minimized
Direct Operating Cost plus Interest	Decreased by 20%
Required Yield per revenue passenger mile (RPM)	Minimized

Table 1: Projected System Level Metric Performance Improvement

Parameter	Translated Qualitative Outcomes
Decreasing Approach Speed	Increased versatility in feasible runway lengths and consequently the aircraft can operate out of more airports.
Decreasing Balanced Take-off Field Length	Take-Off Safety margins are increased and the aircraft is safer to fly.
Decreasing Operating Empty Weight	Increased fuel efficiency and less fuel required to fly comparable mission; saving cost.
Decreasing Nitrogen Oxide Emissions	Environmentally conscious aircraft is increasingly become a market necessity
Decreasing Acquisition Price with Spares	Tangible fiscal incentive for the aircraft manufacturer
Minimizing Research, Development, Testing, and Evaluation Cost	Tangible fiscal incentive for the aircraft manufacturer
Decreasing Direct Operating Cost plus Interest	Tangible fiscal incentive for the aircraft manufacturer
Minimizing Required Yield per revenue passenger mile (RPM)	Tangible fiscal incentive for the aircraft manufacturer

Table 2: Translating Targeted Aircraft Performance Improvement to Tangible Outcomes

2 Baseline and alternative concepts identification

In this section, Analysis of Alternatives (AOA) shall be presented, elucidating the manner in which design space can be built. The analysis encompasses the evaluation of technical feasibility, economic viability, and the degree of alignment with the objectives inherent in all alternative design. Furthermore, the establishment of a well-defined design space empowers to undertake a analytical comparison of diverse potential solutions. This analytical framework facilitates a judicious assessment, providing the capacity to make trade-offs between different measures and ultimately arrive at the optimal outcome aligned with the intended objectives.

When considering possible alternatives, we must first consider the parameters we want alternatives for. A morphological matrix shown below is used to exhibit the various possibilities. Defining parameters were broken up into 3 main parts: Conceptual, Design and Mission.

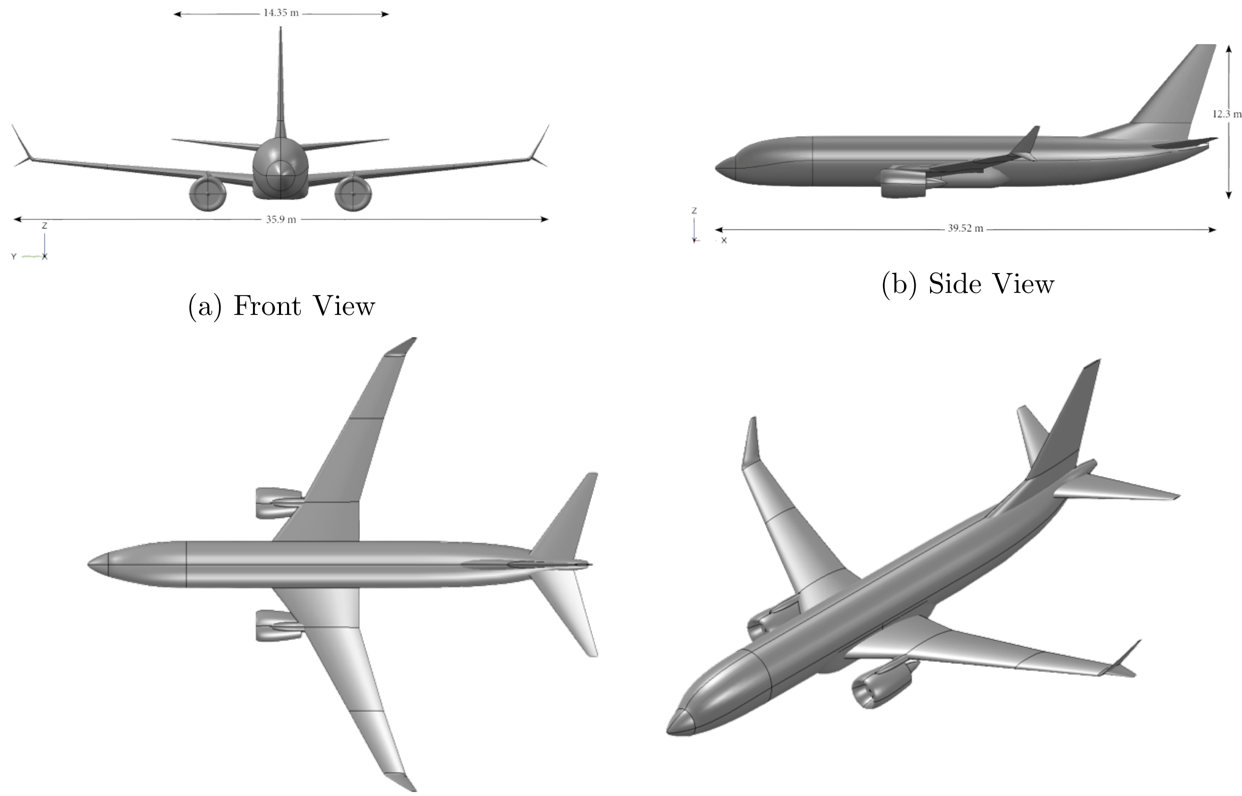
The conceptual aspect of the morphological matrix can yield the most alternatives since an infinite number of different designs exist to complete a transport mission. The design part of the morphological matrix includes the metrics we will be varying in order to obtain the parameters desired in Table 1. The mission part of the matrix details the desired sizing capabilities of the vehicle. The matrix looks as follows with the highlighted parameters being the chosen baseline values for our 210 passenger capable aircraft.

Morphological Matrix		Alternatives			
Conceptual		Wing and Tail	Wing and Canard	Wing, tail and Canard	Sea Plane
	Vehicle Configuration	Joined wing	Blended Wing Body	Flying Wing	Amphibian plane
	Horizontal Tail Location	T -tail	V-tail	on fuselage	
	Vertical Tail Location	two tail booms	on fuselage	under fuselage	
	Controls	Electrical	Hydraulic	Pneumatic	FBW
	Number of Properllors	0	1	2	4
	Structural Material	Aluminum	Titatinum	Steel	Composite
	Pilot	Manned	Unmanned		
	Engine Type	Turbofan	Turbojet	Ramjet	Turboprop
	Number of Engines	2	4	5	
	Engine integration type	Engine **inside** the wing or fuselage	Engine **on** wing or fuselage		
Design	Wing Loading (lbf/ft^2)	75	125	150	250
	Thrust to weight ratio	0.23	0.32	0.45	1
	Wing aspect ratio	7.5	8.09	10.5	12.5
	Wing taper ratio	0.3	0.283	0.24	0.22
	Wing thickness-to-chord ratio (%)	7.5	10	11.8	
	Wing quarter-chord sweep	28	25	29.7	31.1
	Horz. Tail aspect ratio	2	4.5	6	8
	Verti. Tail aspect ratio	1.45	1.64	1.82	1.87
	Bypass Ratio	4	5.5	9	12
	Fan Diameter (in)	55	60	68.3	
	Fan Pressure Ratio	1	1.2	1.65	2
	Low Pressure Compressor Pressure Ratio	1.2	1.53	2	2.4
	High Pressure Compressor Pressure Ratio	8	12.5	20	32
	Fuel Type	JET-A	Electric	Hydrogen	
	Fuel Capacity (gal)	2500	3500	4500	6400
Mission	Range (nm)	1500	2800	4000	6000
	Service Ceiling (ft)	28000	36000	39000	60000
	Maximum Payload (lb)	25000	30000	36000	48000
	Cruise Speed (knots)	250	350	450	600
	Maximum Speed (knots)	275	375	473	625

Figure 1: Morphological Matrix (baselines highlighted in yellow)

Our selected options from the morph matrix and accompanying values are analogous to a

Boeing 767-300ER. This baseline aircraft design for this project shall be illustrated by Fig.2, showing the 3-view configuration of the aircraft and specific characteristics such as number and integration type of the engine.



(a) Front View

(b) Side View

(c) Top View

(d) Isometric View

Figure 2: 3 View of the Baseline Design

After considering the all of the conceptual design choices along with different design and mission options we can calculate the total number of realistic alternatives.

Many of the conceptual design choices are constrained based upon which vehicle configuration is chosen, therefore a rough estimation of the total number alternatives will be calculated. With 8 different vehicle configurations, 2 to 3 horizontal and vertical tail locations, 4 different control methods, 4 different main structural materials, two piloting options, four engine type options, 3 number of engine type options, and two engine integration types we have a total of 9216 alternatives alone, assuming every variable is independent to build a complete and unrefined design space.

$$8 \cdot (3^2) \cdot (4^3) \cdot (2) = 9216 \tag{1}$$

When changing the design options, some of the values do not agree with specific vehicle configurations, so once again a rough estimate will be calculated. With 4 different alternatives and 15 different design parameters and 8 different vehicle configurations, when considering the infeasible options, there are a total of 120 different vehicle choices. When combining this with the conceptual design then there are a total of 1105920 choices. Finally when considering the mission requirements we add an extra 20 possible options bringing our total number of cases to 22118400. If we decide to only consider baseline cases, and possible improved cases then the number of possible design cases drops from 22118400 to 5400. This is because we have constrained our vehicle type to wing and tail and based upon that many conceptual and design alternatives are infeasible.

3 Modeling and simulation

3.1 Mission Profile

In order to accurately size our baseline aircraft, we must "fly" this aircraft through a standard mission profile. We elected for a standardized 11 phase mission typical for a commercial airliner that includes additional air space deconfliction climbs. Following in Figure 3 is our mission profile and accompanying by-stage breakdown of each leg. The mission profile consists of takeoff, climb-1, cruise-1, climb-2, cruise-2, climb-3, cruise-3, climb-4, cruise-4, descent and landing.

The mission profile of commercial airliners usually involve multiple initial climbs before reaching the final cruise segment.

1. Takeoff occurs at Mach number of 0.3. The time taken from the start till the takeoff is not reported, so we assume the mission starts just after the takeoff at $t = 0$ minutes.

2. Climb-1 lasts for about 4 minutes, with a fuel burn up to 2391 lbs. This segment of the mission profile corresponds to the steepest climb.

3. Cruise-1 lasts for less than 2 minutes, with a fuel burn up to 350 lbs. This short cruise is usually taken to avoid obstacles before the next climb.

4. Climb-2 lasts for about 7 minutes and 43 seconds, by consuming about 4800 lbs of fuel. The climb rate is gradual, and by the end of the climb the aircraft reaches the VFS (final segment climb speed) which turns out to be Mach 0.8 in our case.

5. Cruise-2 lasts for about 210 minutes, consuming about 42275 lbs of fuel and covering about 22% of the range.

6. Climb-3 lasts for about 4 minutes and 10 seconds, by consuming about 1087 lbs of fuel. This is a relatively short climb for the aircraft to reache 35,000 ft altitude.

7. Cruise-3 lasts for about 341 minutes, covering 35% total range, and consuming about 69885 lbs of fuel.

8. Climb-4 lasts for only 4 minutes and 22 seconds, with a fuel burn up to 950 lbs. Another short climb until the aircraft reaches 39,000 ft.

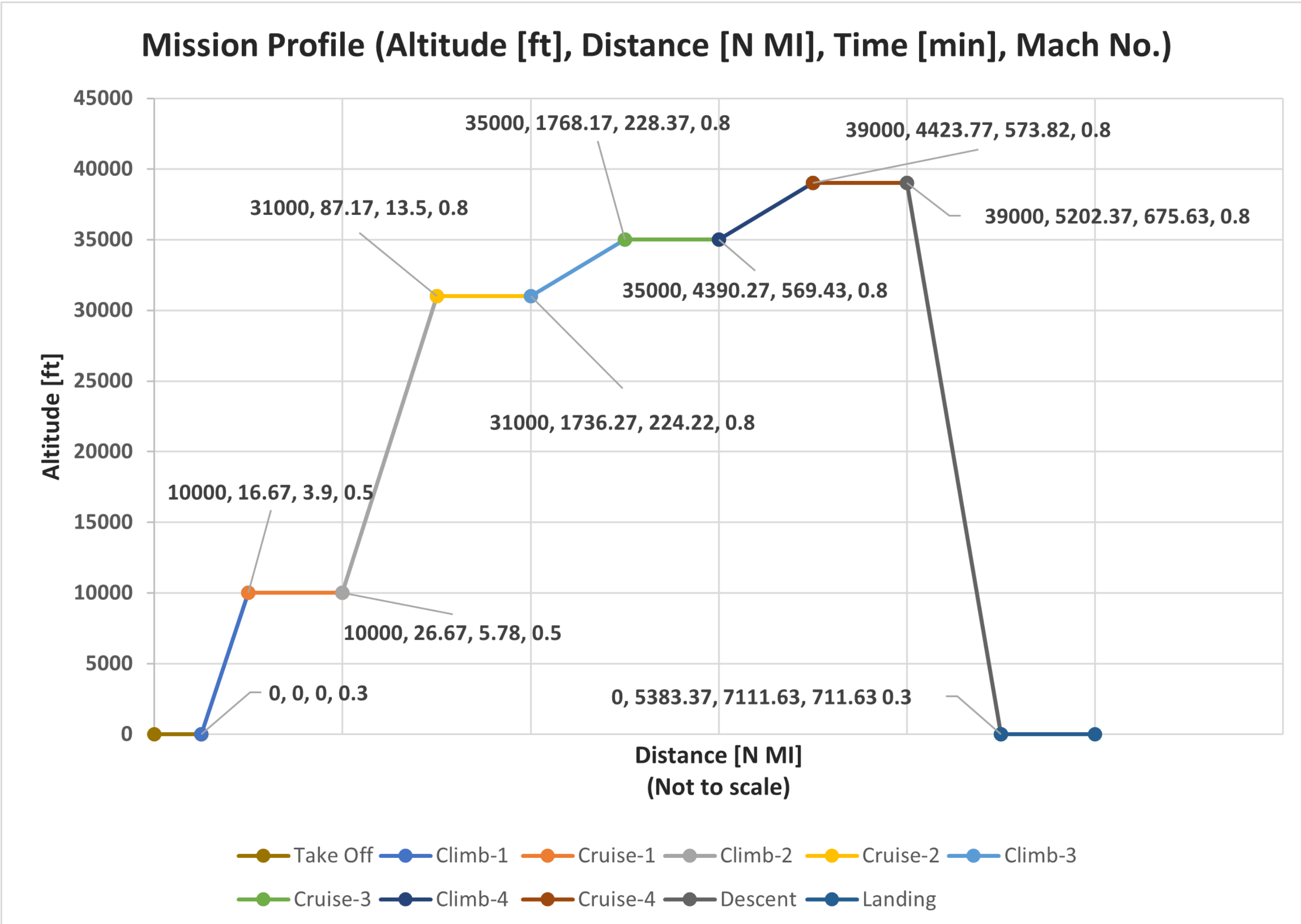


Figure 3: Mission Profile

9. Cruise-4 takes about 102 minutes with a fuel consumption of about 15484 pounds. This is the final cruise segment.

10. Descent phase lasts for about 37 minutes and consumes 2198 lbs of fuel. There is a high probability for an approach phase after descend phase, but it is avoided for brevity.

3.2 Design Point

The design point values are shown in Table 3. These are the base line design point values for our 210 pax aircraft. The design point values change based on the range requirement. When the range requirement is 3200 nautical miles $\frac{T_{sl}}{W_{TO}} = 0.3604$ and the wing loading is $\frac{W_{To}}{S} = 106.22\frac{lb}{sqft}$ for a nautical mile range requirement of 5920 then the thrust to weight ratio is $\frac{T_{sl}}{W_{TO}} = 0.2966$ and the wing loading is $\frac{W_{To}}{S} = 129.08\frac{lb}{sqft}$. The values change depending on the range since more fuel is required to fly longer missions which as a result requires the aircraft to carry more weight.

Parameters	Value at 5920 N MI	Value at 3200 N MI
Thrust to Weight Ratio	0.2966	0.3604
Wing Loading	129.08 lb/sq-ft	106.22 lb/sq-ft

Table 3: Design Point Values

3.3 Weights

The gross, payload, max fuel, and operating weights are shown below in Table 4. The only difference in the weights for the two different ranged air crafts are the weight of the fuel, and therefore the gross weight. Both range missions can carry the same amount of payload. Both range missions also have the same amount of operating costs. The principal weights are shown below in figure 4.

Weight Group	Weight (lb) at 5920 N MI	Weight (lb) at 3200 N MI
Gross	412999.92	339866.98
Payload	54810.00	54810.00
Max Fuel	159749.95	86617.01
Operating	198439.97	198439.97

Table 4: Weight Groups

Weight Groups	Weight Fraction (%)
Wing	22
Empennage	4
Fuselage	21
Landing Gear	10
Airframe Propulsion	4
Thrust Reverser	2
Fuel System	1
Fixed Equipment	21
Hydraulic	1
Passenger Accomodations	14
Avionics	1
Vehicle Total	100

Table 5: Weight Groups

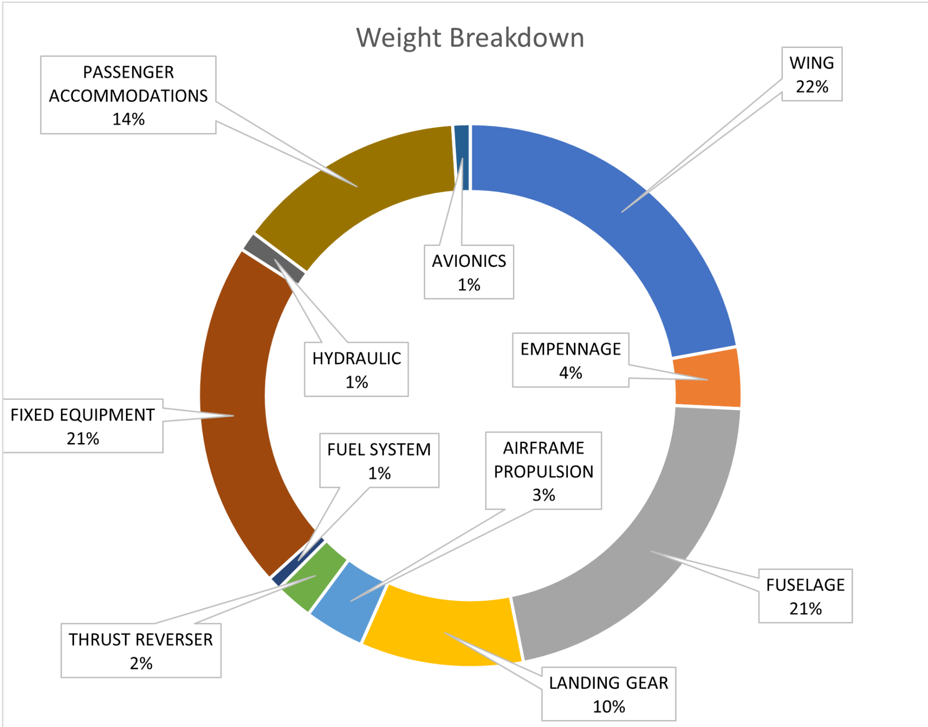


Figure 4: Weight Breakdown in terms of percentage of Total Weight

3.4 Propulsion

The maximum static sea level rated installed thrust per engine is 61242.9 LB, and the fuel consumption during cruise depends upon which cruise segment the aircraft is flying. The first cruise segment is a short cruise that lasts less than two minutes. This cruise burns up to 350 lbs of fuel. The next cruise, which is longer at 210 minutes, consumes 42275 lbs of fuel. The third cruise which is the longest of all the cruises at 341 minutes, consumes the most amount of fuel at 69885 lbs. The last cruise, cruise 4 takes about 102 minutes with a fuel consumption of 15484 lbs of fuel. This brings the total amount of fuel used for all 4 cruises to 127994 lbs of fuel. The specific fuel consumption (SFC) is a good metric of fuel consumption. During cruise it depends upon the altitude and the sizing of the aircraft for different ranged missions. The SFC during cruise at Mach 0.5 with al altitude of 10,000ft for a mission range of 5920 nmi is 0.54896. The fuel consumption during cruise at Mach .5 with an altitude of 10,000 ft for a mission range of 3200 nmi is 0.56857. The SFC for a faster cruise at Mach 0.8 at an altitude of 31000 ft for a mission range of 5920 nmi is 0.58980 and for a mission range of 3200 nmi and at an altitude of 35,000 ft then the SFC is 0.58889.

Parameters	Value for 5920 N MI	Value for 3200 N MI
Max Static Thrust at Sea Level	61242.9 lb	61242.9 lb
SFC [lbm/h]	0.54896 @M=0.5 & Alt=10000	0.56857, @M=0.5 & Alt=10000
SFC [lbm/h]	0.58980 @M=0.8 & Alt=31000	0.58889, @M=0.8 & Alt=35000

Parameters	Value for 5920 N MI	Value for 3200 N MI
L/D$_{Cruise}$ @0.8 Mach (max. reported)	18.804	18.67
L/D$_{Cruise}$ @0.5 Mach (max. reported)	20.131	19.745
L/D$_{Takeoff}$	11.287	15.006
L/D$_{L}anding$	17.916	18.061

3.5 Aerodynamics

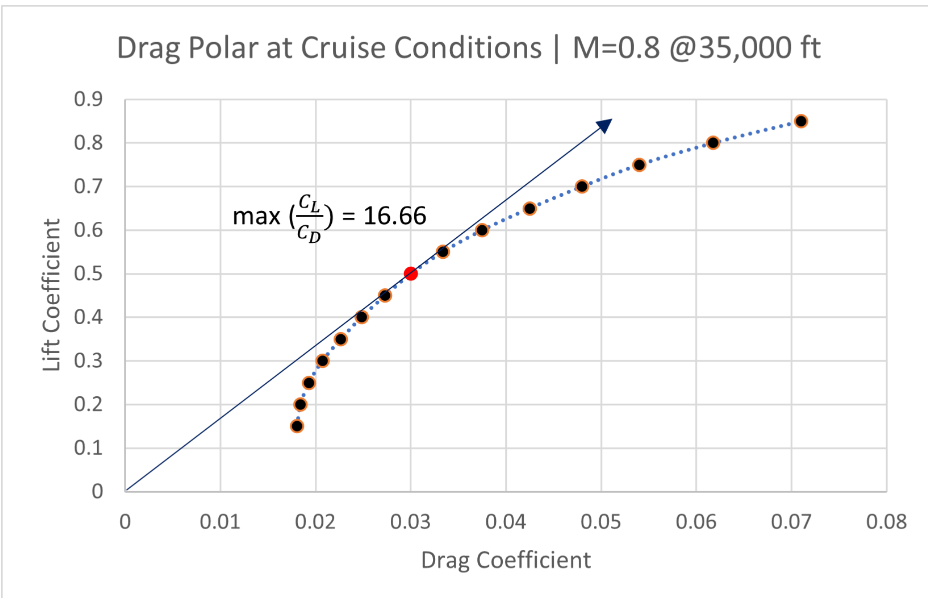


Figure 5: Drag Polar

The drag polar at cruise conditions was calculated by Flight Optimization System or FLOPS. FLOPS was the software we used in our modeling and simulation environment. It is the primary aircraft synthesis software used by the National Aeronautics and Space Administration (NASA). It works by calibrating models to known aircraft data. [5]

For our mission, cruise is at Mach 0.8 with an altitude of 35,000 ft. The parabolic drag polar is shown in Figure 5. As the drag coefficient increases, the lift coefficient increases at a parabolic rate; this is what is expected from a drag polar. The drag polar ranges are: for coefficient of drag value C_D from 0.018 to 0.07, while the parasitic drag is $C_{D0} = 0.018$

3.6 Airframe Manufacturer Economics

As part of the airframe manufacturing process, it's critical to assess the economic viability of the proposed aircraft. To do so, we have executed a manufacturer's cash flow plot and a production schedule. Upon comparing Figure 6 and Figure 7, in the initial days of the production cycle when there was a sharp increase in aircraft manufacturing, the manufacturing was in a state of negative cash flow. Bottoming out after only five years, the manufacturer was then in a sharp increase in cash flow as manufacturing numbers still increased and even maintained a positive state of cash flow as the production began to both level off and slow down. The log log plot of acquisition cost versus quantity of aircraft is indicated in figure 8. The linear plot is indicative of the fact that the cost comes down exponentially as quantity ordered increases.

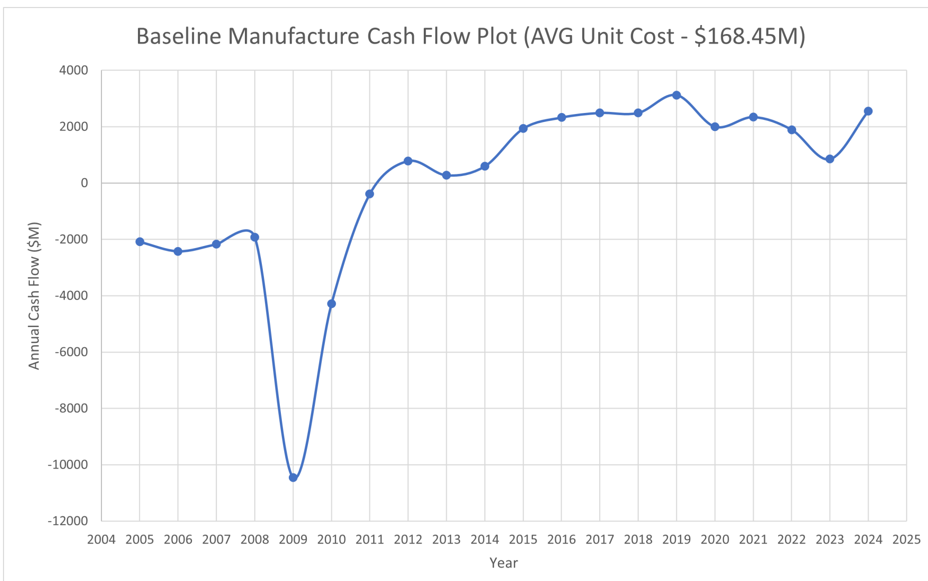


Figure 6: Airframe Manufacturer Cash Flow

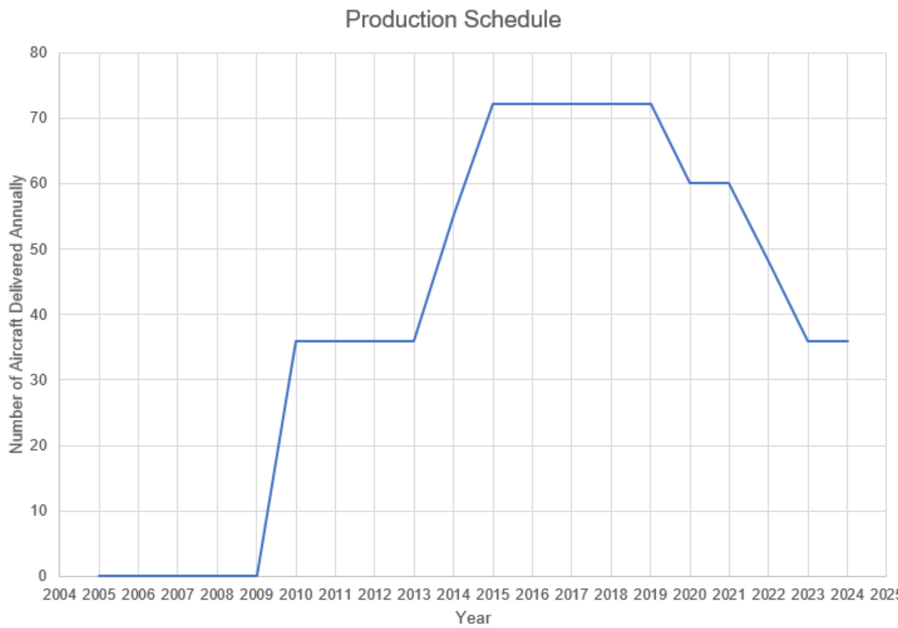


Figure 7: Aircraft Production Timeline

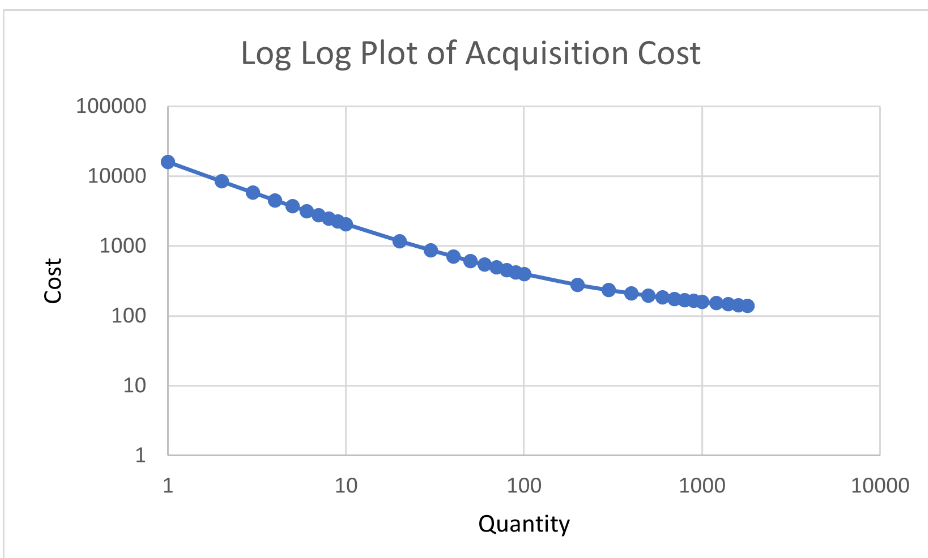


Figure 8: Acquisition Cost

3.7 Airline Economics

Operating Costs

The total breakdown of the direct operating costs and indirect operating costs are shown in the figure 10 and the values are mentioned in table 6.

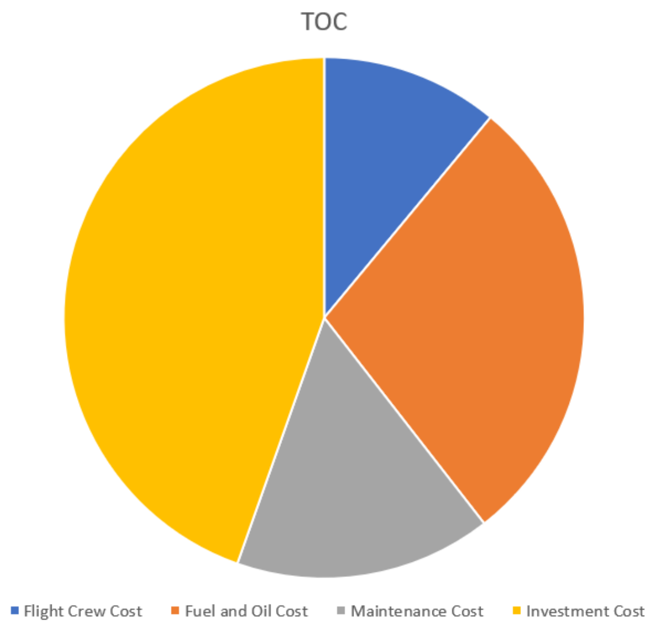


Figure 9: Total Operating Cost

Direct Operating Costs $/Trip	5920 N MI	3290 N MI
Flight Crew ($ 989./Blk hr)	13370	7997
Fuel and Oil ($1.70/gal)	36502	18607
Airframe Labor (1.00 Complexity)	2430	1473
Burden (200.% of Labor)	4859	2945
Material	3361	2066
Engine Labor Total (1.00 Complexity)	426	247
Burden (200.% of Labor)	852	494
Engine Material Cost	7383	4353
Depreciation (20. years,10.% residual)	24699	14039
Financing (100.% @ 8.00% interest)	28460	16177
Hull Insurance (.35% aircraft cost)	1921	1092
Total	124263 USD	69490 USD

Table 6: Direct Operation Cost Breakdown

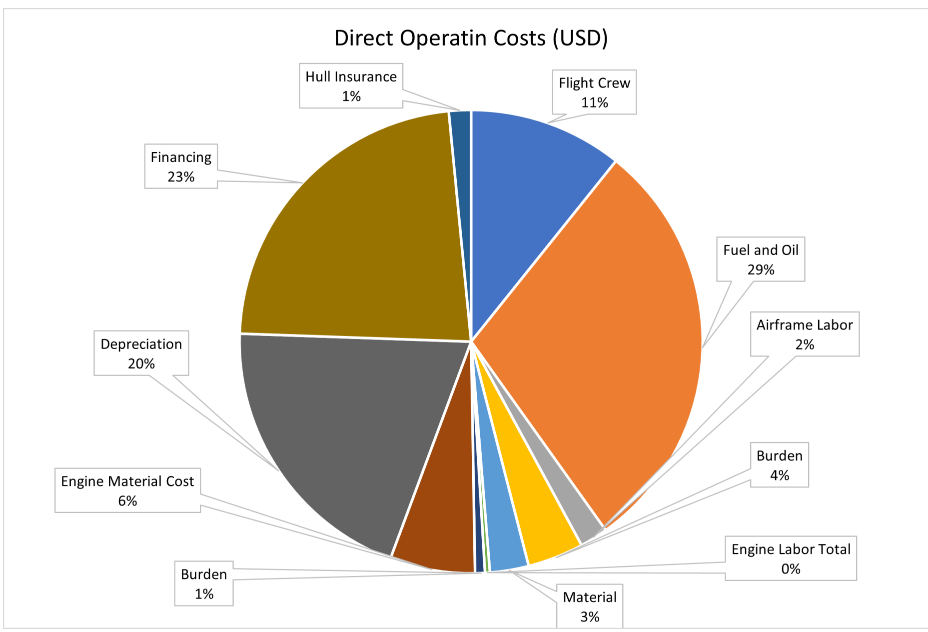


Figure 10: Direct Operating Cost

The indirect cost breakdown is shown in figure 11 and table 7. Together both direct operation cost indirect operation cost constitute total operation cost.

Indirect Operating Costs $/Trip	5920 N MI	3290 N MI
Maintenance - System	1428	860
Maintenance - Local	2148	2148
Aircraft Servicing - Aircraft Cont	2905	1651
Passenger Service - Cabin Crew	7229	4109
Passenger Service - Food and Bev	5072	2883
Traffic Servicing - Passenger Hand	2065	2065
Traffic Servicing - Bag and Cargo	626	626
Passenger Service - Comm/Publ/Res	27363	14791
General and Administrative	12169	6933
Total Indirect Operating Expense	61005 USD	36066 USD

Table 7: Indirect Operation Cost Breakdown

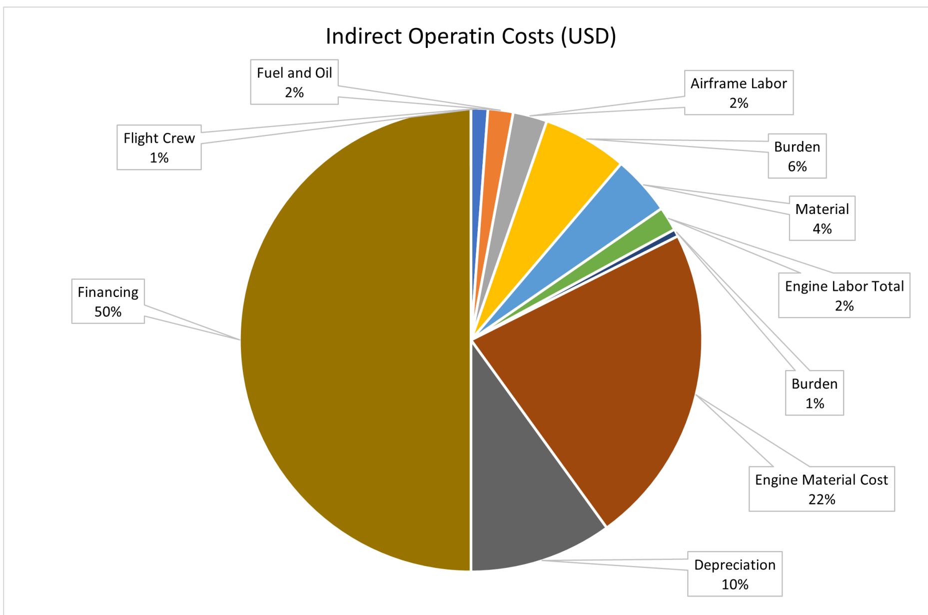


Figure 11: Indirect Operating Cost

Return Of Investment (ROI)

The return on investment for the vehicle throughout its life is shown below through the plots of operating costs, interest, depreciation, pre-tax earnings, net earnings, net cash flow, and discounted cash flow.

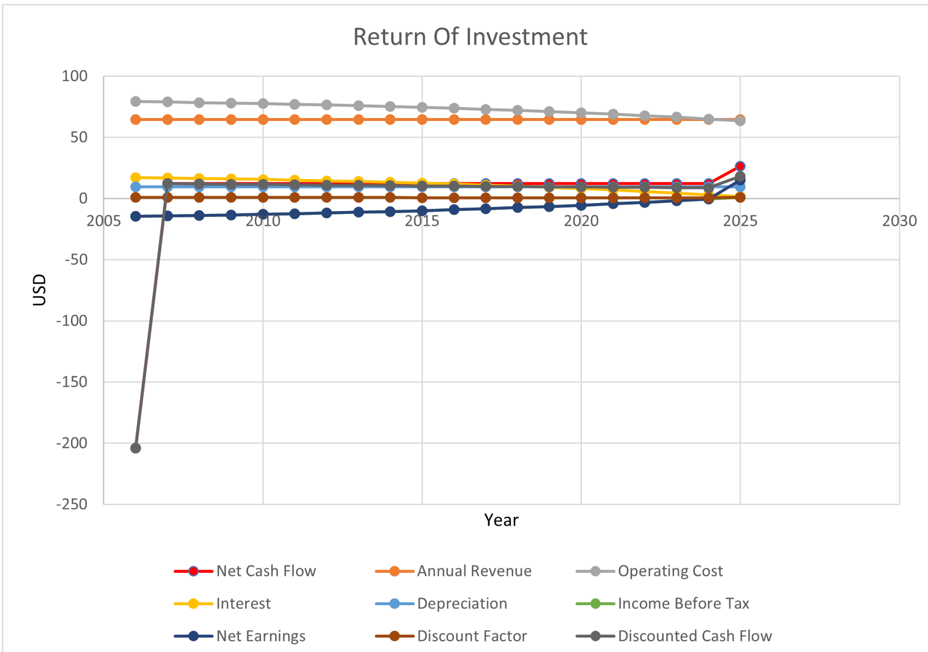


Figure 12: Return Of Investment

3.8 Potential Markets and Competitors

The current aircraft in development is a 210 passenger aircraft. Current competitors for the aircraft in the 210 pax market are the airbus family of A340 aircraft and the single isle narrow body Boeing 737s. Today, there is an emphasis on sustainability in the market along with major players looking to reduce their carbon footprint. Both Boeing and airbus are making developments to reduce their carbon footprint however the family of A340 aircraft and the Boeing 737 will have more emissions than our proposed technology enabled 210 passenger aircraft. The demand for a 210 passengers aircraft is aligned with the new and evolving market (regional travel, preferences of airlines, and environmental concerns), thus allowing for manufacturers to stay ahead in terms of technological advancements and efficiencies to obtain opportunities in the current and future market landscape.

4 Design space exploration

The main target of this section is building a design space from the baseline design and framed by the morphological matrix, creating a proper surrogate model, and conducting a

Monte-Carlo simulation to explore the established design space. An optimization process is also performed through JMP to generate an optimized baseline design which will be used in the later steps to infuse technologies into it to achieve the requirements.

4.1 Design of Experiment

The design of experiment is based on 11 independent control variables shown in Table 8, which are acceptable input parameters of the Environmental Design Space (EDS), the modeling and simulation tool used for design space exploration in this project. The domains of these control variables are properly adjusted from the baseline model, Boeing 767-300ER, as discussed previously in step 2 study on alternatives.

Independent Variables	Range
Wing Loading(WSR)	115-145
Thrust to weight ratio(TWR)	0.28-0.32
Wing aspect ratio(AR)	7.0-9.0
Wing taper ratio(TR)	0.2-0.3
Wing thickness-to-chord ratio(TCA)	0.08-0.14
Wing quarter-chord sweep(SWEEP)	27.0-34.0
Horz. tail aspect ratio(ARHT)	3.0-6.0
Vert. tail aspect ratio (ARVT)	1.0-2.5
Fan Pressure Ratio(FPR)	1.4-2.0*
Low-Pressure Compressor Pressure Ratio(LPCPR)	1.2-2.0
High-Pressure Compressor Pressure Ratio(HPCPR)	10.0-15.0

Table 8: Domain of the Input Variables for Design of Experiments

It is worth noticing that the project description showed 2.0 as an upper bound for fan pressure ratio(FPR), however, through the EDS simulation we observed that many simulations with a FPR greater than 1.72 proved impossible for the EDS simulation to converge. Excluding the failed tests a sufficiently large amount of successful tests were obtained, that's enough to build a surrogate model and proceed to later stages of design.

With 11 independent control variables, each of which is a numerical and continuous variable on the specific domain, a full-factorial design covering all possibilities will result in an excessively enormous amount of tests and, therefore, is practically infeasible. Instead, we separated the design of experiments into two parts: the edge cases and the inner space-filling cases. We employed different methodologies to lower the required tests while still ensuring the result has an acceptable significance.

The 1000 edge cases are used to explore the performance of the set of control parameters at their respective boundaries, in other words, these edge cases compose of different combinations of the maximum and minimum values of the control variables in their respective domains. Another 3999 space-filling cases are generated using Latin-Hypercube design, balancing the maximum spacing and the uniformity inside the design space. A final case is the baseline model with specified set of values for the control variables, so a total number of 5000 tests is generated for EDS to simulate and evaluate.

4.2 Regression

Among 5000 simulation tests conducted in EDS, 1416 tests are proved to be feasible design, excluding the pre-determined baseline model; as shown in figure.13, a scatterplot matrix showing the test results correlated with the 10 response variables this project intended to improve listed in table 2 is presented here.

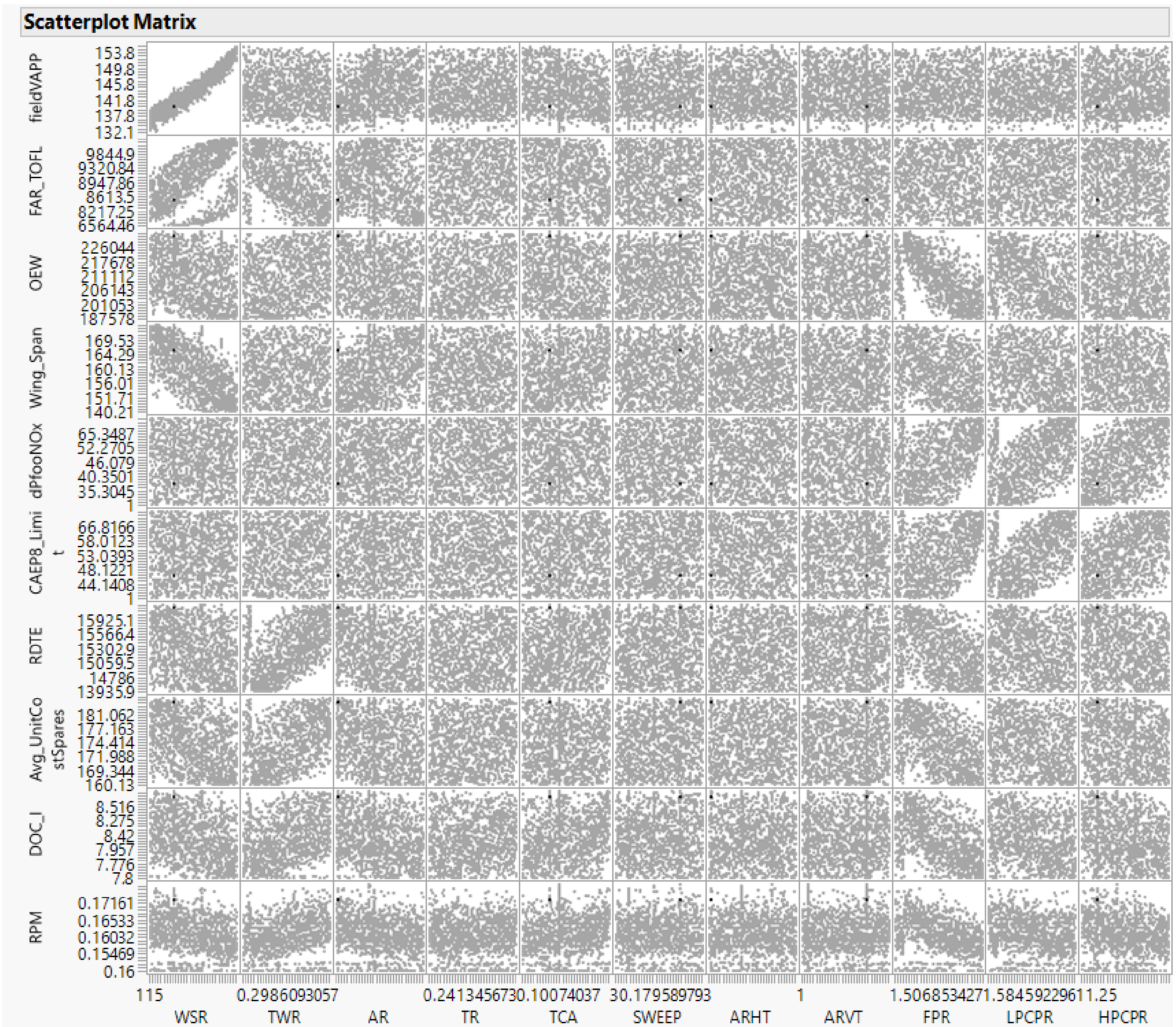


Figure 13: Results of 1416 successful tests in the EDS simulation

The data processing and evaluation are performed in JMP, a statistics tool, and following response surface prediction formulae are generated through regression analysis. All behaviors for the response variables this project is intended to optimize can be properly estimated by the control variables through response surface equations with acceptable precision, except for the FAR_TOFL(Balanced take-off field length), which utilize artificial neural net (ANN) models instead. Some prediction formulae examples are presented below.

Prediction formula for fieldVAPP:

$$
\begin{gathered}
15.236143187031 + 1.83770735561752 \cdot AR + -0.0303050380838459 \cdot ARHT + \\
-0.0542869211462693 \cdot ARVT + 35.5804343119757 \cdot FPR + 1.45020043281355 \cdot HPCPR \\
+5.15170457673414 \cdot LPCPR + -0.251755511235474 \cdot SWEEP + 7.07288358928425 \cdot TCA \\
+ - 4.54832074885233 \cdot TR + -56.1886442205681 \cdot TWR + 0.837330953770898 \cdot WSR \\
+ - 0.125905001623359 \cdot AR^2 + -13.6432098958317 \cdot FPR^2 + -0.0286370397449791 \\
\cdot HPCPR^2 + -0.931949409005354 \cdot LPCPR^2 + -0.00349275368088659 \cdot SWEEP^2 \\
+ - 593.089314949501 \cdot TCA^2 + -0.00136072564273714 \cdot WSR^2 + \\
-0.0120363246178464 \cdot AR \cdot HPCPR + 0.0192153868629463 \cdot AR \cdot SWEEP \\
+0.460566295036306 \cdot AR \cdot TR + 0.00820572122725218 \cdot AR \cdot WSR + \\
-0.236601824546783 \cdot FPR \cdot HPCPR + -15.7181087794252 \cdot FPR \cdot TCA \\
+32.2741687123454 \cdot FPR \cdot TWR + 0.0268575147872539 \cdot FPR \cdot WSR + \\
-0.0923977552038922 \cdot HPCPR \cdot LPCPR + 0.5925380986413 \cdot HPCPR \cdot TCA \\
+0.000809585743538836 \cdot HPCPR \cdot WSR + 2.43568746226401 \cdot LPCPR \cdot TCA \\
+2.26843078353368 \cdot SWEEP \cdot TCA + 0.490261996133774 \cdot SWEEP \cdot TWR + \\
-0.000550181899105685 \cdot SWEEP \cdot WSR + -0.137115504167227 \cdot TWR \cdot WSR
\end{gathered} \tag{2}
$$

Prediction formula for FAR_TOFL:

$$
\begin{gathered}
(-358589331.247058) + 7846356.16874952 \cdot AR^2 + -21884.7848067091 \cdot AR^4 + \\
-148240.718221693 \cdot ARHT^2 + -34614.3643313702 \cdot ARVT^2 + 104567561.503794 \cdot \\
FPR^2 + -6146.05949612297 \cdot HPCPR^2 + -2595045127.00833 \cdot TCA^2 + \\
-2919892858.14995 \cdot TWR^2 + 34121221879.3168 \cdot TWR^4 + 31938.4092556006 \cdot WSR \\
^2 + -42489.3545957316 \cdot LPCPR \cdot AR^2 + 6139.92097003258 \cdot SWEEP \cdot ARHT^2 \\
+ - 661772.555529369 \cdot AR^2 \cdot FPR^2 + -18366478.727522 \cdot AR^2 \cdot TWR^2 \\
+ - 145.30938711377 \cdot AR^2 \cdot WSR^2 + -485926652.713558 \cdot FPR^2 \cdot TWR^2 \\
+ - 1000.5532161852 \cdot FPR^2 \cdot WSR^2 + 28610764416.9055 \cdot TCA^2 \cdot TWR^2 \\
+ - 166074.856599921 \cdot TWR^2 \cdot WSR^2
\end{gathered} \tag{3}
$$

Prediction formula for OEW:

$$\begin{gathered}\mathrm{EXP}(35.9930691958316 + -1.49833525968804 \cdot Log(AR) + 0.00465221822258895 \cdot \\ Log(ARHT) + 0.0142214082895786 \cdot Log(ARVT) + -10.1696255104319 \cdot \\ Log(FPR) + -1.53936110964131 \cdot Log(HPCPR) + -1.20236696471396 \cdot \\ Log(LPCPR) + -2.09147666407945 \cdot Log(SWEEP) + 2.0901740436977 \cdot \\ Log(TCA) + -0.18373514166069 \cdot Log(TR) + 3.12065014290248 \cdot Log(TWR) \\ + -3.68320958577004 \cdot Log(WSR) + 0.263161476679309 \cdot Log(AR)^2 + \\ -0.0127448446026785 \cdot Log(ARVT)^2 + 6.12614519245341 \cdot Log(FPR)^2 \\ +0.208571166376131 \cdot Log(HPCPR)^2 + 0.375431686224689 \cdot Log(LPCPR)^2 \\ +0.263128809041152 \cdot Log(SWEEP)^2 + 0.247664156526372 \cdot Log(TCA)^2 \\ +0.710126709857112 \cdot Log(TWR)^2 + 0.337509616149425 \cdot Log(WSR)^2 \\ +0.2038852000081 \cdot Log(AR) \cdot Log(FPR) + -0.205341780827688 \cdot Log(AR) \cdot \\ Log(TCA) + 0.0741195500308754 \cdot Log(AR) \cdot Log(TR) + 0.425968351949697 \\ \cdot Log(FPR) \cdot Log(HPCPR) + -0.675863122391532 \cdot Log(FPR) \cdot \\ Log(LPCPR) + -0.23227129834095 \cdot Log(FPR) \cdot Log(SWEEP) + \\ -0.0856563327882751 \cdot Log(FPR) \cdot Log(TR) + -2.15099800850313 \cdot Log(FPR) \\ \cdot Log(TWR) + 0.236464285147041 \cdot Log(FPR) \cdot Log(WSR) \\ +0.395056283582821 \cdot Log(HPCPR) \cdot Log(LPCPR) + -0.199692184561173 \cdot \\ Log(SWEEP) \cdot Log(TCA) + -0.05609752118574 \cdot Log(TCA) \cdot Log(TR))\end{gathered} \tag{4}$$

4.3 Goodness of Fit

A strict validation of the goodness of fit of all the prediction models built either on response surface equations or artificial neural networks is conducted, and the results are presented in Table.9.

The results show that the prediction models fit the actual behaviors of the data collected in the simulation tests to a sufficiently good degree. This is evident since we observe R^2 to be greater than 0.95, RME and RFE for all the models,

Table 9: Goodness of Fit Analysis

Response Variables	R^2	MFE		MRE	
		mean	Std Dev	mean	Std Dev
fieldVAPP	0.9995	-3.6e-14	0.116	-5.0e-3	0.12
FAR_TOFL	0.9544	0.000593	0.0228	0.00472	0.02777
OEW	0.9741	9.604e-15	0.010	-2.1e-4	0.011
Wing_Span	0.9943	-2.12e-4	0.656	0.04071	0.707
dPfooNOx	0.9935	2.185e-14	1.31	-8.0e-3	1.12
CAEP8_Limit	0.9911	-2.2e-14	1.048	9.0e-3	0.403
Avg_UnitCostSpares	0.9876	1.51e-14	4.15e-3	7.27e-5	4.45e-3
RDTE	0.9883	-1.181e-5	0.0044	4.73e-5	0.0044
DOC_I	0.9874	-1.85e-15	4.70e-3	1.1e-4	4.94e-3
RPM	0.9865	0.163	5.57e-3	0.163	5.73e-3

4.4 Prediction Profiles

In order to properly understand our regression, a detailed sensitivity analysis must occur. It involves identifying which input variables of the regression yielded the most significant effect on our output variables of interest. We took a three-step approach to action it:

1. Identify on the Prediction Profiler within JMP our output variables of interest. These are:
   - Approach Speed - VAPP
   - Operating Empty Weight - OEW
   - Wing Span
   - Nitrogen Oxide Emissions - dPfooNOx
   - Nitrogen Oxide Certification Limit - CAEP8 Limit
   - Average Unit Cost
   - Direct Operating Cost with Interest - DOC I
   - Revenue Passenger Mile - RPM
   - Research, Development, Testing, and Evaluation Cost - RDTE
   - Balanced Take off Field Length - FAR TOFL
2. Interpret the Prediction Profiler. The Prediction Profiler conducts sensitivity analysis by holding all other variables constant except for two: the input variable to examine and the output variable in question. As such, if an input variable has no sensitivity and/or effect on an output variable's status, a non-correlated relationship will be graphically depicted by a constant relationship, with marginal to no slope in the line. Conversely, our output variables of interest will be characterized as highly sensitive

to input variables where that graphic relationship shows a non constant, high slope linear, quadratic, or logarithmic relationship.

3. Complete sensitivity analysis by examining these graphic relationships in the Prediction Profiler and select the most sensitive input variable to output variable of interest relationships.

The following graphs and accompanying descriptions show these sensitivity relationships. Note the non constant, linear to quadratic relationship the input variables have on the output variables in questions.

Approach Speed

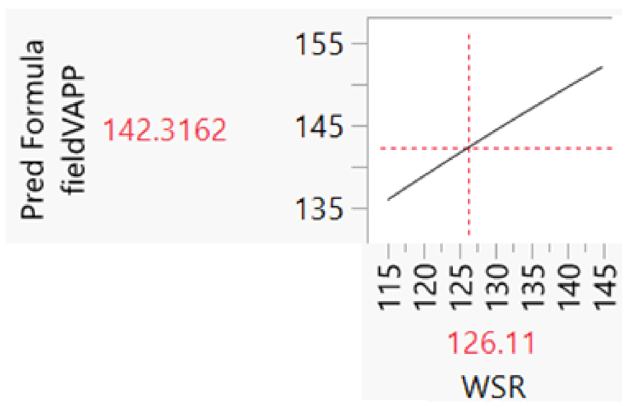


Figure 14: Approach Speed Sensitivity

As illustrated, approach speed is most sensitive to changes in wing loading. This is logical since take-off velocity is proportional to the square root of wing loading.

Operating Empty Weight

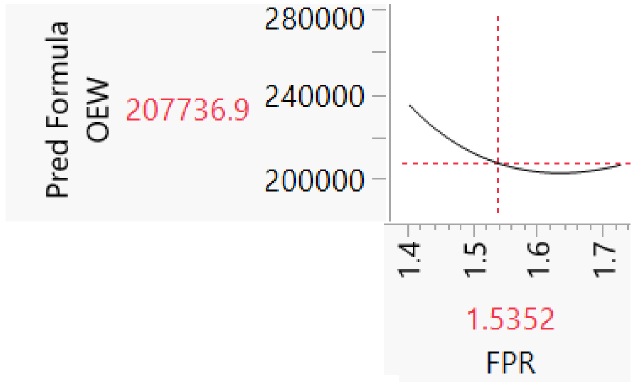


Figure 15: Operating Empty Weight Sensitivity

As illustrated, OEW is most sensitive to changes in fan pressure ratio (FPR). The reason is FPR heavily influences the thrust produced, which in turn affects the total empty weight that can be carried.

Wing Span

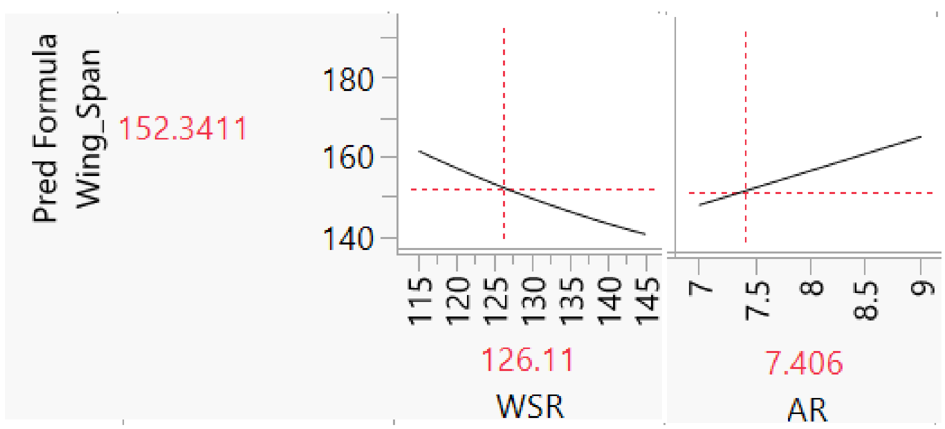


Figure 16: Wing Span Sensitivity

As illustrated, Wing Span is most sensitive to changes in wing loading (WSR) and aspect ratio (AR). Wing span is inversely proportional to wing loading, hence wing span decreases with increase in wing loading. Wing span is directly proportional to aspect ratio, hence it increases with increase in aspect ratio.

Nitrogen Oxide Emissions

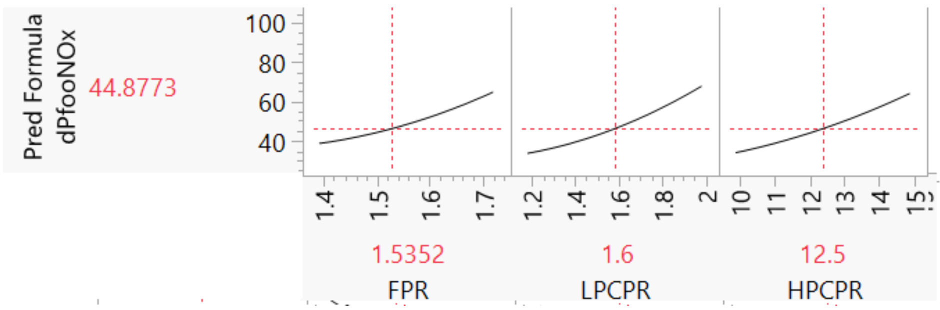


Figure 17: Nitrogen Oxide Emissions Sensitivity

As illustrated, Nitrogen Oxide Emissions are most sensitive to changes in fan pressure ratio (FPR), low-pressure compressor pressure ratio (LPCPR), and high-pressure compressor pressure ratio (HPCPR). The exact relationship between them is not evident, but one can argue that higher fan pressure ratio results in higher temperature inside the combustor. Higher temperature results in a faster combustion process that leads to less time for the fuel to burn. Hence it results in partial incomplete combustion of the fuel and contains less cleaner combustion products. Hence the NOx emissions are expected to increase.

Nitrogen Oxide Certification Limit

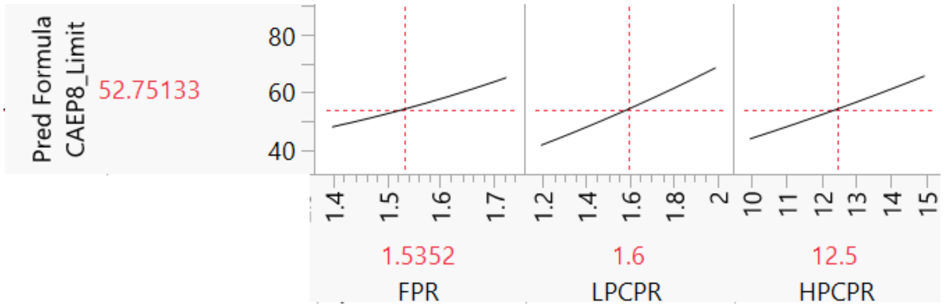


Figure 18: Nitrogen Oxide Certification Limit Sensitivity

As illustrated, the Nitrogen Oxide Certification Limit is most sensitive to the same changes as Nitrogen Oxide Emissions, FPR, LPCPR, and HPCPR. This intuitively makes sense as both emission metrics would be tethered to similar if not the same input variables. The argument is similar to the NOx emissions.

Average Unit Cost

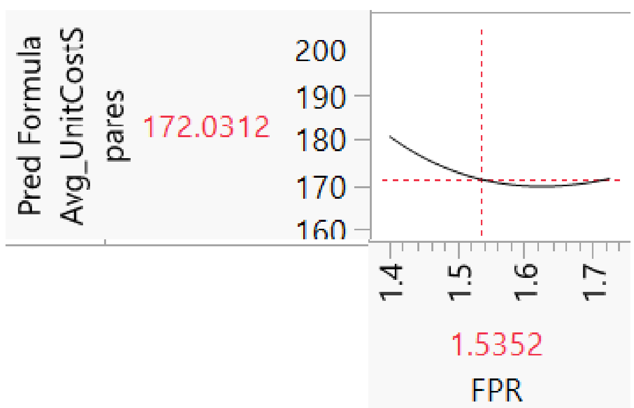


Figure 19: Approach Speed Sensitivity

As illustrated, Average Unit Cost is most sensitive to changes in fan pressure ratio (FPR).

Direct Operating Cost with Interest

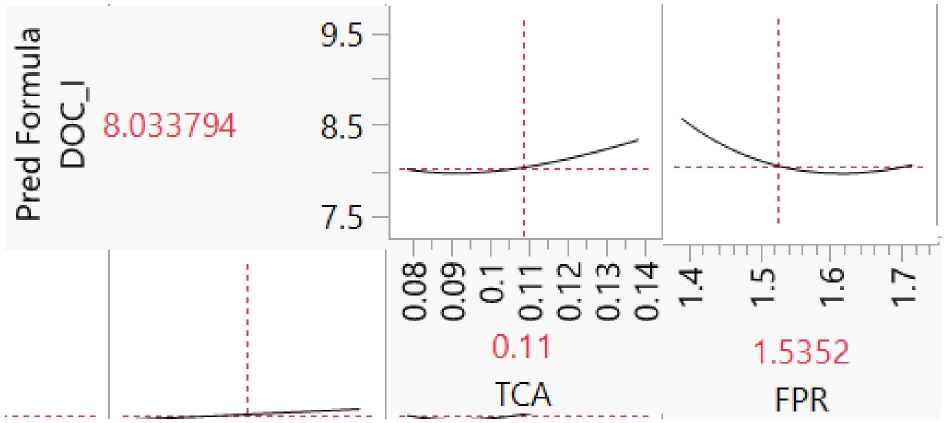


Figure 20: Direct Operating Cost with Interest Sensitivity

As illustrated, Direct Operating Cost with Interest is most sensitive to changes in wing thickness to chord ratio (TCA), and fan pressure ratio (FPR).

Revenue Passenger Mile

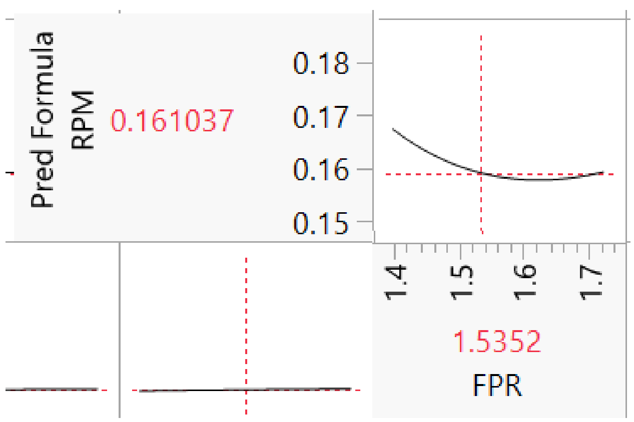


Figure 21: Revenue Passenger Mile Sensitivity

As illustrated, Revenue Passenger Mile is most sensitive to changes in fan pressure ratio (FPR).

Research, Development, Testing, and Evaluation Cost

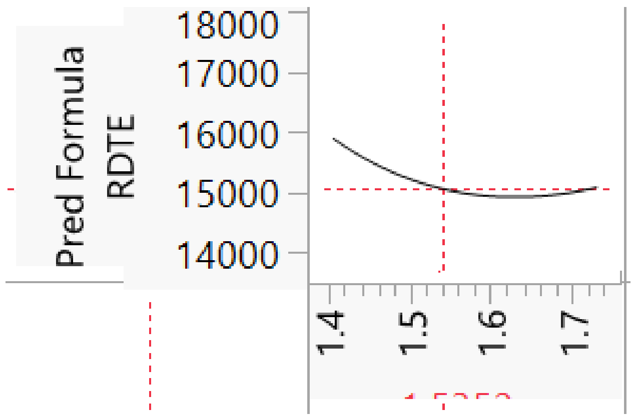


Figure 22: Research, Development, Testing, and Evaluation Cost Sensitivity

As illustrated, the Research, Development, Testing, and Evaluation Cost is most sensitive to changes in the fan pressure ratio (FPR).

Balanced Take off Field Length

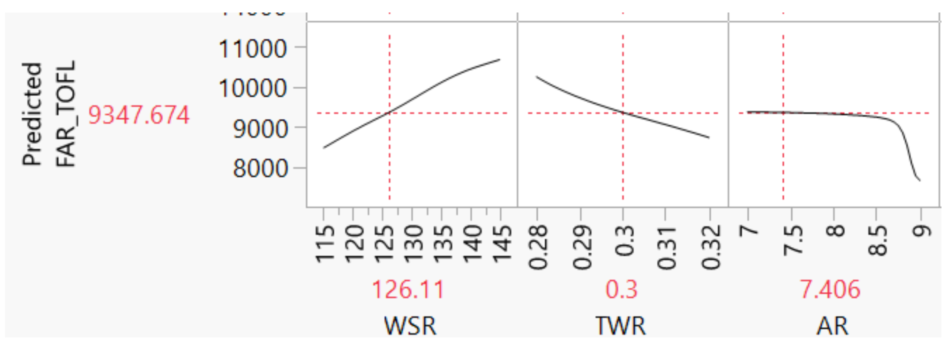


Figure 23: Balanced Take off Field Length Sensitivity

As illustrated, Balanced Take off Field Length is most sensitive to changes in Wing Loading (WSR), Thrust to Weight Ratio (TWR) and Aspect Ratio (AR).

Considering the holistic sensitivity analysis, fan pressure ratio (FPR), Wing Loading (WSR) and seem to be the most dominant input variables in determining the values for our output variables of interest. This is consistent with Pareto Analysis, as a small percentage of input variables are responsible for the largest portion of output variable values.

4.5 Stepwise Fit

The step wise fit was calculated for each response by using JMP. The stepwise fit outputs an approximate equation, or formula, for each response variable by applying certain input variables at different levels and either adding them one at a time, and measuring the resulting effects, or by starting with all input variables and removing them one at a time. This process shows us how the response will change when more input terms are added to the equation. At each step the error of the model is recorded and the final model that is chosen has the least amount of error with the most amount of terms. The types of terms that are added are the input terms, the input terms multiplied by other input terms for up to a total of four terms, and the input terms raised to the fourth power. The reason for only allowing the confounding effects to take place for only four variables at a time is because this is the desired order to perform the step wise fit. Some advantages of the step wise fit process are

1. The step wise fit at the end of the fitting process automatically selects the best combination of inputs

2. The step wise fit can also be simpler when compared to response surface equations since it only includes the best combination of inputs and does not include any inputs that do not change the response enough

When viewing the results of step wise fit an equation has been created for each response. The step wise fit equations can be compared with the response surface equations. When comparing the step wise fit equations to the response surface equations we notice that they are not exactly the same. The inputs that are included in the formulas for the step wise regression are the inputs that affect the regression the most, and not all inputs are included. The values of the coefficients of the inputs differ, but the dominant inputs are the same between both the response surface equations and the step wise fit. If a higher order was used when calculating the step wise fit model, an increased fidelity for the formulas for the step wise fit can occur. However, at the fourth order many of the higher order terms have been accounted for and minimal results will occur from increasing the order of the fit. If the order is increased over fitting may occur. It is also possible for the step wise regression to over fit responses that may primarily be controlled by noise effects. Another disadvantage to step wise fits, in general, is the step wise fit may not model nonlinear data sets properly.

4.6 Contour Plots

Two contour plots are created for the first portion of the project: a performance based contour plot and an economics based contour plot. The performance based contour plot contains the variables that affect the performance, these variables are: field V_{app}, Operating Empty Weight, Wing Span, and balanced take off field length. The economics based contour plot contains the variables that affect the economics of the aircraft such as: Acquisition price with spares, research development testing and evaluation cost, direct operating cost plus interest, and required yield per revenue passenger mile. The Contour plots for the first portion of the project are shown below.

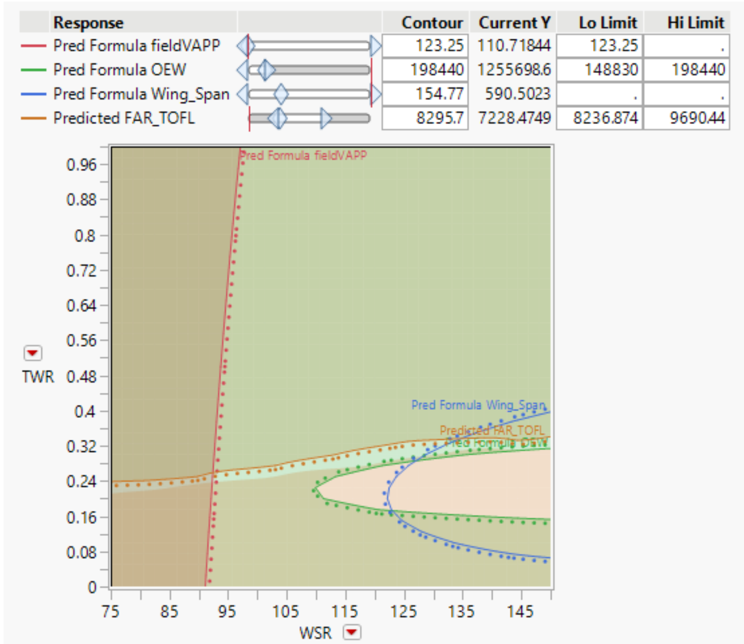


Figure 24: No feasible region identified in the contour plot for Performance

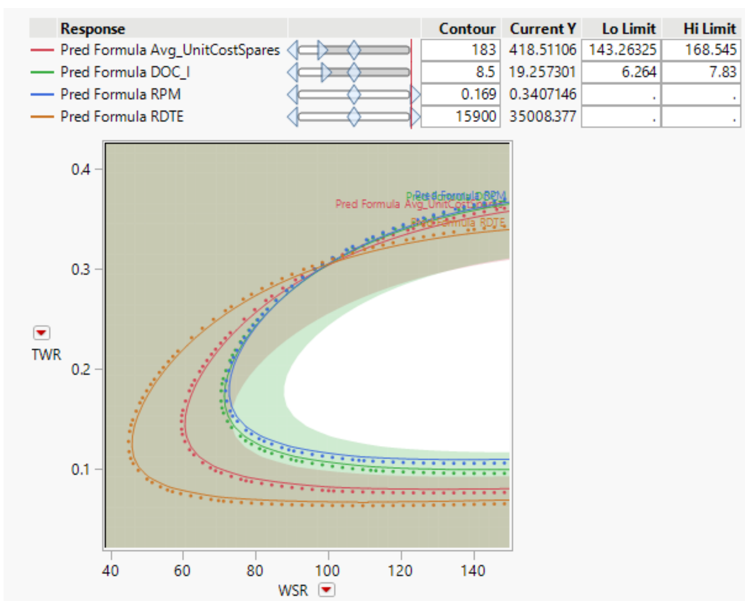


Figure 25: Feasible region identified in the contour plot for Economics

The feasible space is shown as the white region in the plots. In the performance contour plot no feasible space available. This is expected since the target requirements are very stringent. A feasible space exists for the economics contour plot. It is possible that if requirements were to be relaxed then that relaxation of requirements could result in a feasible space. This option is explored next.

4.7 Feasible Space

As previously denoted in the Contour Plot Section, there is currently no feasible design space. This means with the given requirements imposed by the stakeholders coupled with our current technological constraints of our proposed aircraft, it is presently impossible to design an aircraft that can meet all requirements. Consequently, we can either infuse new technologies that yield the aforementioned requirements, or we can relax the requirements to a degree in which a feasible design space presents itself on the contour plot. Acknowledging that further detailed analysis via cumulative distribution functions (CDFs) for the responses will present a more thorough lens for exploring technology infusions, we will examine here the hypothetical relaxation of requirements to yield a feasible design space.

From the project context and stakeholder requirements, the most competitive aircraft in future markets will be able to meet environmental and emission constraints. Accordingly, these target values must remain unchanged in effort to design a an environmentally emissions conscious aircraft that will be competitive in future markets, and will not be relaxed. Additionally, with a feasible space shown in the economics contour plot, these values must also remain unrelaxed. Therefore, we must relax our target performance requirements in order to establish a feasible design space.

With wing span being an established constraint, the only target values for performance targets that we can relax are the approach speed, balanced take-of field length, and operating empty weight. Examining the contour plot reducing these values by half of their proposed target improvements would be able to yield a feasible design space. Accordingly, our recommended new target parameters in order to develop a feasible design space, are:

- Approach Speed - Reduce by 7.5 Percent instead of 15 Percent
- Balanced Take-off Field Length - Reduce by 7.5 Percent instead of 15 Percent
- Operating Empty Weight - Reduce by 12.5 Percent instead of 25 Percent.

Again, this feasible design space exploration and explanation is only considering the option of requirements relaxation. Relaxing the constraints, however, did not yield any feasible design space. Further analysis will explore technology infusions as a mechanism for exploring the design space in order to create a feasible space.

4.8 Monte Carlo and Optimized Baseline Generation

Monte Caralo simulation with 10,000 cases was run with the surrogate models, and the cumulative distribution function plots are shown below in figure 9.5. The distributions used seed the initial design variables are all random and uniform. All the desirability functions are minimized in order to assess the feasibility and viability of the new optimized baseline design. The figure 33 shows the optimized baseline design generated through the surrogate model, the response and design variables of the optimized baseline are highlighted in red text.

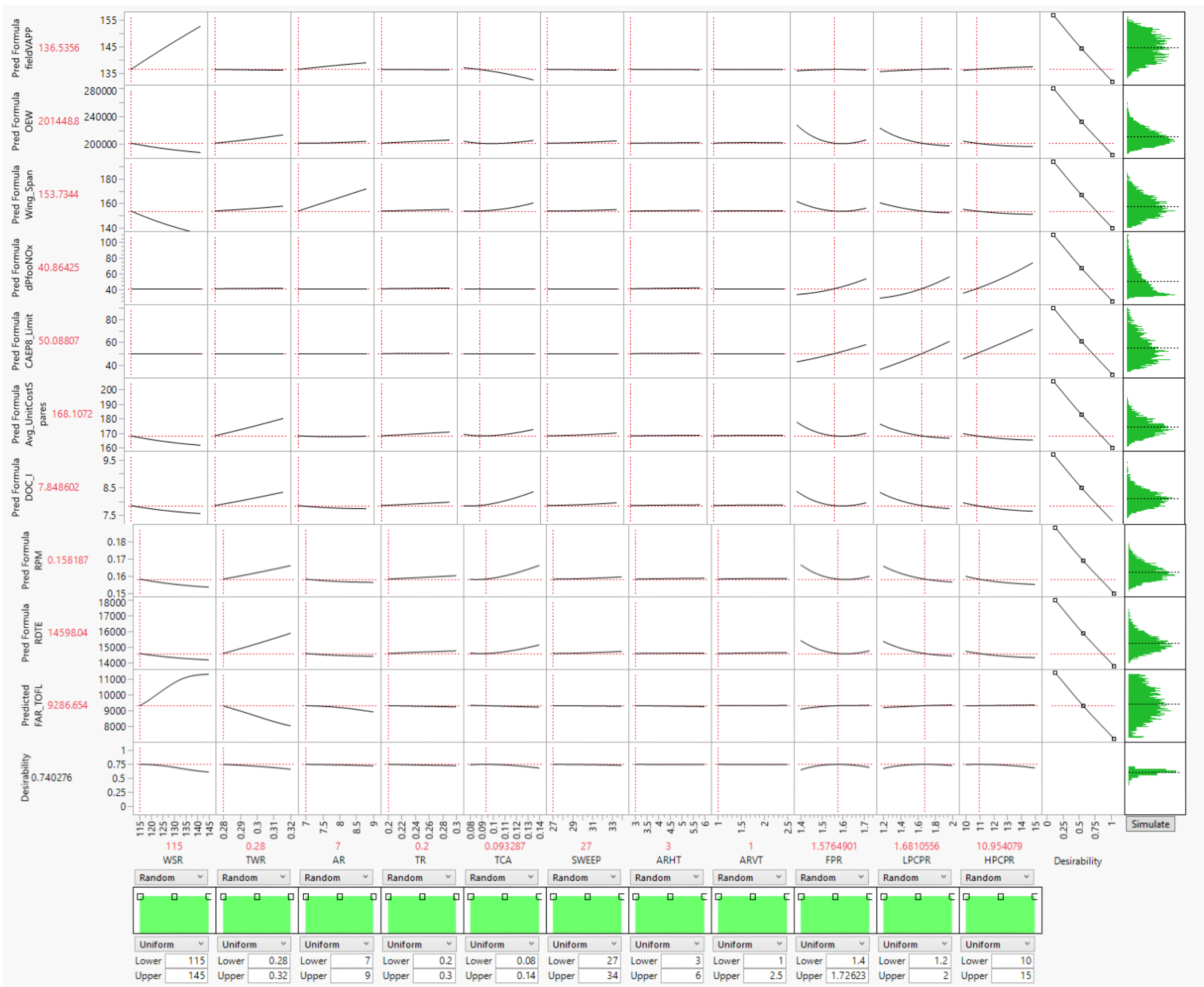
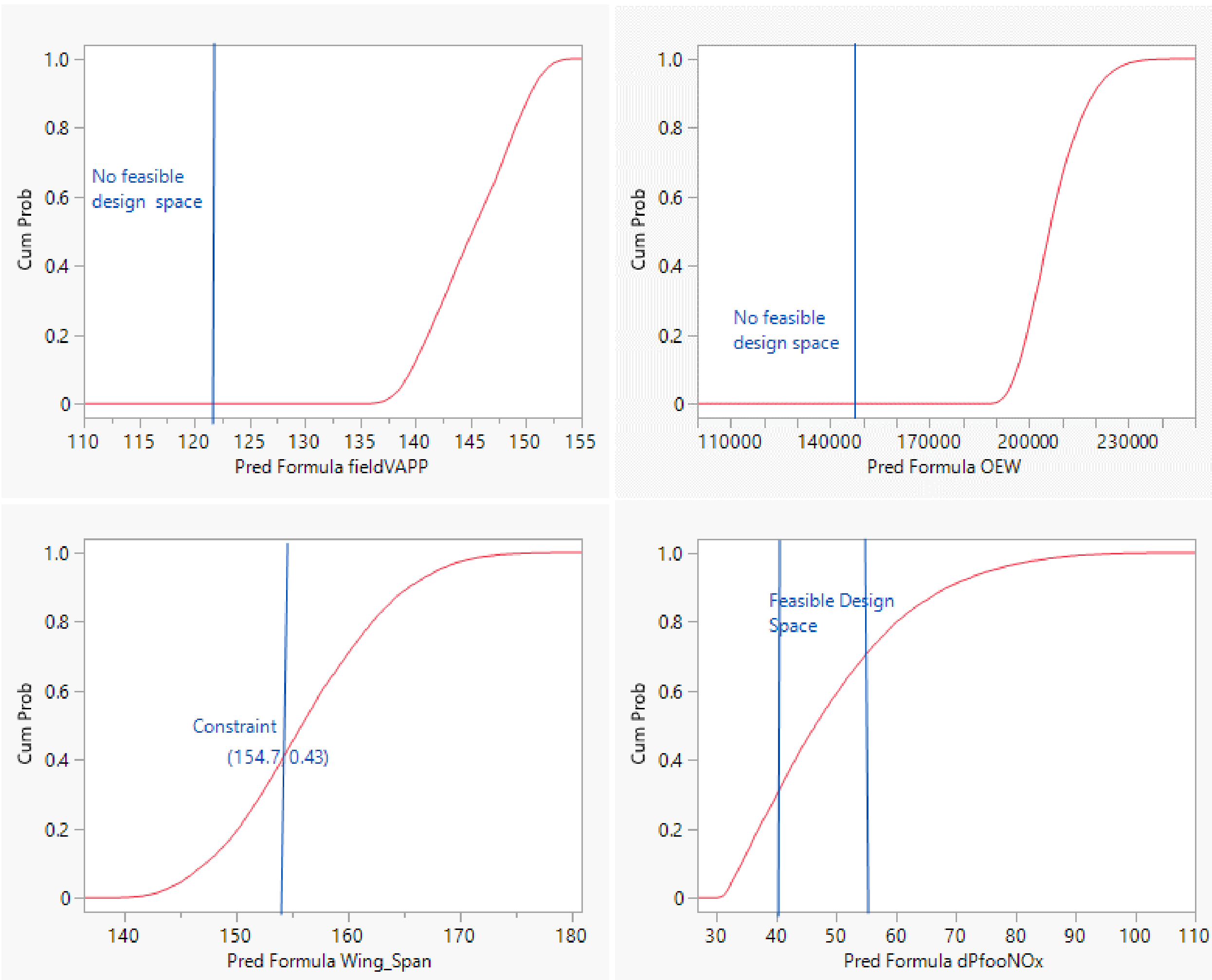


Figure 26: Histographs to the far right represent the Monte Carlo Simulations, the red colored values show optimized input variables and responses

5 System feasibility & Viability determination

5.1 Visualizing Feasibility

As an output of our Monte Carlo, cumulative distribution functions or CDFs are generated. These CDFs enable us to see the probability of yielding an acceptable value from our objective metrics. Feasibility is indicated by a line that within predicted range. Figure 28 illustrates our CDFs.



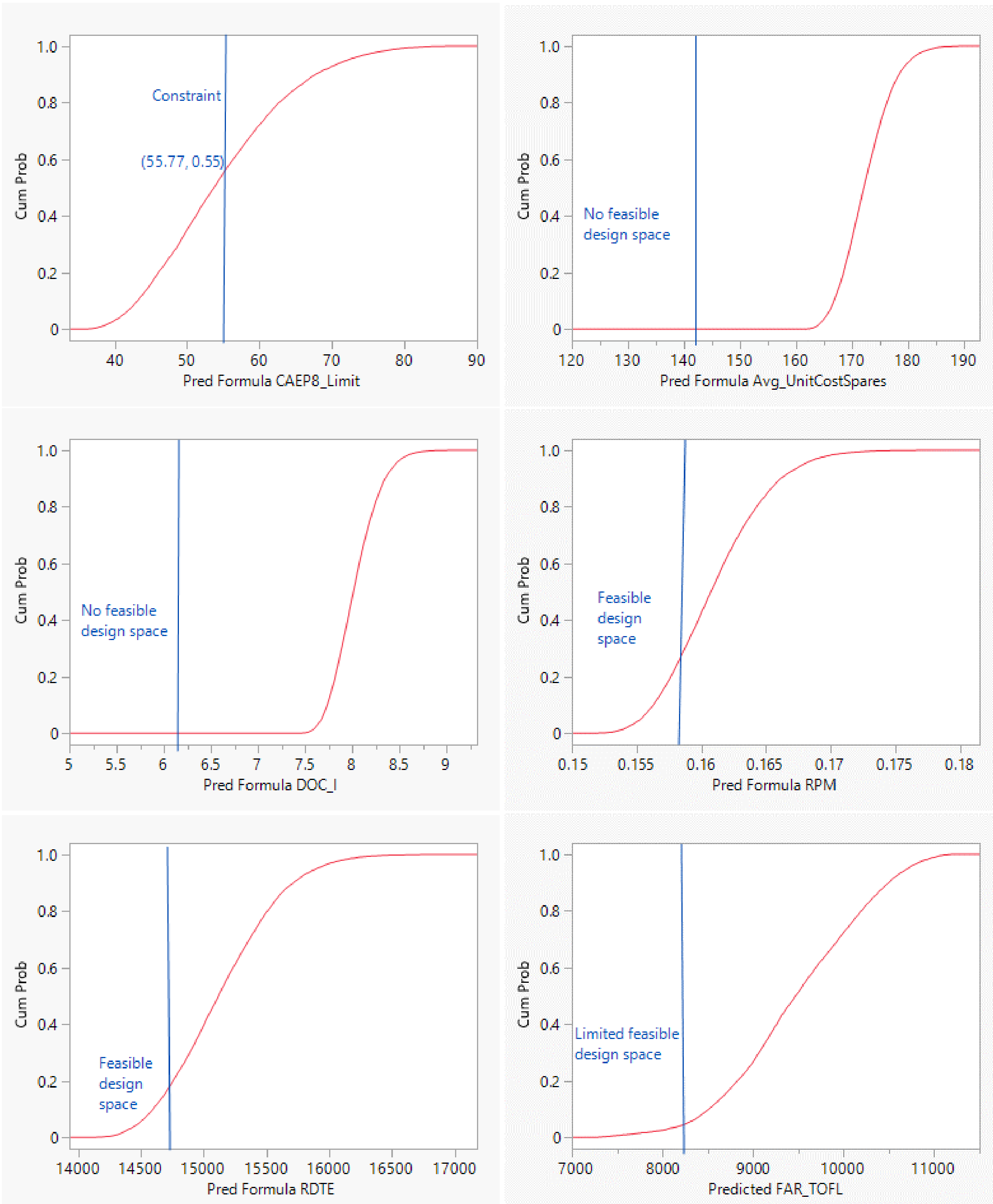


Figure 28: Cumulative Distribution Function from Monte Carlo Simulations

A feasible design space exists for a number of outputs, however infeasible design space also exists for some outputs. For the prediction formula of field approach velocity, no feasible design space exists. For the prediction formula of operating empty weight, no feasible design space exists. For the prediction formula of wingspan a feasible design space exists with a 43 percent probability. For the prediction formula of dPfooNOx a feasible design space exists. For the prediction formula of the CAEP8 Limit a feasible design space exists. For the prediction formula of the average unit cost plus spares, no feasible design space exists. For the prediction formula of direct operating costs plus interest, no feasible design space exists. For the prediction formula of RPM a feasible design space exists. For the prediction formula of RDTE, a feasible design space exists. For the prediction formula of FAR_TOFL a feasible design space exists, however it is quite limited. A summary of what was written above is shown below in the table.

Response	Feasible (Y/N)
fieldVAPP	N
OEW	N
Wing_Span	Y
dPfooNOx	Y
CAEP8_Limit	Y
Avg_UnitCostSpares	N
DOC_I	N
RPM	Y
RDTE	Y
FAR_TOFL	Y

5.2 Optimized Baseline

The table below showcases the chosen design variables new optimized baseline. On the left hand side of the table, the design variables are listed. The middle column is the original baseline values for the 210 pax aircaft. The values on the right hand side represent the new optimized baseline design variables. A number of the variables are minimized to the lower bounds of the 210 pax aircraft. Some of the design variables, like the low pressure compressor ratio, and the high pressure compressor ratio are not the lower bounds of the values.
These output values are the values from the optimized design variables processed through the environmental design space in order to generate an optimized baseline output. The optimized baseline design variable values were chosen based on the requirements for the optimization process. It is possible that there are multiple combinations of the best optimized baseline, however this baseline was chosen since it was developed from the original baseline and is expected to help our parameter outputs move in their desired directions.

Design Variables	**Baseline Design**	**Optimized Baseline Design**
WSR	129.0805	115
TWR	0.2966	0.28
AR	8.091	7
TR	0.2458	0.2
TCA	0.1095	0.093287
SWEEP	30.73	27
ARHT	4.5	3
ARVT	1.82	1
FPR	1.645	1.5764901
LPCPR	1.5265	1.6810556
HPCPR	12.59	10.954079

5.3 Comparison between Baselines

The optimized baseline parameter outputs are shown in the table below. The left hand side of the table contains the names of the response variables we are interested in changing to reach target metrics. The middle column, labeled optimized design, is split into two different columns. One column for the output from the surrogate model, and one column for the EDS generated out puts. The output values for the surrogate model come from using the response surface equations developed in the previous step. The output values for the EDS generated output column come from EDS as an output. The right hand side of the table has a baseline design EDS output column, which shows the EDS output for the original baseline design. This baseline will serve as the vehicle the technologies will be added on to.

A table comparing the optimized baseline and the original baseline design are shown below. The values in bold under the optimized baseline design have slightly larger values compared to the original baseline design. These values are the operating empty weight, the direct operating cost plus interest, and the required yield per revenue passenger mile. All the other responses are lesser than the original baseline design albeit marginally. The new 3 view for the optimized baseline is shown below in Figure 35.

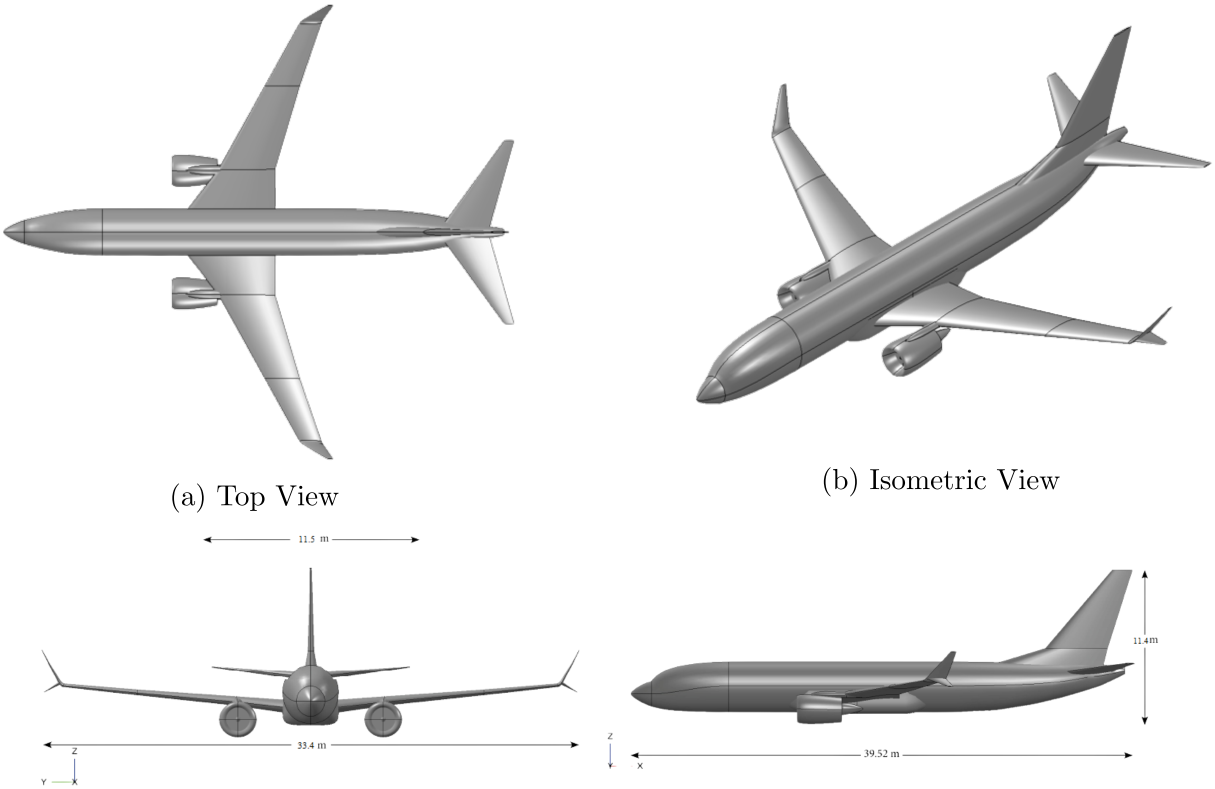
	Optimized Design		Baseline Design
Responses	**Surrogate Model Output**	**EDS Generated Output**	**EDS Output**
fieldVAPP	136.5356	136.6	145
FAR_TOFL	9286.654	9442.25	9690.44
OEW	**201448.8**	**202356**	198440
Wing_Span	153.7344	153.93	154.77
dPfooNOx	40.86425	42.1177	50.338
CAEP8_Limit	50.08807	49.7954	55.7654
RDTE	14598.04	14635.8	14763.6
Avg_UnitCostSpares	168.1072	168.481	168.545
DOC_I	**7.848602**	**7.874**	7.83
RPM	**0.158187**	**0.15875**	0.15773

5.4 Alternative Options

Currently, there is no feasible space on the performance contour plots. We want to have a feasible space so there are two options available to us.

- Relax Requirements
- Infuse technologies

The first option, relaxing requirements, is not feasible for the purpose of the project. Originally, the performance requirements needed to be relaxed in order to create a feasible space, however that is not advisable for a new aircraft wanting to enter the market and separate themselves from their competitors. Since the other constraint plots have feasible spaces then we do not have to adjust or modify those to create feasible spaces. As technologies are added the performance contour plot will change, and will allow for a feasible space. These new technologies can also affect the other contour plots so we must also account for that possibility. Technological infusing is the most appropriate way to obtain a feasible design space. We cannot afford to relax requirements, and therefore must infuse technologies to obtain the desired modified outputs.



(a) Top View

(b) Isometric View

(c) Front view optimized

(d) Side view optimized

Figure 29: 3 View of the Optimized Design

6 Technology alternatives specification

6.1 Researching Technologies

Given that our converged optimal design point does not lie within a feasible space, we need to explore injecting technologies that will improve response performance to a degree that widens the design space aperture and present a region where the optimal design point can now exist within a feasible design space. Furthermore, the injection of these technologies serves not only to develop a feasible design space and improve the performance of the aircraft, but also reach environmental goals consistent with the Long Term Aspirational Goal (LTAG) for net zero carbon emissions. [6]. The International Civil Aviation Organization (ICAO) has identified a collective goal of reaching net zero carbon emissions by 2050. As such, by assessing new technologies that not only improve aircraft performance, but also reduce nitrogen oxide emissions and operate within the nitrogen oxide certification limit, the collective of these technologies will be referred to as LTAG technologies.

6.2 Information on the Technologies

No.	LTAG Technology	LTAG Technology Description	Impacted Variables	Technology Readiness Factor (TRL)
T3	Damage Arresting Stitched Composites	Resin-infused dry fabric structure can reduce airframe weight	FRFU , FRWI	9
T8	Adaptive Wing / Variable Camber	In flight wing geometry alteration reduces induced drag	FCDSUB	6
T12	Riblets	Ribbing fences that create span wise viscouse force to act on boundary layer and reduce skin friction drag	FCDO, FRFU, FRWI	8
T20a	Active Compressor Clearance Control	Establishing clearance between blade tips and casing at takeoff allowing more flow to bypass blades and increase engine efficiency	HPC, HPX, sAccess_Wt	8
T20b	Active Compressor Clearance Control	Aspiration induced removal of low energy flow to slow engine blade speed and increase engine efficiency	HPC_AFC_nStages , HPC_AFC_LossRatio, HPC_FlowControl, sAccess_Wt	6
T23	Active Turbine Clearance Control: Mechanically Actuated	Reduces spacing between turbine blades, reducing air leakage and improving engine efficiency	HPT_eff, LPT_Deff, sAccess_Wt	9
T27	Advanced Thermal Barrier Coating (TBC)	Ceramic coating coupled with a nickel based superalloy to allow increased turbine inlet temperature	HPT_delta_desVaneTemp2, HPT_delta_desVaneTemp1, HPT_delta_desBladeTemp, LPT_delta_desVaneTemp, LPT_delta_desBladeTemp	6
T29a	Ceramic Matrix Composites Vanes	Provides high material strength at very high temperatures that can allow for increased turbine inlet temperature	HPT_delta_desVaneTemp2, HPT_delta_desVaneTemp1, HTP_Stator_rho, LPT_delta_desVaneTemp, LPT_Stator_rho	7
T29b	Ceramic Matrix Composites for Exhaust Core Nozzle	Provides high material strength at very high temperatures that can allow for decreased exhaust core nozzle densities.	Core_Nozz_s_Wt	7
T32a	Highly Loaded Compressor	Through optimized non-axisymmetric end wall design and advanced casing treatments, increase loading capacity and and minimized efficiency losses	HPT_Dutip, HPC_FSPRmax, HPCPR	7
T32b	Highly Loaded Turbine	Increased loading reduces number of turbine stages. Accomplished through blade shape and endwall shape optimization	HPT_Load, LPT_Load, HPT_eff, LPT_Deff, ATD_Bleed	7
T65	Rich, Quench, Lean (RQL) Zone Combustor	Ensuring combustion stability (Rich Burn) and reducing nitrogen oxide emissions (Lean Burn) relative to published environmental (CAEP2) Standards	d_Burn_dP	9
T80	Advanced Sandwich Composites	Skin technology that incorporates a lattice composite sandwiched between two thin plates: yields a high structural integrity for little weight	FRFU, FRHT, FRVT, FRWI1, FRWI2	9

Table 10: Technologies Information

The above table serves as a comprehensive discussion of all explored LTAG technologies. Each technology is discriminated by an identifying number. A description of both how the LTAG technology operates and how it consequently impacts aircraft performance is accompanied by their corresponding EDS variable that measures that performance change. Finally, a Technology Readiness Level (TRL) of the LTAG Technology shows the maturity and industry tested spectrum for the selected technologies. With our technologies identified and the mechanisms with which they alter aircraft performance described, we are now postured to explore the measured values of these technological impacts.

Impact	Variable	Type	T3	T8	T12	T20a	T20b	T23	T27	T29a	T29b	T32a	T32b	T65	T80
Engine Weight Fraction	sAccess_Wt	DELTA				0.0162	0.0108	0.0162							
Bleed Flow Injected in the Duct	ATD_Bleed	DELTA											0.005		
Core Nozzle Weight Scalar	Core_Nozz_s_Wt	MULT									-0.325				
Burner Pressure Drop Intercept	d_Burn_dP	DELTA												.0001	
Lift Independent Drag Factor	FCDO	MULT			-0.03										
Factor to increase or decrease all subsonic drag coefficients	FCDSUB	DELTA		-0.05											
Fuselage Weight Factor	FRFU	MULT	-0.1		0.001										-0.1
Horizontal Tail Weight	FRHT	MULT													-0.1
Vertical Tail Weight	FRVT	MULT													-0.1
Total Wing Weight	FRWI	MULT	-0.1		0.001										
First term in Wing Weight Equation	FRWI1	MULT													-0.1
Second term in Wing Weight Equation	FRWI2	MULT													-0.075
Ratio of Loss Coefficient with Endwall and Boundary Layer Active Flow Control	HPC_AFC_LossRatio	SCALAR					1.76								
Number of HPC stages to appyly AFC efficiency gain to	HPC_AFC_nStages	ABSOLUTE					2								
HPC Efficiency delta at Aero Design Point	HPC_Deff	DELTA				0.01									
HPC tip speed delta at Aero Design Point	HPC_Dutip	ABSOLUTE										-337.18			
Bleed Flow required per stage	HPC_Flow Control	DELTA					0.01								
Maximum HPC 1st stage PR	HPC_FSPRmax	ABSOLUTE										1.845			
Pressure Ratio HPC	HPCPR	ABSOLUTE										29.2661			
HPT blade temperature increase	HPT_delta_desBladeTemp	DELTA							150						
HPT Vane 1 temperature increase	HPT_delta_desVaneTemp1	DELTA							150	660					
HPT Vane 2 temperature increase	HPT_delta_desVaneTemp2	DELTA							150	660					
HPT Adiabatic efficiency at Aero Design Point	HPT_eff	DELTA						0.009					0		
HPT GE Loading	HPT_Load	MULT											0.28		
HPT Stator Material Density	HPT_Stator_rho	ABSOLUTE								0.2028					
Engine Horse Power Extraction	HPX	DELTA				0.5									
LPT Efficiency Adder	LPT_ Deff	DELTA						0.001					0.04		
LPT Blade temperature increase	LPT_delta_desBlade Temp	DELTA							150						
LPT Vane Temperature Increase	LPT_delta_desVane Temp	DELTA							150	660					
LPT GE Loading	LPT_Load	MULT											0.28		
LPT Stator Material Density	LPT_Stator_rho	ABSOLUTE								0.2028					

Table 11: Technologies Impact Matrix

The above Technological Impact Matrix shows how the injected technologies will affect select outputs and variables of aircraft performance. There are four different magnitudes for how these technological operators will impact specific aircraft performance parameters.

- Delta: This k factor changes the baseline value by altering to a summarized change, positive or negative
- Absolute: This k factor changes new minimum or maximum values by changing them to an absolute value
- Multiplicative: This k factor change is multiplied to the baseline to change the minimum and maximum values.
- Scalar: This k factor changes the minimum and maximum values by altering the values to a scalar quantity defined as a multiplicative factor of 1 plus or minus the summation of k factor changes.

With the total composite of all k factors accounted for, we can now apply this to our current problem. By calculating the total k factor changes for all technology injections, a new Design of Experiments (DOE) can be developed. This new DOE will account for all previous input variables and the above input variables altered to the corresponding composite k factor. Exploring the possible range of permutations of technology combinations, we will be able to identify a new design space and possible new optimum design point that meets the previous constraint diagram. However, not all technologies are compatible with each other. Certain technologies may have very conflicting goals, or they might have very similar performance addition in which it is redundant to integrate both the technologies. The technology compatibility matrix is presented below, it consists of the technology that are simply incompatible with each other. This incompatibility is due to redundancy. For example, we cannot have both stitched composites and sandwich composites on the aircraft at the same time.

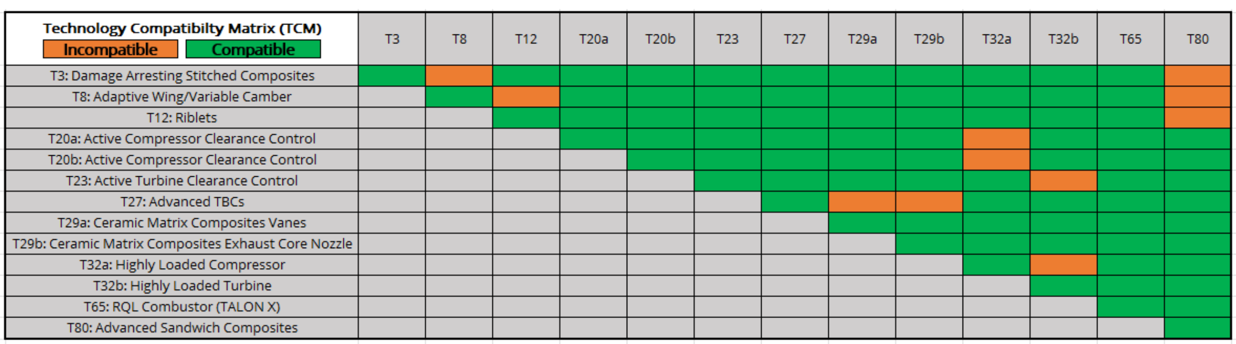


Figure 30: Technology Compatibility Matrix

6.3 Uncertainty in Impacts

Given that the values provided in the the technology impact matrix are deterministic, it's important to understand that these k factor changes have an inherent epistemic error associated with them. To account for this, we need to examine the corresponding technology readiness levels (TRL) of each constituent technology and combination of technologies. A combination of technologies that have a relatively high combined TRL means that there will be less epistemic uncertainty in the composite of the deterministic k factors. Conversely, a combination of technologies with a relatively low combined TRL will have a low maturity at recommended implementation and the corresponding k factor and impact of their implementation on the overall performance of the aircraft will have a larger spectrum of estimated error. To reduce the distribution of epistemic uncertainty, which would be to increase the fidelity of the application of a k factor from a technology infusion, we need to raise the TRL. Raising TRL can happen with inherent technological maturity, but also, through validating performance of technological infusions through a scaled test. All are critical when considering a selected technology combination with varied TRL values.

7 Technology alternatives assessment

7.1 Introduction of the Step

To assess alternatives enabled by implementing different new technologies, an appropriate and quantitative method used to evaluate the impact of different combinations of new technologies implemented must be established.

As shown in TABLE.10, a total number of 13 technologies is considered as potential for this design project, and because the implementation of a technology is a discrete variable with only two levels (absent or present), a full factorial design of experiments with a number of trials required:

$$\text{number of trials} = 2^{13} = 8192 \tag{5}$$

This is an excessive number of trials and cannot be easily reduced if the experiments are going to be performed with or without the implementation of the technologies. Therefore, the design of experiments will be performed on k-factors, which is a simplified, single factor capturing the crucial aspect of the impact of the technologies on various EDS variables used in this project.

Since k-factors are impact-measuring factors, they can be regarded as continuous in the domain. They thus can be used to create surrogate models based on the partial-factorial design of experiments, which can significantly reduce the number of trials required and simplify the complexity of the problem, as well as facilitate the analysis and prediction of the system's behavior implemented with different technologies, supporting decision-making process discussed later.

The evaluation of technologies' impact to be performed is then a meta-model of each system response variable as a function of the m vector elements, where j is the number of k-factors, and ϵ is the prediction error of the surrogate model. A second-order Response surface equation(RSE) used to represent the quantitative relation of the meta-model is shown below:

$$R = \beta_0 + \sum_{i=1}^{m} b_i k_i + \sum_{i=1}^{m} b_{ii} k_i^2 + \sum_{i=1}^{m-1} \sum_{j=i+1}^{m} b_{ij} k_i k_j + \epsilon \tag{6}$$

Unlike the RSE generated in step 4, which also includes the 3rd-order relationship between input variables, this RSE is solely built to assess the impacts of technologies, so all the design variables are regarded as irrelevant and will be held constant at their optimized baseline values discussed previously.

7.2 Identification of Variables

Based on the works discussed in step 6, a cross-panel (Technologies vs. System's Response Variables) k-factors data is shown in the TABLE.11. It is worth noticing that for different response variables, different calculation methods of assessing the impact of technologies, including DELTA, MULT, SCALAR, and ABSOLUTE as shown below, must be used.

$$\textbf{ABSOLUTE: } k_{new} = k_i \tag{7}$$

$$\textbf{DELTA: } k_{new} = k_{baseline} + \sum_{i=1}^{n} k_i \tag{8}$$

$$\textbf{SCALAR: } k_{new} = k_{baseline} \times (1 + \sum_{i=1}^{n} k_i) \tag{9}$$

$$\textbf{MULT: } k_{new} = k_{baseline} \times \prod_{i=1}^{n} (1 + k_i) \tag{10}$$

7.3 Regression Diagnostics

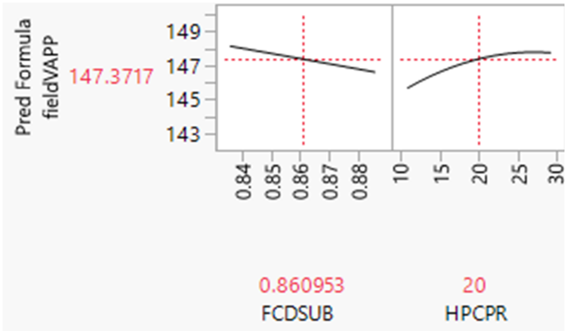
Information regarding the regression diagnostics is shown below. The goodness of fit for each of the k factor surrogates that have been applied to each variable is shown below, in the form of R^2. The MFE and MRE statistics including the mean and standard deviation are shown in the table below. The minimum and maximum percent errors for each of the output variables are estimated to be between 3.61% and -1.32%.

		MFE		**MRE**		**Surrogate Model**
Responses	R^2	**mean**	**std dev**	**mean**	**std dev**	**RSM/ANN**
fieldVAPP	0.985982	0.00E+00	0.125318	0.0014872	0.15588	RSM
FAR_TOFL	0.9294641	0.0003247	0.035221	0.0013816	0.048105	ANN
OEW	0.96272	2.00E-05	0.004089	-0.000179	0.005128	ANN
Wing_Span	0.980887	∼0	0.33134	-0.00163	0.42197	RSM
dPfooNOx	0.9991979	0.0002413	0.016075	0.0000439	0.016815	ANN
CAEP8_Limit	0.999978	0.00E+00	0.135791	0.0009215	0.18023	RSM
RDTE	0.9868461	∼e-6	0.001539	0.0000139	0.002024	ANN
Avg_UnitCostSpares	0.987061	∼e-13	0.3571	-0.002243	0.45468	RSM
DOC-I	0.98577	∼e-12	0.020498	-0.00005	0.025923	RSM
RPM	0.984561	∼e-9	0.000341	∼e-6	0.000432	RSM

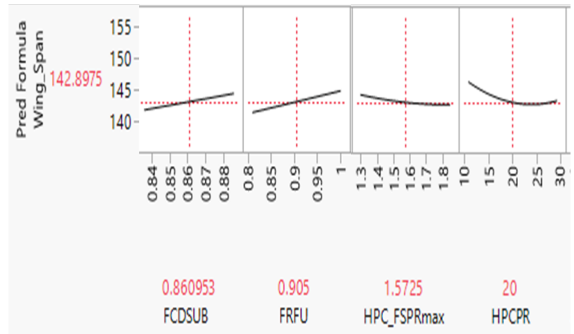
From the table shown above the largest model fit errors are visible in the environmental impacting variables, dPfooNOx and CAEP8_limit.

7.4 Profiler

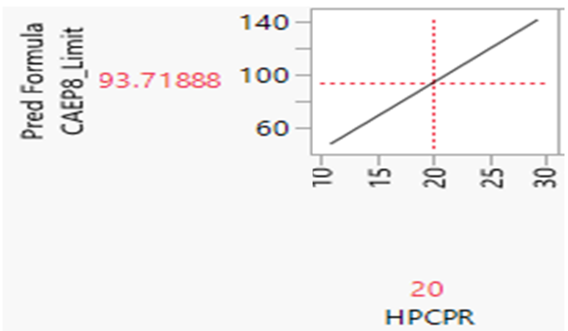
The prediction profiler that qualitatively depicts the relationships between the k factors and the output variables is shown below in Figure



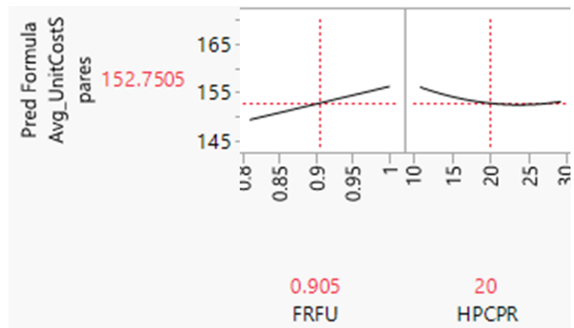
(a) Prediction Profiler fieldVAPP



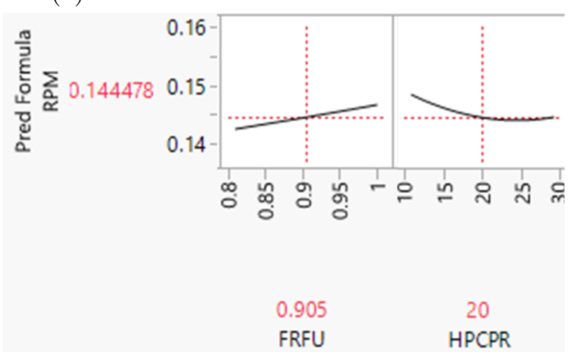
(b) Prediction Profiler Wing Span



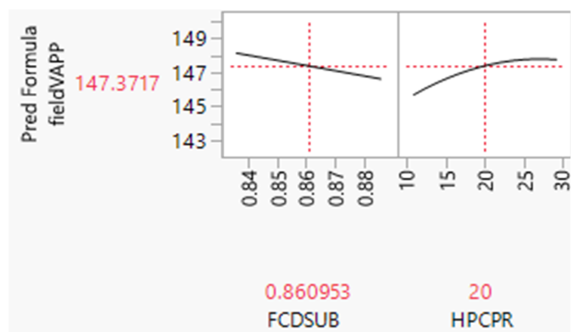
(c) Prediction Profiler CAEP8 Limit



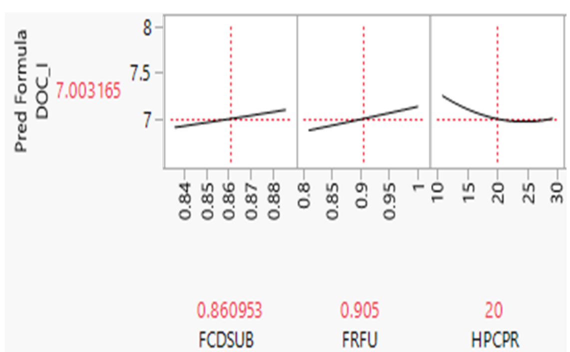
(d) Prediction Profiler AvgUnitCosts



(e) Prediction Profiler PRM



(f) Prediction Profiler fieldVAPP



(g) Prediction Profiler DOC-I

Figure 31: Prediction Profiler of responses as functions of K factors

7.5 Filtered Monte Carlo

A Monte Carlo simulation of 10,000 cases is run on the surrogate models, and all the design points that satisfy the constraints are filtered. A total of 236 cases satisfy the constraints. All the design points revolve around the mean value of K factors as shown in the table below The scatter plot matrix of these filtered cases are shown below A few key observations are

K-Factors	Mean K factor values
ATD_BleedFlow	0.002704935
Core_Nozz_s_Wt	0.860167389
FCDO	0.971233135
FCDSUB	0.938793935
FRFU	0.896665281
FRHT	0.954611987
FRVT	0.945990499
FRWI	0.946955255
FRWI1	0.95023728
FRWI2	0.961135215
HPC_AFC_LossRatio	1.845898874
HPC_AFC_nStages	1.050089977
HPC_Deff	-0.005739824
HPC_Dutip	-13.15610237
HPC_FlowControl	0.004842101
HPC_FSPRmax	1.603226657
HPCPR	11.61042216
HPT_delta_desBladeTemp	82.4023912
HPT_delta_desVaneTemp1	395.1765837
HPT_delta_desVaneTemp2	410.5305848
HPT_Load	0.676316988
HPT_Stator_rho	0.258697127
HPX	250.0248858
LPT_Deff	0.049528068
LPT_delta_desBladeTemp	68.96197022
LPT_delta_desVaneTemp	391.3932064
LPT_Load	2.706482388
LPT_Stator_rho	0.267574508
sAccess_Wt	0.172199656
d_Burn_dP	0.023584905
HPT_eff	0.906437906

detailed below:

1. The minimum approach speed (fieldVAPP) that could be obtained with the infusion

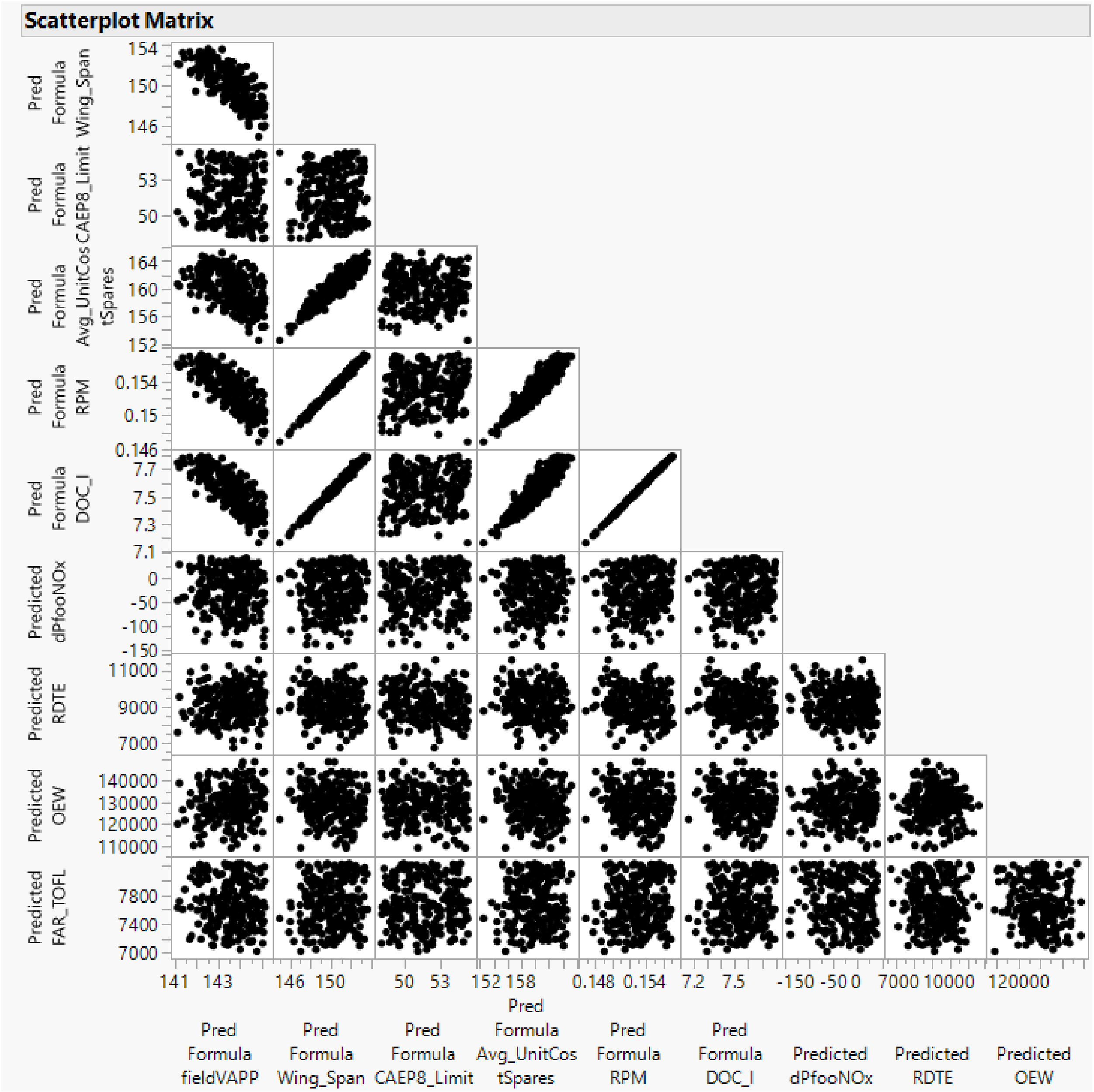


Figure 32: Scatter Plot Matrix of Filtered Monte Carlo Simulations

of technology is around 140.10, while the target requirement is 123.25. The baseline configuration had around 145, and the decrease in approach speed due to the technology infused is only about 3.38%.

2. The minimum acquisition price with spares (Avg UnitCostSpares) is about 145.48, while the target is about 143.26 which is marginally close to the minimum price. Similarly required direct operating cost plus interest (DOC_I) is 6.26, while the minimum

obtained is 6.57. Though the requirements for both these metrics are not strictly satisfied, the minimum values obtained by infusing technologies good enough for practical purposess

3. The minimum operating empty weight (OEW) obtained by infusing technologies is about 101434 which is 32% lower than the required target of 148830! Similarly the desired reduction in balanced take-off field length (FAR_TOFL) is 8236.874 but the infused technology can result in a minimum of 6913. These reductions are quite significant and the technologies infused might be promising in terms of reducing the operating empty weight and balanced take-off field length.

4. It should be noted that the constraints satisfied above are based on K factor values that may not ideally exist in the first place since monte-carlo simulation might assume partial combination of technologies that are non-existent. Hence the observations should be taken with a pinch of salt. More promising observations can only be trusted after obtaining the response surface equations of the system metrics in terms of the technologies instead of the K-factors. This leads us to the next step 7.6

Based on the observations above it is likely possible that certain constraints need to be relaxed. For instance, approach speed may never be practically achieved. Either the technology might not be mature enough, or we might have to look into other alternative technologies that might satisfy the requirement. More details are revealed in section 8.3

7.6 Technology Profiler

The impact of different combinations of technologies is shown in a profiler plot; these technologies are in either present or absent situations. The approach to develop these profiler plots is performed in four steps:

1. Create a DOE with full factorial for all 13 technologies, these values are either 0 or 1, meaning each technology is either present or absent

2. Calculate the corresponding K factors for all the 31 inputs using equations 7

3. Use the prediction formulae created in Regression Analysis to create the responses for the corresponding K-factor values

4. Create surrogate models for the responses with the technologies (i.e 0 or 1 values) as the inputs

5. Obtain the profiler plots for the technology as per the obtained surrogate models

The R^2 of the fit, mean and standard deviation of the model fit errors (MFE) and model representative errors are as shown in the table below:

Responses	R^2	MFE		MRE		Surrogate Model
		mean	std dev	mean	std dev	
fieldVAPP	∼1	e-14	0.00058	e-6	0.0005921	RSM
FAR_TOFL	0.9848	0.01034	1.01	-0.0298	1.3816	ANN
OEW	0.9996	1.42E-04	0.1366	2.38E-03	0.1375	ANN
Wing_Span	∼1	e-14	0.00174	0.000031	0.0017242	RSM
dPfooNOx	0.99986	e-14	0.5024	0.0094	0.4832	RSM
CAEP8_Limit	∼1	e-15	0.20217	0.0010767	0.195192	RSM
RDTE	0.9994	5.00E-05	0.0823	0.00015	0.082563	ANN
Avg_UnitCostSpares	∼1	e-15	0.00216	e-5	0.0021602	RSM
DOC-I	∼1	e-16	0.00012	e-6	0.0001176	RSM
RPM	∼1	e-17	2.00E-06	e-9	2.10E-07	RSM

7.7 Infusion on a Fixed Geometry

It's indeed possible that the impact of combinations of technologies is different on different design geometries, for example, some technologies may improve the performance of turbofan engine but totally irrelevant to turboprop engine, but considering that there are 13 potential technologies, plus 11 design variables in this project, mixing them up will increase the complexity of the system and difficulty of designing experiment exponentially.

Separate them in two independent set of variables help ensure the consistency, comparability, and simplicity of the design process. By keeping the design geometry fixed while assessing the impact of technologies, ensures that any changes in response variables can be properly attributed more directly to the implementation of the technologies being assessed, preventing any noise caused by the variations in the underlying design. Similarly, it also enables meaningful comparative studies and performance evaluation among different combinations of technologies. And the most importantly, studying 24 inter-dependent variables, and a mixture of continuous and discrete variables is much more complicated than studying two independent sets(one with 13 variables, the other with 11) of variables; for example, the full factorial design of experiment discussed earlier in this step,

$$2^{24} = 16777216 \tag{11}$$

Comparing to 8192, which is already considered as excessive, even with partial factorial design or optimal design method, the number of trials required still cannot be reduced to a reasonable number.

A more economically viable way to solve this problem might be iterative design, following the steps specified below:

1. evaluate design parameters, find optimized baseline

2. evaluate technologies based on the fixed and optimized design parameters

3. given the optimized combination of technologies implemented, repeat step 1, verifying that if a new design geometries can further enhance the performance

7.8 Probabilistic Technology Impacts

For our purpose of the project the impact of technologies that we are adding to the aircraft are occurring in a deterministic manner, thus giving us *one* result. If we were to, however, use a probabilistic approach then we can recognize that there are multiple possible future states and we can only estimate the likelihood of each state rather than predicting a single certain outcome. Some probabilistic methods could be

1. Risk Analysis: Identifying the potential risks associated with infused each technology and or multiple technologies

2. Cost-Benefit Analysis with Probabilistic Modeling: Adding a probability distribution to each the costs and the benefits to see how they could vary and then computing expected values

3. Monte Carlo simulations using a non uniform distribution: doing this allows a distribution of unknown probabilistic entities and can allow for a range of possible outcomes of a technologies impact under uncertainty.

The most beneficial of these probabilistic methods would be a combination between Risk analysis and Cost-Benefit analysis as decision makers are typically interested in financial benefits or gains, along with the amount of risk they need to undertake to obtain those financial benefits and gains. If a decision maker is at risk of jeopardizing the company based on the attempt of the inclusion of new technologies then they may think twice before commencing a technology injecting project.

7.9 Additivity

When describing additivity in the context of technologies, this essentially assumes that the individual impacts of technologies can be summed in order to get an impact of multiple technologies. This also means that these technologies are assumed to not have an impact on each others performance when injected into the same aircraft. There are several scenarios where this assumption does not hold up. One scenario is the inclusion of technology 3, resin infused dry fabric structure, and technology 80 skin technology composite sandwich. Technology 3 is included to reduce weight, and technology 80 is included to increase structural integrity, however with the inclusion of technology 3 the structural integrity can decrease and with the inclusion of technology 80 the weight can increase, thus making it possible to have no benefits with the inclusion of both technologies. An example of non additive technologies that have already been included in aircraft today would be the integration of winglets into aircraft wings. The winglets are designed to improve aerodynamic efficiency by reducing wingtip vorticies and there for drag. If we were to use the additivty assumption then we can assume that adding winglets to an existing aircraft would linearly improve fuel efficiency based on performance data however the actual impact is not purely additive. In reality, the performance gains from winglets can be affected by other factors like

1. The design of the wing: Its possible the original wing geometry was not optimized to take advantage of winglets, resulting in a not purely additive interaction between the wing and the winglet.

2. The flight regime of the aircraft: winglets are typically used at high altitudes and long flight durations meaning their contribution to the efficiency of the aircraft is not constant but varies with the operation of that aircraft.

3. Structural Implications: Adding winglets can alter the load distribution on the wing which could affect the structure of the wing, incurring the need for further design changes beyond the addition of the winglets themselves in order to prevent deformation of the wing.

With a non valid assumption an analytical approach could be used instead, something involving system dynamics modeling, and including interaction analyses which can help take into account the relationships and dependencies between different technologies.

7.10 Decision Matrix

The decision matrix is created from the feasible combination families of technologies. Essentially after the technology constellation plot is created only a certain number of the alternatives will be able to meet the constraints. These technology families will then be weighted and evaluated in the next step, step 8, in which TOPSIS will be performed. More information on that regarding and the decision matrix will be included in step 8. The decision matrix can be seen in the JMP journal but for clarity the first few rows of the decision matrix have been presented below, the rest of the matrix is avoided in the report as it is too long (8000+ rows) to be imported here.

T3_val	T8_val	T12_val	T20a_val	T20b_val	T23_val	T27_val	T29a_val	T29b_val	T32a_val	T32b_val	T65_val	T80_val
0	0	1	0	1	0	1	1	0	0	1	1	1
0	0	1	1	0	1	0	1	0	0	1	1	0
0	0	1	1	1	0	1	0	1	0	1	0	1
0	0	1	0	1	0	0	1	1	0	1	1	0
0	0	0	1	1	0	0	1	0	0	0	0	0
0	0	1	1	0	0	0	1	1	0	0	1	1
0	0	0	0	1	1	0	0	0	0	1	1	1
0	0	0	1	0	1	1	1	1	0	1	1	1
1	0	0	0	0	1	1	1	1	0	0	1	0
0	0	1	0	1	0	0	0	1	0	1	1	1
1	0	1	1	1	0	0	1	0	0	1	1	0
0	0	0	0	1	1	0	1	1	0	0	1	0
0	0	1	0	1	0	1	1	0	0	1	0	1
0	0	1	0	1	1	1	1	1	0	1	1	1
0	0	0	1	1	0	0	1	1	0	0	0	0
0	0	0	0	0	1	0	1	0	0	0	1	0
1	0	0	1	0	1	0	1	1	0	1	1	0
0	0	0	0	1	1	0	1	1	0	0	0	0

Figure 33: First few rows from the Decision Matrix

8 Family of alternatives selection

In this section the best mix of technologies to satisfy the system level metrics will be selected. The selection of best family of alternatives is inherently subjective, and depends on the weights created by the decision maker, therefore no single answer will fulfill all customer requirements. Three approaches are proposed to account for the sensitivity of the problem.

1. Multi-attribute decision-making techniques in the form of TOPSIS (Technique for Order of Preference by Similarity to Ideal Solution)

2. Technology space constellations

3. Technology sensitives: one-to-one technology comparisons

Different decision making methods are necessary for a technology family selection because it allows the decision maker to get a holistic view of the possible outcomes. If all of the possible outcomes are available to the decision maker then the best outcome can be selected. In reality, a combination of the approaches is nessasry to get decent results. The technology profilier determines which family of technologies should be shown on the constellation plot. The constellation plot determines the feasible alternatives and TOPSIS determines the best feasible alternatives with varying weights. The three approaches are described in detail below.

8.1 Decision Making Methods

8.2 TOPSIS

Topsis is based on the concept that the chosen alternative should be the closest to the theoretical best in all dimensions positive ideal solution and the furthest from the theoretical worst in all dimensions negative ideal solution. Topsis uses a decision matrix and allows the decision maker to create relative weights, ultimately allowing for different solutions with differently weighted criteria. The decision matrix that topsis uses has two dimensions. The first dimension is the possible alternatives. In our case this will be the different families of technologies that can be applied to our aircraft in order improve our metrics. The improved metrics is the second dimension of the decision matrix, the evaluation criteria. Once the decision matrix is formed and the criteria are weighted. The values are normalized by the evaluation criteria, or divided by the sum of the squares of the criterion. This allows for comparisons to be made on the same scale. After normalizing, determine if the criteria is to be maximized or minimized. Next, the positive ideal solution is identified by selecting the maximum values of the maximization criteria and the minimum values of the minimization criteria. The negative ideal solution is also identified by selecting the minimum values of the maximization criter and the maximum values of the minimization criteria. Finally, a distance is calculated between the alternative solutions and the positive ideal criteria. This separation distance is calculated by using the formula shown below.

$$S_i = \sqrt{\sum (Alternative\_values - Pos\_or\_Neg\_Ideal\_Value)^2}$$

Where i represents for each criteria, and the positive or negative ideal value is used based on the maximization or minimization of the criteria. Once the separation distances are calculated for each criterion, a closeness value is calculated which determines the best alternative based on the largest closeness value. The closeness value can be caluclated with the formula shown below.

$$C_i = \frac{S_i}{S_i^* + S_i}$$

where S_i- is the separation distance for the alternative from the negative ideal solution, and S_i^* is the separation distance from the positive ideal solution. An ideal solution will have a closeness value of 1. Since weighting is dependent upon the decision maker we can simulate a decision maker by creating ten different weighting schemes in order to see which family of technologies will be selected with different weighting schemes. 10 different weighting scenarios will be used to select the top 10 technology mixes. One advantage of topsis is it has the ability to combine qualitative and quantitative data. The qualitative data is transformed into numbers usually on a 1 through 9 scale. In our case we have no qualitative metrics, only quantitative so we do not have to be concerned with numerically transforming our qualitative variables.

8.3 Technology space constellations

A technology space constellation plot, or Tspace constellation plot, shows the possible alternatives with specific combinations of technologies. The Tspace constellation plot is a diagonal matrix and has the response variables that we are interested in changing on the x axis and the input modifiable variables on the y axis. Wee can see the general relationship between the response and input variables based on the general shape of the constellations. If the constellation is elliptical and in a positive direction then there is a general postive correlation. If the constellation is elliptical and in a negative direction then there is a general negative correlation. If the constellation plot shows a circle then there is no correlation between the two variables. An example of the three types of constellation correlations are shown below.

With the constellation plot we can begin to apply constraints to visualize which combinations of technologies allow for a feasible space. The constellation plot with feasible technologies is shown in section 8.6 filtered constellations.

As mentioned in section 7.5, the final conclusion on the scope of technology infusion is summarized below.

1. The minimum approach speed (fieldVAPP) that could be obtained with the combination of technologies is around 143.57, while the target requirement is 123.25. The baseline configuration had around 145. This confirms that observation in section 7.5. This constraint must be relaxed, or an alternate set of new technologies needs to be explored.

2. The minimum balanced take-off field length (FAR_TOFL) obtained is 9550.34. While it is lower than the baseline, it is still 16% higher than the desired requirement.

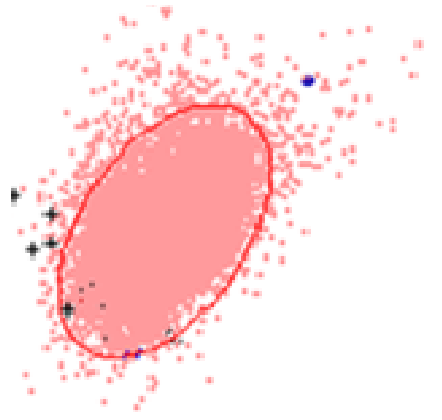


Figure 34: A constellation showing a positive correlation

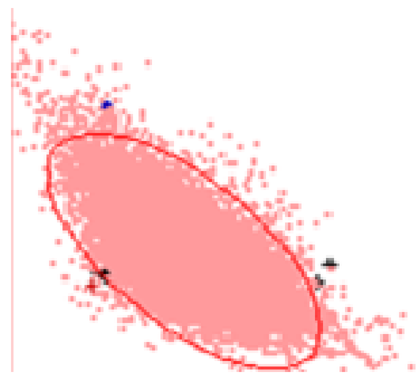


Figure 35: A constellation showing a negative correlation

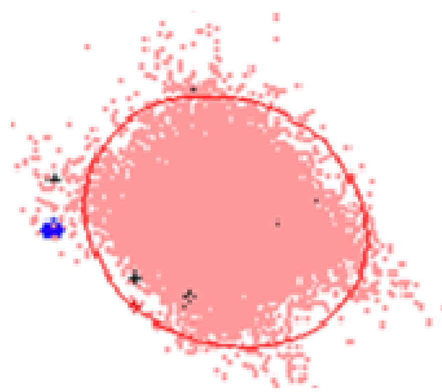


Figure 36: A constellation showing no correlation

3. Desired Operating Empty Weight (OEW) is 148830, while the minimum that is possible is 164870. Though not surprising, this observation contradicts bullet 3 in section 7.5. This is expected since, as mentioned earlier in bullet 3 in section 7.5, it might assume a partial combination of technologies that is practically non-existent. Hence, the OEW

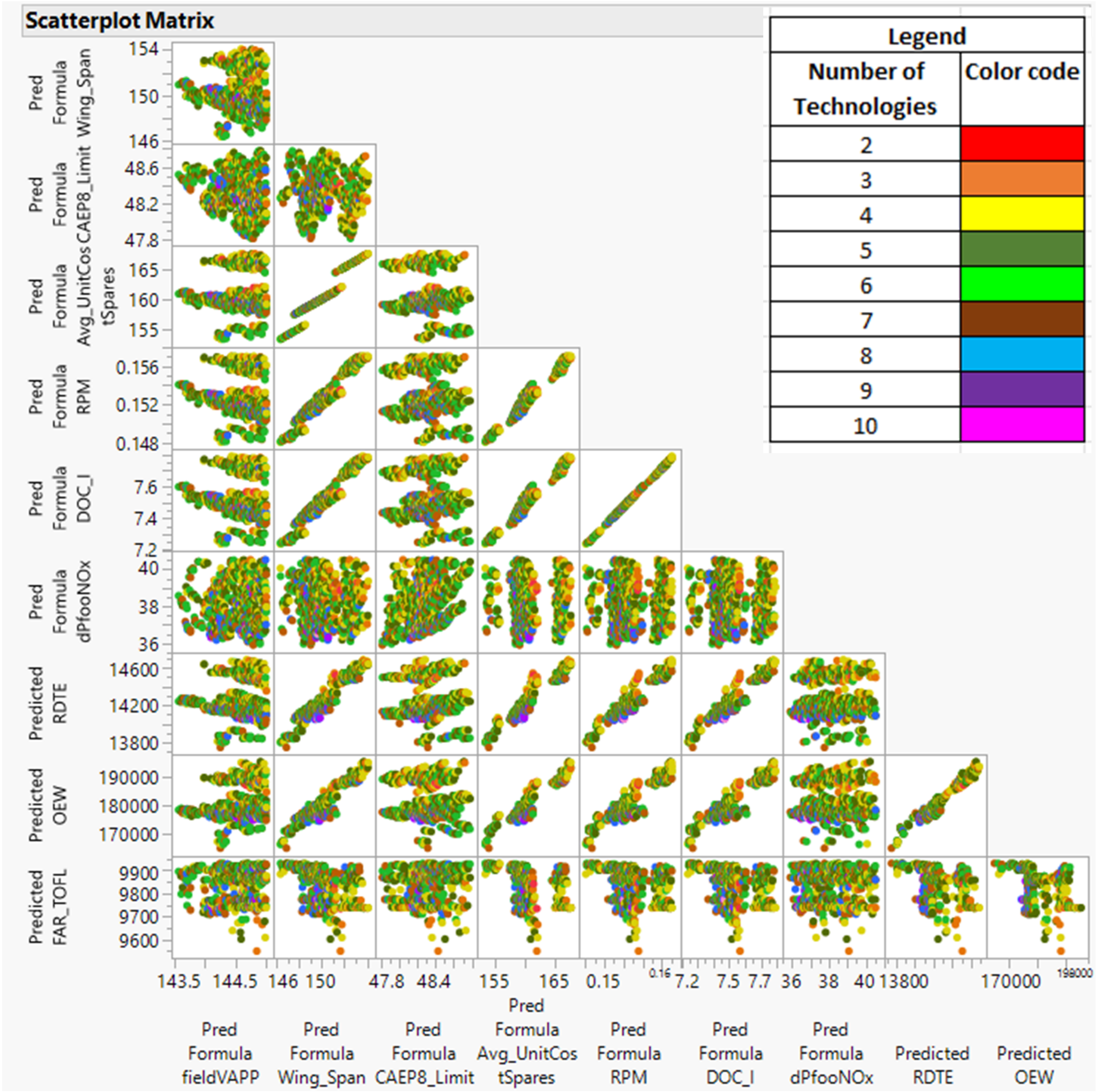


Figure 37: Technology Space Constellation with feasible design points

constraint is also not satisfied and needs to be relaxed.

4. The wing span constraint is satisfied since the minimum that can be obtained is 146.3, while the constraint is 154.1.

5. The desired NOx emissions is 40.27, and the practically achievable minimum is 35.9. This is a tremendous improvement in terms of achieving sustainable goals, and the technological growth is quite promising. The minimum CAEP8_Limit achieved is 47.81,

about a factor of 1.166 times lower than the desired requirement.

6. The minimum Acquisition price with spares is about 153.36, while the desired requirement is 143.36. A similar trend is observed for Direct operating cost plus interest. Both these constraints need to be relaxed too.

System metrics	Requirement	Baseline	Minimum Obtained by infusing technologies	Requirement Satisfied?
fieldVAPP	123.25	145	143.57	No
FAR_TOFL	8236.874	9690.44	9550.34	No
OEW	148830	198440	164870	No
Wing_Span	154.77	154.77	146.36	Yes
dPfooNOx	40.2704	50.34	35.91	Yes
CAEP8_Limit	55.7654	55.77	47.81	Yes
RDTE	Minimime	14763.60	13749.8	Minimized
Avg_UnitCostSpares	143.26325	168.55	153.36	No
DOC_I	6.264	7.83	7.238	No
RPM	Minimize	0.15773	0.14803	Minimized

Table 12: Comparing requirements vs. achievable limits due to technology infusion

As seen in the table above, certain requirements are strictly satisfied while others are not. There is a possibility that the set of technology under consideration has not matured enough to satisfy the constraints. The other possibility is that we need to find other alternative technologies that might satisfy the requirements.

8.4 Technology sensitivity study

The technology sensitivity study compares the technologies visually by using a technology profiler. In a technology profiler the technologies are listed across the x axis and the responses are listed on the y axis. One thing to note with the technologies is they are individually placed along the x axis, and combinations of technologies are not shown. The effects of a combination of technologies can be viewed by turning on multiple technologies. Therefore, with the technology profiler plot we can see how each technology impacts each response variable, and which ones have the greatest impact on those variables. We can also see if any technologies have negative impacts on certain response variables. This will allow us to visualize and consider possible technology combinations. Each technology on the x axis has an on state and an off state. The off state is typically shown on the left of the technology and the on state is shown on the right of the technology. Using a technology profiler plot a sensitivity study can be performed. To do this two technologies must be turned on so the effects of the technologies on the response variables can be viewed. This must be performed for each double selection combination of technologies. After the sensitivity study is performed the technologies that have the greatest impact on our response variables can be viewed. We can also use the technology profiler to perform the impacts of multiple technologies rather than comparing one on one. The technology profiler for our project can be shown below,note the base line values are highlighted in orange, and the profiler has all technologies turned off.

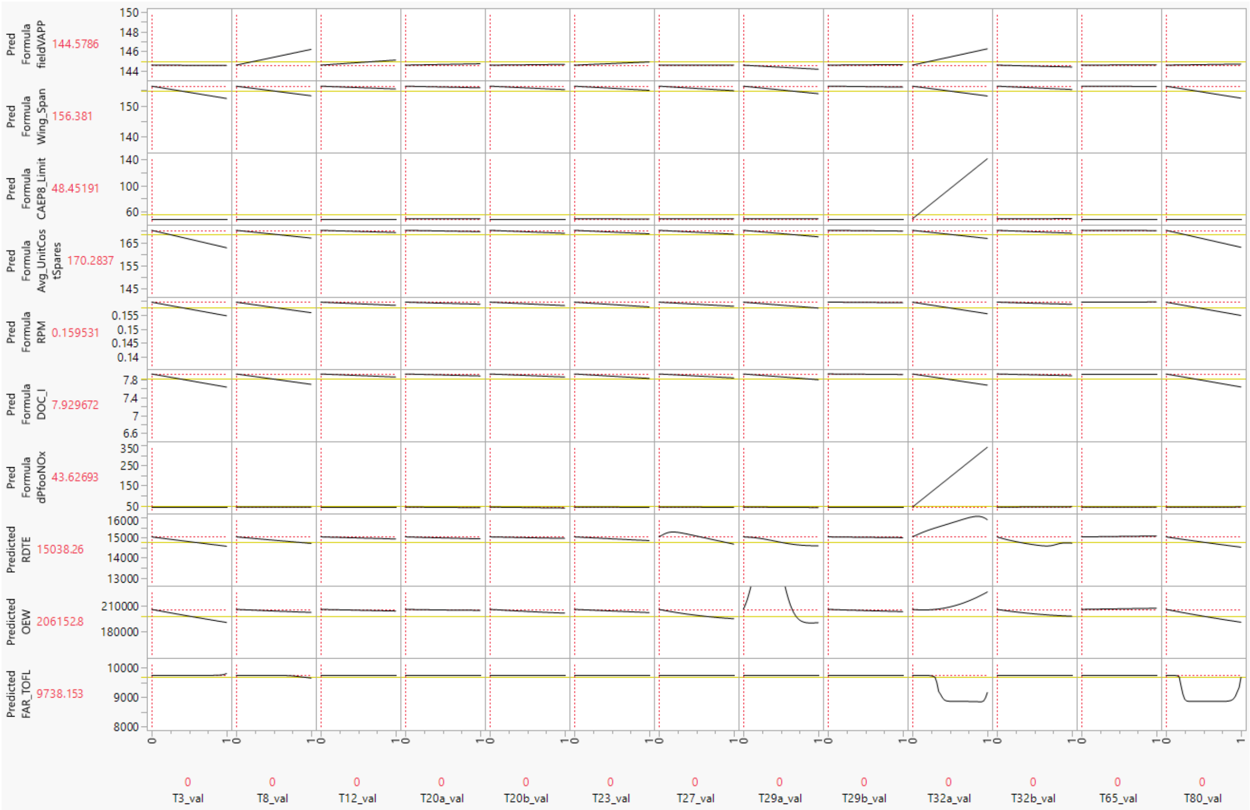


Figure 38: Technology Profiler

8.5 Scenarios

For the TOPSIS step it is required to show at least ten different weighting scenarios to select the top 10 technology mixes. A table for TOPSIS scenarios and the weighting of each criteria is shown below. Some of the weighting for the criteria are determined randomly, and some of the weightings are different for fun. The different weighting of TOPSIS can simulate how different decision makers feel about the alternatives. For simplicity only the top technology mix for each weight is shown in the table below, however the top 5 technology mixes for each the first weighting scenario are shown in table 13.

Scenario	field VAPP	Wing _Span	CAEP8 _Limit	Avg _UnitCost Spares	RPM	DOC_I	dPfoo NOx	RDTE	OEW	FAR _TOFL
1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
2	0.05	0.075	0.075	0.2	0.05	0.075	0.075	0.2	0.1	0.1
3	0.1	0.05	0.15	0.08	0.07	0.1	0.12	0.08	0.15	0.1
4	0.11	0.09	0.1	0.1	0.08	0.11	0.11	0.09	0.1	0.11
5	0.09	0.11	0.08	0.12	0.1	0.09	0.11	0.1	0.1	0.1
6	0.1	0.1	0.09	0.11	0.09	0.08	0.13	0.11	0.09	0.1
7	0.08	0.12	0.11	0.09	0.1	0.1	0.1	0.09	0.11	0.1
8	0.11	0.09	0.1	0.11	0.08	0.12	0.09	0.1	0.1	0.1
9	0.09	0.1	0.11	0.1	0.09	0.11	0.1	0.1	0.1	0.1
10	0.1	0.09	0.12	0.09	0.1	0.1	0.1	0.1	0.1	0.1
11	0.5	0.25	0.1	0.1	0.01	0.01	0.01	0.01	0.01	0
12	0.3	0.02	0.05	0.01	0.1	0.12	0.2	0.05	0.1	0.05
13	0.02	0.05	0.03	0.05	0.1	0.42	0.15	0.1	0.05	0.05
14	0.25	0.25	0.05	0.05	0.01	0.02	0.12	0.1	0.1	0.05
15	0.15	0.05	0.3	0.1	0.05	0.05	0.1	0.1	0.05	0.05

Table 13: A table showing the weighting scenarios for TOPSIS

8.6 Filtered Constellations

The filtered constellation plot is created from the original constellation plot, however the filtered constellation plot has constraints applied to only show the feasible technology family alternatives.

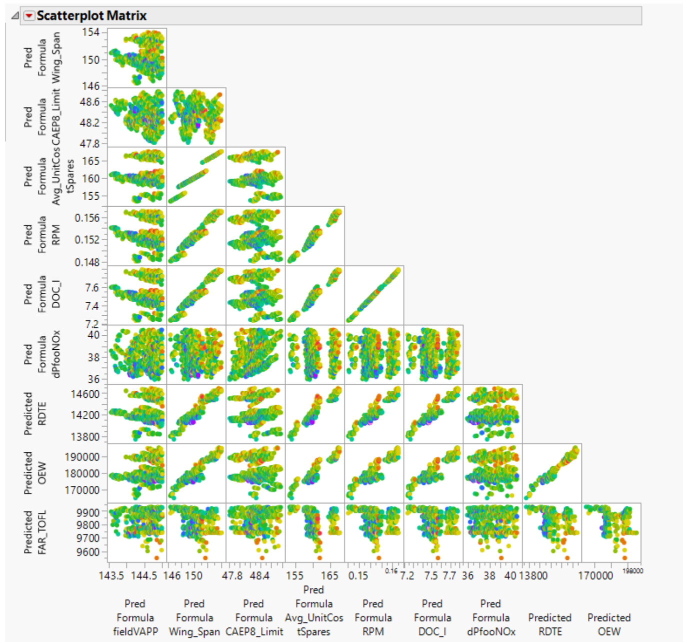


Figure 39: A technology constellation plot showing the feasible alternatives

Legend	
Number of Technologies	Color code
2	
3	
4	
5	
6	
7	
8	
9	
10	

Figure 40: The legend for the colored feasible constellation plot

8.7 Sensitivities

The sensitivities for each technology, and how they affect the out put variables can be seen through the technology profilier plot. For the following technologies, the profiler plot will be provided and that technology will be turned on, with all the other technologies turned off. The baseline values of the outputs are shown with a horizontal orange line on the plots. The amount the technology then affects the baseline values can be seen visually by determining the distance between the orange baseline line and the black technology profilier line. Once again, when performing this technology study, all other technologies other than the one of interest will be turned off.

Technology 3 Damage Arresting Stitched Composites

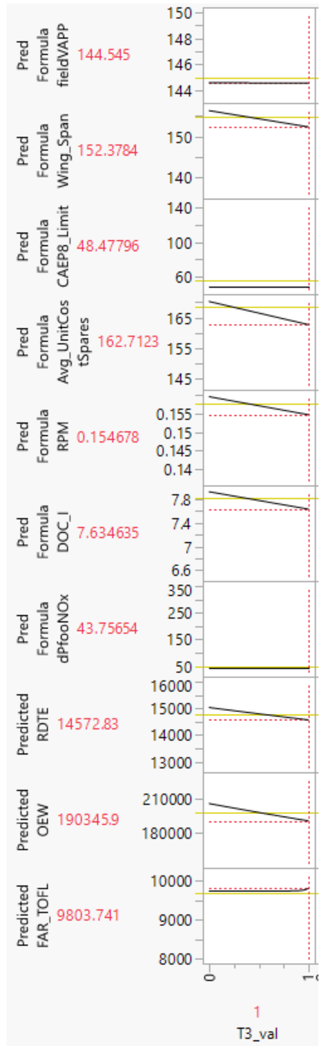


Figure 41: Sensitivity Study for T3

Technology 8 Adaptive Wing/Variable Camber

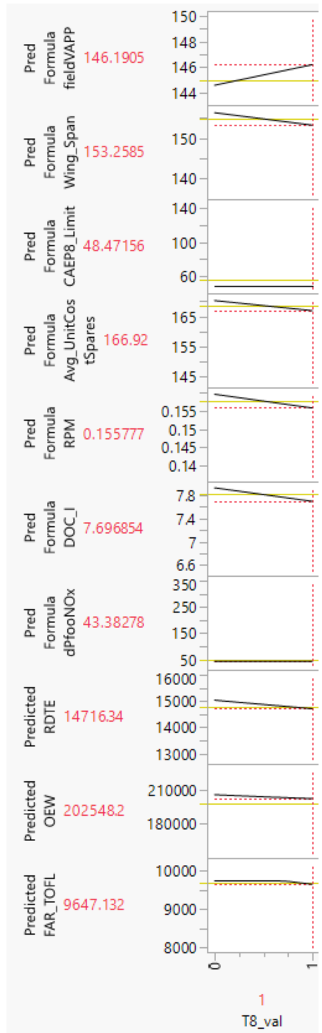


Figure 42: Sensitivity Study for T8

Technology 12 Riblets

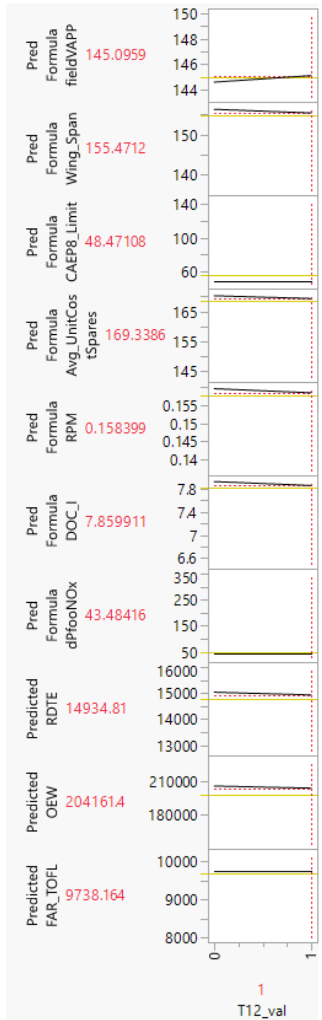


Figure 43: Sensitivity Study for T12

Technology 20a Active Compressor Clearance Control

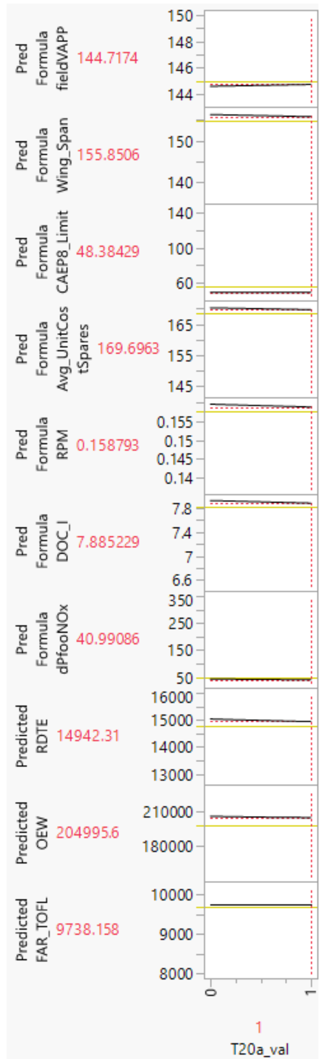


Figure 44: Sensitivity Study for T20a

Technology 20b Active Compressor Clearance Control Aspiration

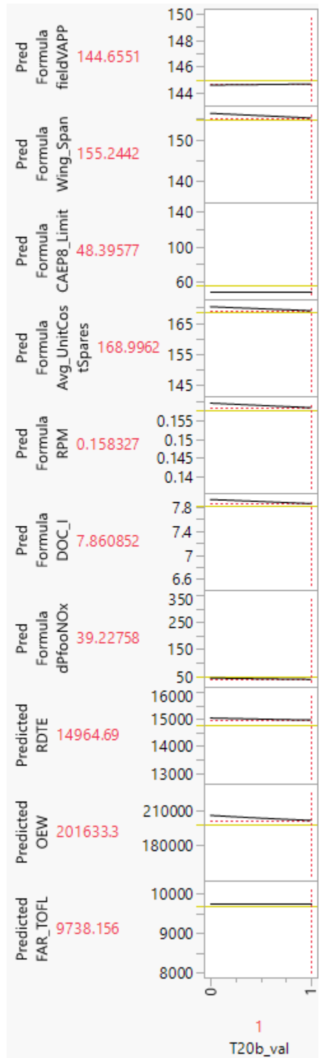


Figure 45: Sensitivity Study for T20b

Technology 23 Active Turbine Clearance Control: Mechanically Actuated

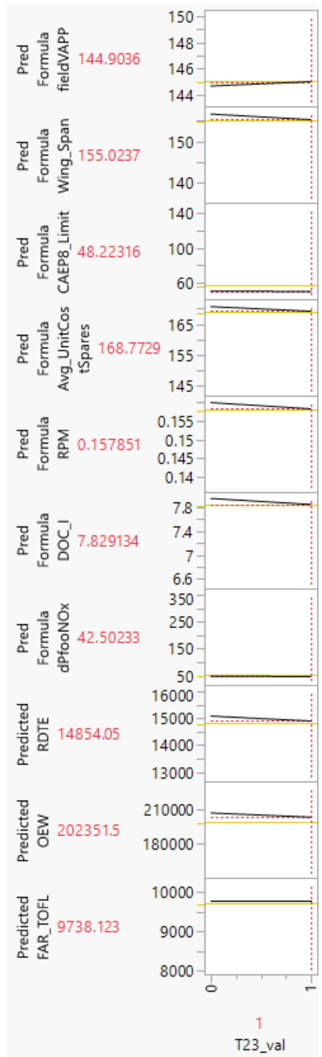


Figure 46: Sensitivity Study for T23

Technology 27 Advanced Thermal Barrier Coating (TBC)

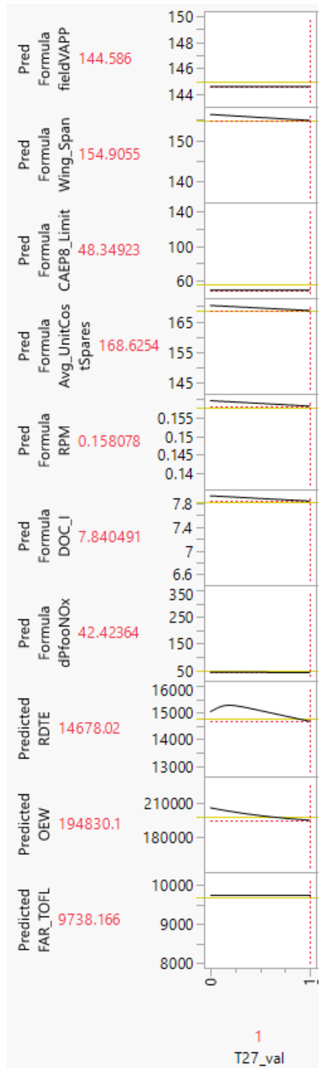


Figure 47: Sensitivity Study for T27

Technology 29a Ceramic matrix Composites Vanes

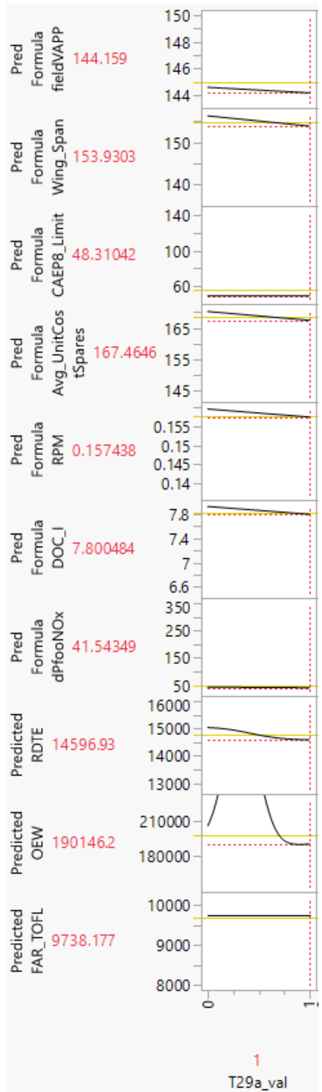


Figure 48: Sensitivity Study for T29a

Technology 29b Ceramic Matrix Composites for Exhaust Core Nozzle

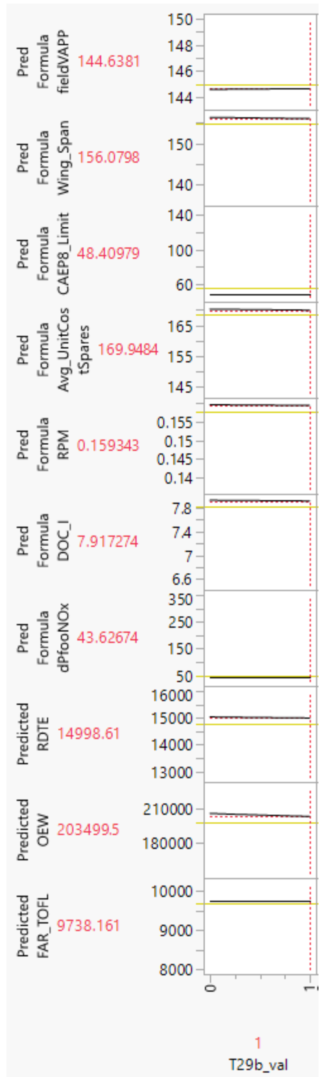


Figure 49: Sensitivity Study for T29b

Technology 32a Highly Loaded Compressor

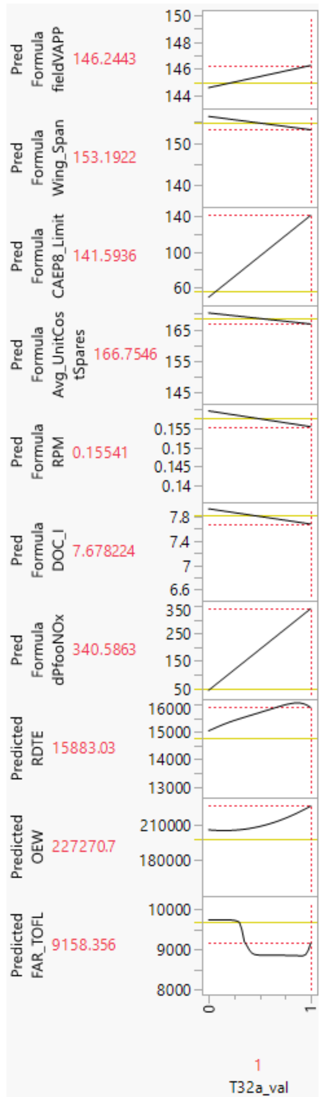


Figure 50: Sensitivity Study for T32a

Technology 32b Highly loaded Turbine

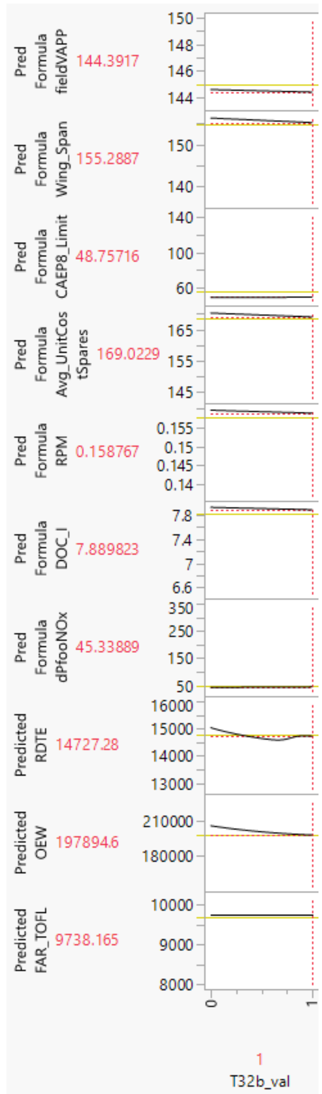


Figure 51: Sensitivity Study for T32b

Technology 65 Rich Quench, Lean (RQL) Zone Combustor

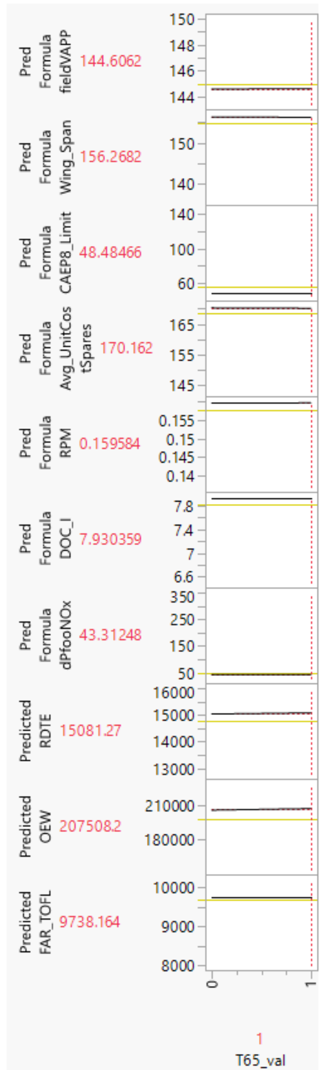


Figure 52: Sensitivity Study for T65

Technology 80 Advanced Sandwich Composite

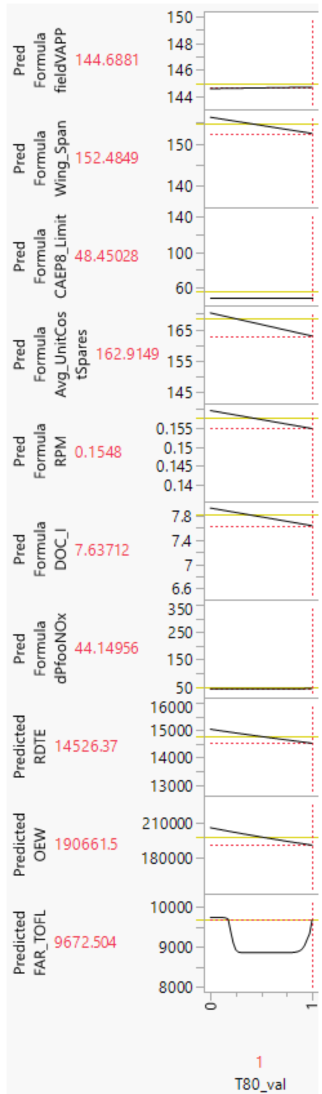


Figure 53: Sensitivity Study for T80

8.8 Probabilistic Sensitivities

Similar to the Probabilistic technology impacts section in step 7, the probabilistic sensitivities are primarily being analyzed in a deterministic manner. This means that we are focusing on the direct influence of individual technologies on baseline metrics from an original geometric design. However, if we were to introduce a probabilistic approach to calculate these sensitives this could significantly alter the findings and interpretations. Probabilistic sensitivity analysis incorporates variability and uncertainty in the inherent technological factors and their impacts, by offering a more realistic assessment. Performing this probabilistic sensitivity analysis could reveal a certain spectrum of effects rather than single point estimates. This approach can help understand the robustness of the design under varying conditions in the face of uncertain technological performances. As an example, a technology that shows an influence in a deterministic analysis, may have a high probability of significantly altering a baseline metric under certain conditions, thus highlighting a vulnerability or an opportunity in our design. Since this method reflects real world scenarios more accurately certain factors such as material properties, manufacturing tolerances, and operating conditions can vary and provide a more comprehensive understanding of how each technology might perform under a range of possible scenarios, thus offering an insight of the reliability of the technologies in different operational contexts. As an example the range of possible improvements in aerodynamics due to a new material could alter the overall vehicle's performance metrics as well, thus creating confidence intervals rather than a single deterministic value.

8.9 Select the Best Set

To obtain the possible family of technologies we can view the filtered Monte Carlo technology constellation plot. The filtered plot shows the feasible alternatives. These alternatives must be evaluated in TOPSIS therefore, in order to select the best family of technologies we can analyze the results of TOPSIS. When viewing the TOPSIS results we can see that the best alternative for 14 out of the 15 weighting scenarios is the inclusion of Technology 12 Riblets, Technology 20b, Active compressor clearance control,Technology 29b, Ceramic Matrix Composite Vanes, Technology 32b, Highly Loaded Turbine, and Technology 65, RQL zone combustor. Since the TOPSIS tables are quite large, and there are over 15 of them with 10 rows each (one row for each of the best technology alternative), the first five rows of the first weighting scheme will be presented below instead.

The first, or highest ranked alternative relates to case 843, or the technologies of 12, 20b, 29b, 32b and 65 which were explained above. The metrics of interest are also shown in the table. It is possible that if more extreme weighting schemes were considered then a different technology family could have ended up on top, however from the 15 tables the top two technology families remained consistent. The technologies for technology family 7011, are Technology 20b, Active compressor clearance control, and Technology 32b, highly loaded turbines, along with the addition of technology 12, riblets. For only one weighting scheme, scheme 11, technology family 7011 is ranked the highest, however for the other weighting schemes technology family 843 is the ranked as the best alternative. Therefore, the best

Rank	field VAPP	Wing _Span	CAEP 8 _Limit	Avg _Unit Cost Spares	RPM	DOC _I	dP foo NOx	RDTE	OEW	FAR _TOFL	Number
1	144.9	153.69	48.71	167.3	0.15	7.77	40.21	14650.01	195494.83	9738.16	843
2	144.9	153.85	48.72	167.46	0.15	7.78	40.07	14643.92	195067.82	9738.16	7011
3	144.96	153.48	48.67	167.05	0.15	7.76	39.91	14641.95	194751.42	9738.17	4583
4	144.67	153.08	48.21	166.55	0.15	7.73	40.2	14511.54	191259.1	9856.03	2458
5	144.68	153.03	48.25	166.5	0.15	7.73	40.27	14509.98	190954.17	9854.58	6611

Table 14: A table showing the first five alternatives for the first weighting scheme

alternative is indeed technology family 843.

8.10 Missing Element

One element that is missing from the analysis shown above is the price of the technologies. We understand that it is not free to inject an aircraft with technologies especially if they are new. This process will be costly, however the return on investment will also increase, as the air crafts capabilities are greater than the previous non-technologically innovated aircraft. If the new technologically enable aircraft was to be sold at the same price as the base line aircraft then we are expecting a loss of 38.305 millions of dollars, this expected loss is approximately 500,000 dollars less than the original baselines 0% ROI loss. In order to obtain a 12 percent Return on Investment (ROI) the projected price of the aircaft is 199.470 million dollars. This price is only 31.02 millions of dollars greater than the baseline 0% ROI design. When comparing the 12 % ROI between the baseline and technology infused designs then the baseline design must charge 216.299 millions of dollars to reach a 12 % ROI, this value is 16.829 millions of dollars more compared to the technology infused aircraft. With the additional cost of development comes the benefits of having a better airplane and being able to meet emission goals. Since the technology infused airplane is also more fuel efficient the aircraft manufacturer can charge less for the aircraft, or in reality they would sell the new aircraft at the same price and have larger profit margins by increasing the overall revenue of the project. The cash flow plot for the technology infused aircraft is shown below in figure 51.

Additional details for the both the baseline and technology infused aircraft are shown in the table below. Something to note, the 0% ROI of the baseline aircraft is 168.545 millions of dollars, and the 4.8% ROI for the tech infused aircraft is 170.915 Millions of dollars meaning we can charge approximately an extra two million dollars and be profitable compared to charging 168.545 millions of dollars and being at a loss of 38.710 millions of dollars.

ROI Metric	Baseline	Technology infused
Price per aircraft at 0% ROI	168.545	155.377
Price per aircraft at 4.8% ROI	185.399	170.915
Price per aircraft at 12.6% ROI	219.108	201.99

Table 15: Baseline vs Technology infused aircraft, with price in millions of dollars

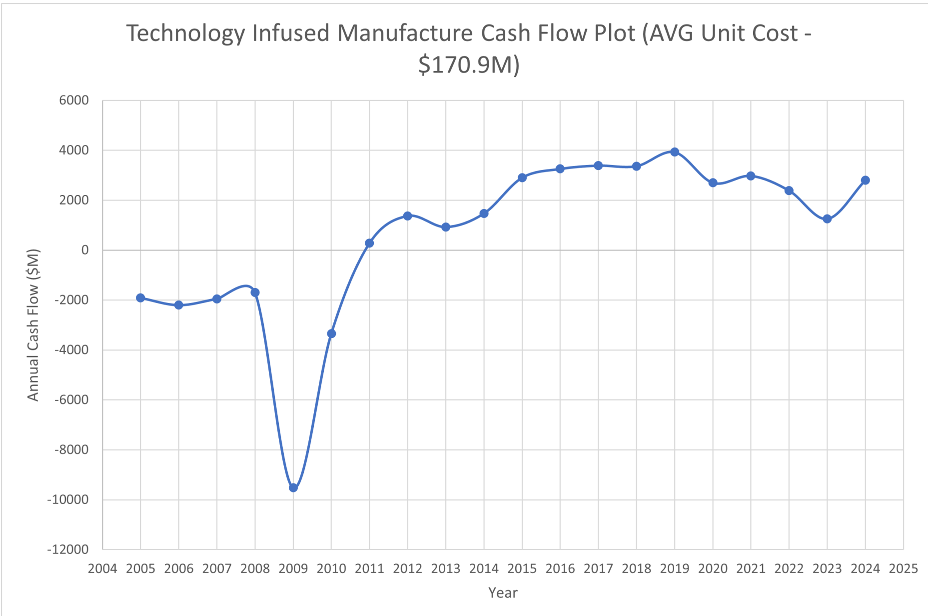


Figure 54: Manufacturer Cash flow plot for technology injected aircraft

Note

Just because this selection of technologies can meet the given requirements with some relaxed constraints does not necessarily mean its is the best economically. Some additional calculations must be performed, like analyzing the future cost of fuel for the aircraft given different fuel prices. These more in depth economics calculations will be shown later on in the report.

9 Closing the loop

9.1 The chosen technology-infused combination

The best selection of technologies was case 843, or the combinations of technologies 12, 20b, 29b, 32b and 65. As a refresher the technologies are tabulated below (in no particular order).

Technology	Description
Technology 12 Riblets	Ribbing that create span wise viscous force to act on the boundary layer and reduce skin friction drag.
Technology 20b Active Flow Control	Aspiration induced removal of low energy flow to slow engine blade speed and increase efficiency.
Technology 29b Ceramic matrix composites for exhaust core nozzle:	Provides a high material strength at very high temperatures that can allow for decreased exhaust core nozzle densities.
Technology 32b Highly loaded turbine:	Increased loading reduces number of turbine stages. Accomplished through blade shape and end wall shape optimization.
Technology 65 Rich, quench, lean, zone combustor:	Ensuring combustion stability (rich burn) and reducing nitrogen oxide emissions (lean burn) relative to published environmental (CAEP2) standards.

Note

When considering infusing technologies into a new aircraft design, it is often not feasible to infuse more than one or two new technologies into a next-generation aircraft. Accordingly, we recommend a three phase approach to infusing these technologies.

1. Phase 1: Introduce T32b immediately. This technology is the perfect intersection of technology readiness, individualized sensitivity to the response variable, and only yielding medium research and development degree of difficulty.

2. Phase 2: Introduce T12 and T65 two years after the first technology infusion. This buys time for the comparatively lower technology readiness levels and research and development degrees of difficulty to reach a viable status for infusion.

3. Phase 3: Introduce T20b and T29b two years after Phase 2, four years after the initial technology introduction in phase one.

The reason for this phasing is due to a combination of technology readiness level, research and development degree of difficulty (RD3), and individualized sensitivity. While the mathematics alone yield our preferred technology combination of T12, T20b, T29b, T32b, and T65, some critical thinking must be applied to other elements for optimal technology selection. Exploring the trade space between technologies with high payoff to the response (individualized sensitivity), high levels of maturity and TRL, and consequently, a low accompanying epistemic uncertainty surrounding their forecasted impact, and the research and development degree of difficulty which directly correlates to cost need to be explored. As such, our phasing structure optimizes all three, selecting the technologies with sizeable impact, relative levels of readiness, and enabling more time for further technology maturity development for the later phases of implementation.

9.2 New Model

Further details about the technology combination can be shown in the table below. The table is split into two portions with the double horizontal line. The first half of the table are the response variables as an effect of the inclusion of technologies and the second half of the table's values are the inputs that resulted in the response variables. A final case containing the values of design variables and k-factors for the chosen design is run in EDS.

Response Variable	Value
fieldVAPP	144.9
FAR_TOFL	9658.46
OEW	201859
Wing_Span	156.18
dPfooNOx	86.8146
CAEP8_Limit	78.4857
RDTE	14608.4
Avg_UnitCostSpares	167.826
DOC_I	7.724
RPM	0.15621

Input Variable	Value
WSR	126.3607
TWR	0.290655
AR	8.150575
TR	0.249925
TCA	0.102391
SWEEP	30.61731
ARHT	3.927464
ARVT	2.091796
FPR	1.521411
LPCPR	1.977389
HPCPR	14.67734

9.3 Technology Impact Study

The comparison between the baseline, optimized baseline and the one with the technology infused is shown in terms of the system metrics. These comparisons are also being made with respect to the EDS produced outputs, not our surrogate model.

System Metrics	Baseline	Optimized Baseline	Technology Infused Baseline
fieldVAPP [knots]	145	136.6	144.9
FAR_TOFL [ft]	9690.44	9442.25	9738.16
OEW [lb]	198440	202356	195494
Wing_Span [ft]	154.77	153.93	153.69
DPfooNOx [g/kN]	50.34	42.12	40.21
CAEP8_Limit	55.77	49.79	48.71
Avg_UnitCostSpares [M$]	168.55	168.48	167.32
RDTE [M$]	14763.6	14635.8	14650.0
DOC_I [cents/ASM]	7.83	7.874	7.77
RPM [$]	0.15773	0.15878	0.15626

9.4 Final Design Iteration

After performing the most recent DoE (with 5000 cases) on our technology aircraft, we have obtained the optimized technology baseline that includes all 5 of the technologies we suggest implementing. Two economic and four noise variables were taken into account for making the DOE. The fuel price was varied between 75%–300% of its baseline value, the two labor rates were varied between a +/- 50% bounds, and a 60%–100% range for the learning curve. The baseline values for each of the variables are shown below.

Variable	EDS Name	Baseline	Type
Operational Vehicles Demanded	NV	800	Economic
Utilization (hours/year)	U	5325	Economic
Fuel price ($/gl)	COFL	1.7	Noise
Engineering labor rate ($/hr)	RE	89.68	Noise
Tooling labor rate ($/hr)	RT	54.86	Noise
Airframe learning curve factor (%)	LAERN1	82	Noise

The table below shows the system metric values for the optimized technology infused design.

System Metrics	Optimized Technology Infused Design
fieldVAPP [knots]	135.5
FAR_TOFL [ft]	9429.24
OEW [lb]	194688.8
Wing_Span [ft]	153.23
DPfooNOx [g/kN]	41.76
CAEP8_Limit	50.97
RDTE [M$]	111.475
Avg_UnitCostSpares [M$]	14073.73
DOC_I [cents/ASM]	5.778
RPM [$]	0.1252

Final Design Economics

The optimized technology infused baseline will cost manufacturers less when compared to the original optimized baseline design. The aircraft manufacturer will break even several months sooner. The aircraft manufacturer has a return of investment of 4.8% with an aircraft price of 270.02 Millions of dollars (FY 2023). For the airlines, with the optimized technology infused baseline the average yield per RPM has a value of .146 dollars. A 10% return on investment for the airlines means that the airline would have to purchase the optimized technology infused design at a price of 315 million dollars (FY 2023). Once again if the airline decides to purchase multiple aircraft then they could possible obtain a discount, thus reducing the acquisition cost and increasing the potential profit.

9.5 Assessing the Feasibility of the Advanced Concept

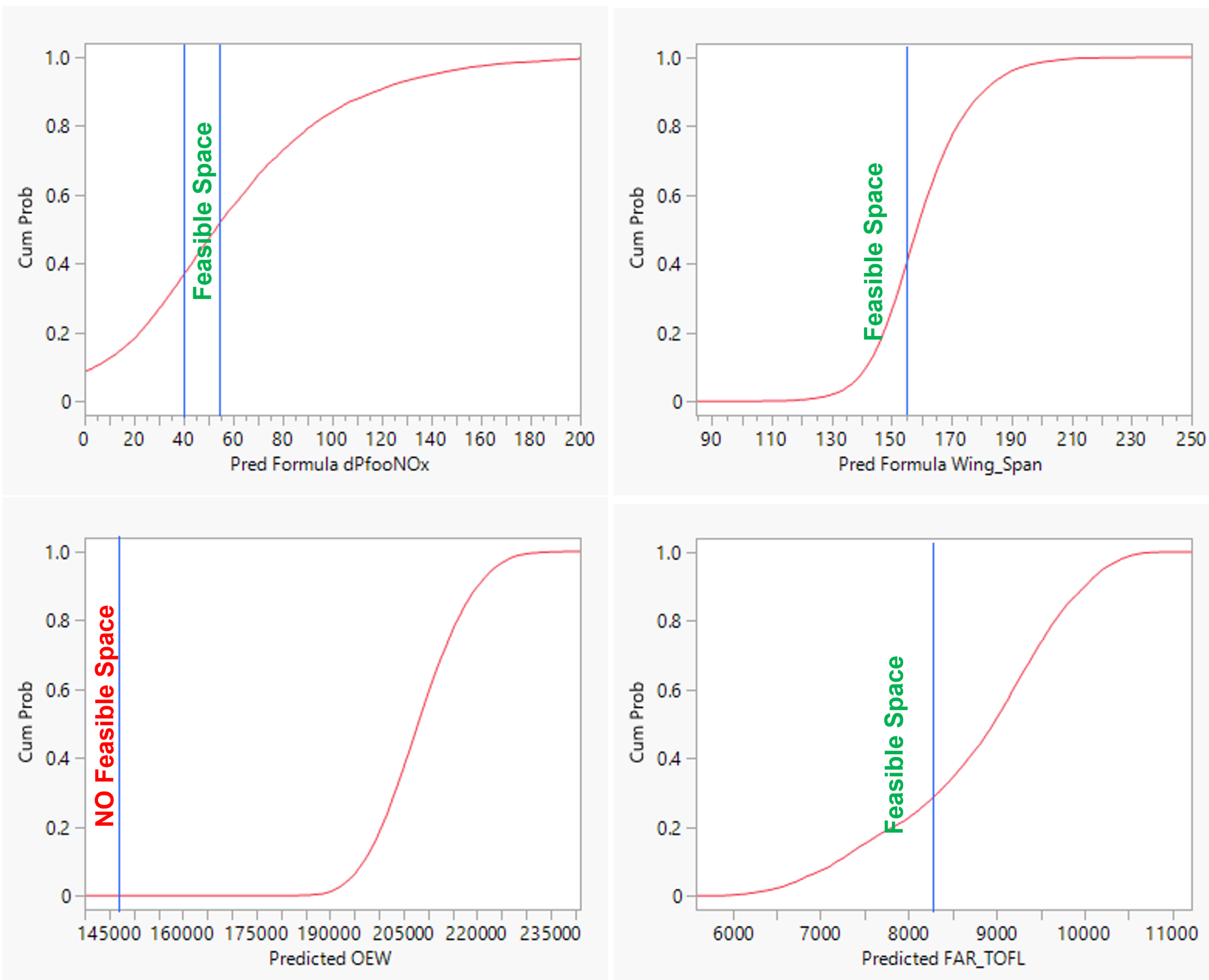
Unfortunately there is also no feasibly design space if we are considering the all of original requirements. We still do not meet the of the customer constraints. We are still to meet the following requirements.

1. Field approach velocity: The field approach velocity had a requirement of 123.5 knots, while the optimized technology infused (OTI) design had an approach velocity of 135.5 knots.

2. Take off field length: The take off field length requirement was 8236.87 ft while the take off field length for the OTI design was 9429.24 ft

3. Operating Empty Weight: The requirement for operating empty weight was the aircraft having an OEW of 148830 lbs. The OTI design had an OEW of 194688.8 lbs.

These requirements listed above are only performance requirements. If the customer can consider relaxing a few of the performance requirements set, then the potential to generate a large amount of money exists. All of the other 7 requirements were met. A Monte Carlo study was performed for the technology-infused design space. CDF plots including the targets for each metric are shown below.


Cum Prob
Feasible Space
Pred Formula dPfooNOx
Feasible Space
Pred Formula Wing_Span
NO Feasible Space
Predicted OEW
Feasible Space
Predicted FAR_TOFL

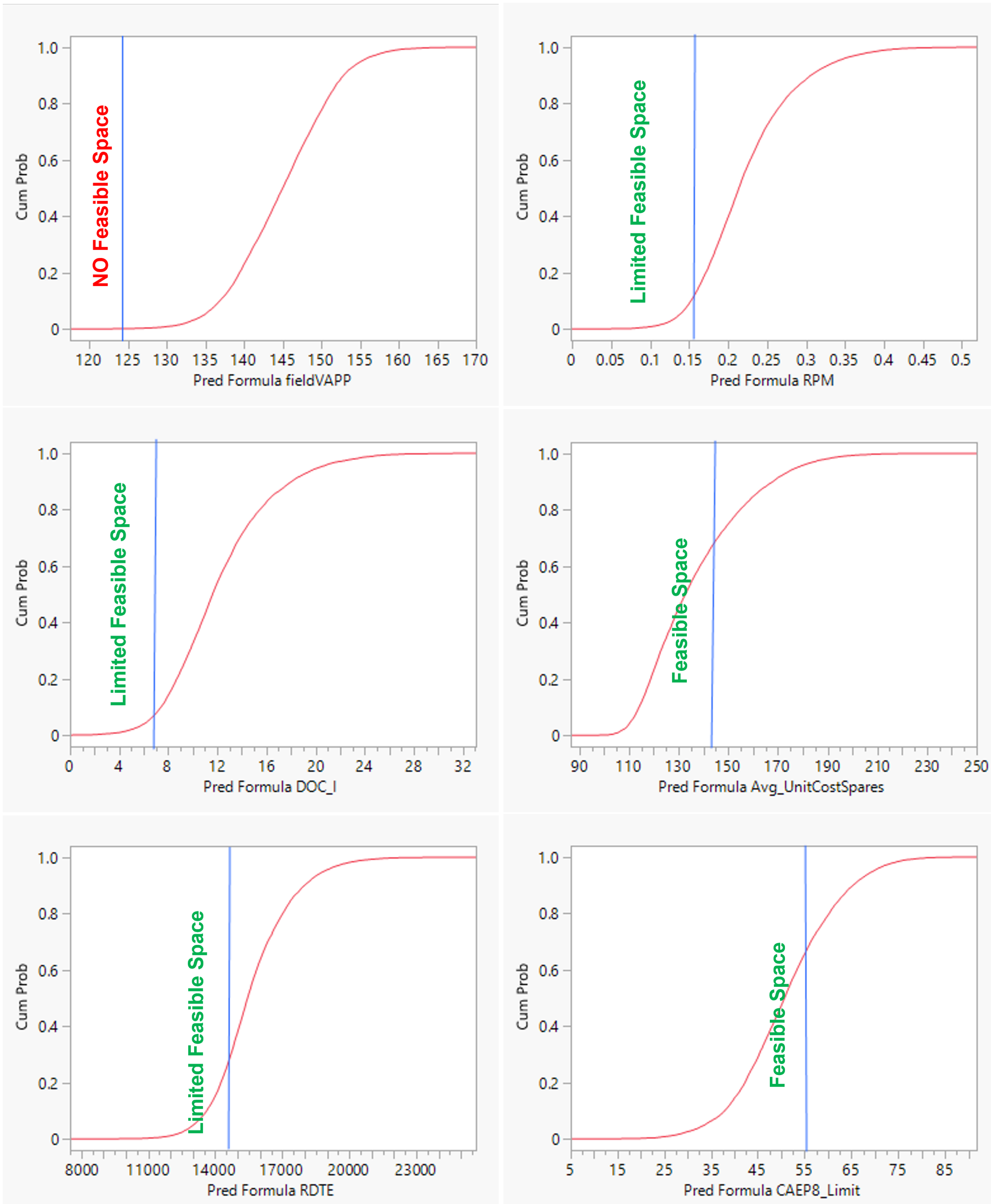


Figure 56: Cumulative Distribution Function from Monte Carlo Simulations

A filtered Monte Carlo study is performed using scatterplots. The constraints are applied as filters and the resulting space is visualized. Only ten designs satisfy all the relaxed constraints. The constraints were relaxed after analysing all the different alternatives with the combination of technologies infused.

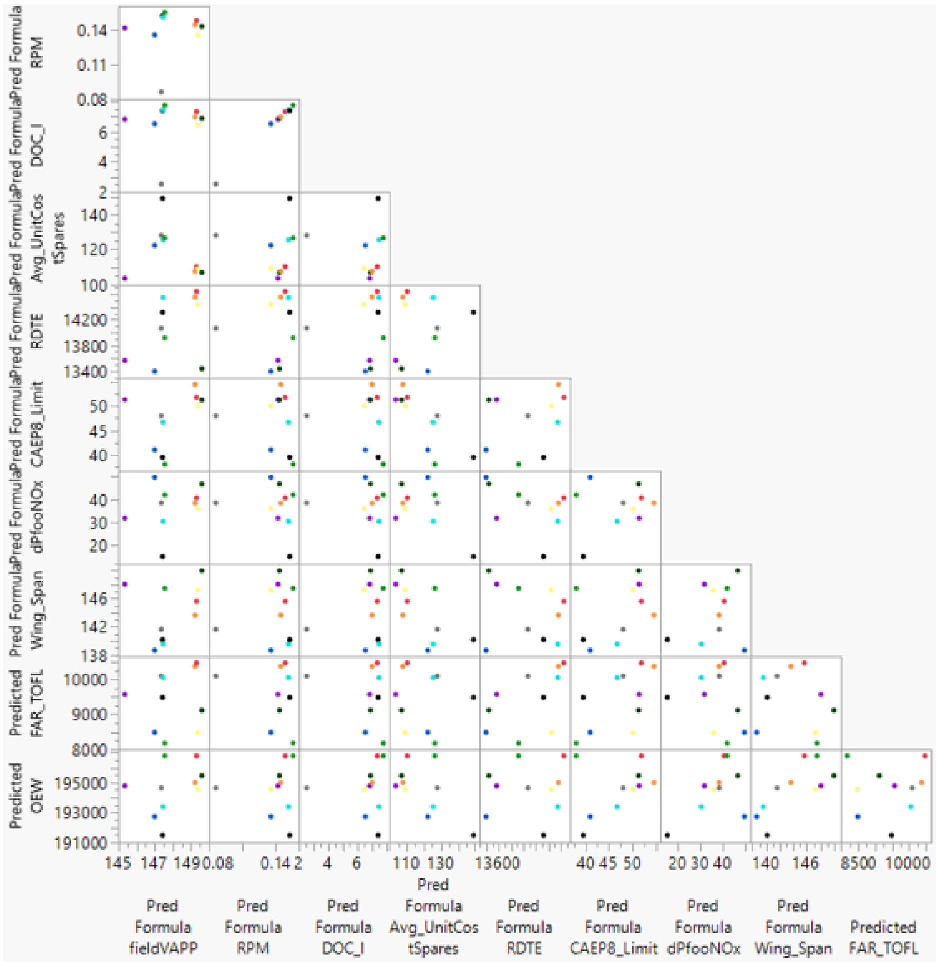


Figure 57: Manufacturer Cash flow plot for technology injected aircraft

9.6 Robustness Analysis

A combination of parameters were selected which are most robust against the noise variables. This was performed so after analysing their sensitivity and the partial derivatives in JMP. The plots can be visualized in the JMP journal. The optimized design with the technology infused was obtained after designing them against this robust analysis process. The prediction profiler below summarizes the trends between performance metrics and variability in the noise variables before the optimization process. Though there seems to be some correlation between the variables and the outputs. In reality, the correlation does not make sense.

Because wing span does not depend on engineering labor rate. But the profiler plot says otherwise. Such correlations are erroneous since there is no physical or mathematical law connecting the two. And if surrogate models are built forcibly under such conditions then erroneous correlations are unavoidable.

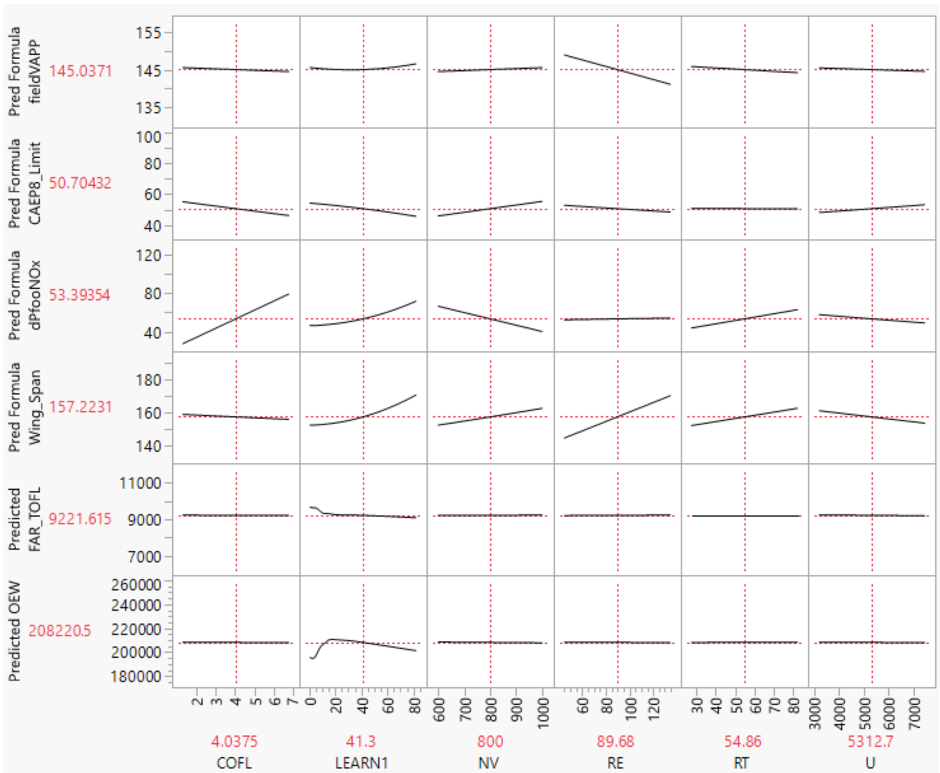


Figure 58: Trends between performance metrics and noise variables

9.7 Comparison to previous baselines

A table summarizing the comparison of the designs is shown below. The table also includes percent reduction when comparing the optimized technology infused design to the baseline design.

Comparison of Performance Parameters

When comparing the optimized technology infused design we can see that there is a 6.6 % reduction in the field approach velocity. Since the approach velocity is decreased we can save some money on the operating costs of the aircraft.

System Metrics	Baseline	Optimized Baseline	Optimized Tech--nology Infused	% Reduction to Baseline Design compared
fieldVAPP [Knots]	145	136.6	135.5	6.6
FAR_TOFL [ft]	9690.44	9442.25	9429.24	2.7
OEW [lb]	198440	202356	194688.8	1.9
Wing_Span [ft]	154.77	153.93	153.23	1
DPfooNOx [g/kN]	50.34	42.12	41.76	17
CAEP8_Limit	55.77	49.79	50.97	8.6
RDTE [M$]	168.55	168.48	111.475	33.9
Avg_UnitCostSpares [M$]	14763.6	14635.8	14073.73	4.7
DOC_I [cents/ASM]	7.83	7.874	5.778	26.2
RPM [$]	0.15773	0.15878	0.1252	20.6

Table 16: A table detailing the comparisons of the baselines' designs

Comparison of Emissions

We have also managed to satisfy the dPfooNOx requirements and by optimizing the technology infused design we obtain an extra 17 % reduction in nitrogen oxide emissions.

Comparison of Economics

Additionally, we have reduced all of the economic parameters with the reduction of research, development, testing and evaluating costs by over 33 %. Overall this optimized technology infused aircraft performs excellently economically.

Comparison of CDFs

Finally, as we see in Figure 55, when comparing the feasible design spaces as given by our CDFs, we can see that there remains no feasible design space without requirement relaxation for Operating Empty Weight (OEW) and Approach Velocity (fieldVAPP). However, all other variable do have a feasible design space as denoted in the CDFs, albeit some are quite limited. This directly contrasts with the baseline CDFs, as not a single feasible space was visible upon examination of the CDFs. Therefore our technology infusion coupled with minimal requirement relaxation generates a workable solution space for developing our new aircraft.

10 Business case generation

In this section of the report a business case for the NBA aircraft will be written and detailed below. Commercial aviation is quite desirable amongst the worlds population. In 2017, 37 million commercial fights carrying 4.1 billion passengers were flown [1]. ICAO expects the air transport industry to balloon to 1.6 trillion per annum of the GDP as early as 2036. Also, there is an increase in the demand for airplanes that are emission conscious. Therefore the industry is demanding aircraft to meet stringent carbon emissions constraints. The Committee of Aviation environmental protection (CAEP) denotes all future aircraft entering production must meet specific carbon dioxide and other emissions' thresholds. Narrow body aircraft, like large single aisle, and small twin aisle have unmatched versatility. NBAs can move anywhere from 150 to 300 passengers and up to 30,000 lbs of cargo. Boeing estimates that this year almost 30,000 new NBA will be needed. Therefore the industry is in need for an aircraft design solution that can meet the stringent performance and emissions requirements.

10.1 Solutions and Options

Through out the report details of the analysis have been shown. Originally there was no feasible design space, and no economically viable design space. In an attempt to create a design space, different technologies were infused with the aircraft. Even after the technological infused a there was still no feasible design space, so we decided to relax some of the requirements in order to create a feasible design space. After relaxing the performance requirements to create a feasible design space, a viable design space was found within our economics contour plot. Therefore we suggest the inclusion of several technologies to add to the baseline design.

1. Technology 12 Riblets: Ribbing that create span wise viscous force to act on the boundary layer and reduce skin friction drag.

2. Technology 12 Riblets: Ribbing that create span wise viscous force to act on the boundary layer and reduce skin friction drag.

3. Technology 29b Ceramic matrix composites for exhaust core nozzle: Provides a high material strength at very high temperatures that can allow for decreased exhaust core nozzle densities.

4. Technology 32b: Highly loaded turbine: Increased loading reduces number of turbine stages. Accomplished through blade shape and end wall shape optimization.

5. Technology 65: Rich, quench, lean, zone combustor: ensuring combustion stability (rich burn) and reducing nitrogen oxide emissions (lean burn) relative to published environmental (CAEP2) standards.

We understand that realistically it is difficult and costly to infuse five different technologies at the same time, therefore an implementation plan has been defined within the implementation plan section 10.6.

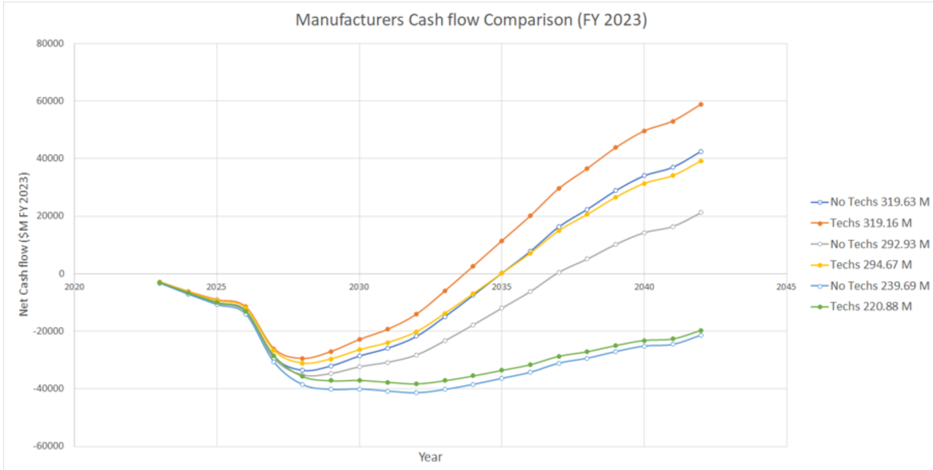


Figure 59: A plot detailing the manufacturers cash flow for baseline and technology infused aircraft

10.2 Cost benefit Analysis

Ana analysis of how much potential profit can be seen with the manufacturer cash flow plot shown in figure 57.

The resulting cash flows are adapted for FY 2023, and the 20 year production schedule has also been shifted so it will begin this year (2023). The lines involving the technology infused aircraft have solid dots, while the lines involving the baseline aircraft have open circle dots. The two similar priced aircraft that can be easily compared on the graph are an aircraft with no technologies price at 319.63 million USD, and an aircraft that is infused with technologies priced at 319.16 million USD. Both of these aforementioned aircraft are the top two lines at the end of the 20 year period, with the baseline aircraft just managing to beat out the cheaper 294.67 M technologically infused aircraft towards the end of the 20 year period. At the end of a 20-year period the technology infused aircraft outperforms the baseline aircraft by roughly 16.3 billion dollars for a similar aircraft price.
We can also compare the return on investment for both the baseline and the technology infused aircraft.

When comparing the 10% ROI values for the baseline and the technology infused aircraft, the baselines Average Yield/RPM is .158 while the technology infused aircraft's Average Yield/ RPM is .146 The price of the baseline aircraft is 341.75 M USD (FY 2023) The final aircraft price of the technology infused aircraft is 315.05 M USD (FY 2023), this price is 26.698 Million dollars less than the baseline aircraft for the same RPM From the chart shown in figure 58, we can deduce that the inclusion of technologies creates a significant difference in the ROI increasing the ROI for the same average yield per revenue passenger mile by about .6%. The technology infused aircraft also has lower aircraft prices for the same average yield per revenue passenger mile. Therefore, the infusion of technologies allows the aircraft manufacturer to charge more, thus increasing revenue

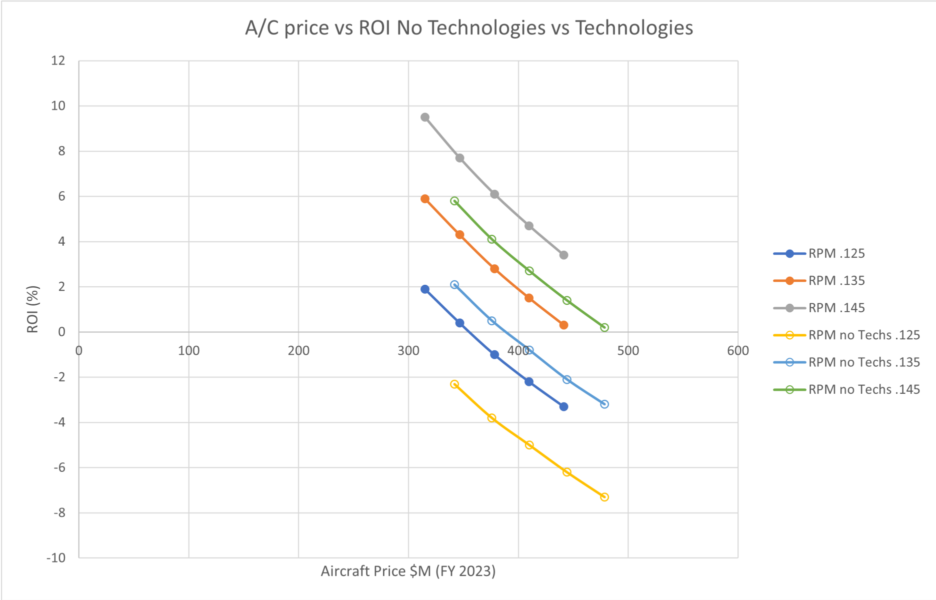


Figure 60: A plot detailing the Aircraft price vs ROI for baseline and technology infused aircraft

Note

Note that these prices within the cash flow plot do not include the inclusion of the prices of the cost of the technology. Most of these technologies that will be infused within the aircraft are going to be developed by other entities. Therefore the manufacturing company may have to pay money for use of those new technologies, however we do not estimate this money to come out of the budget for producing this new technology infused aircraft.
Also, these values shown in the economics plots are for a specific 20 year production schedule, and both the baseline aircraft and the technology infused aircraft are expected to produce 800 total aircraft with having the following production schedule shown in table 17 in the appendix.

10.3 Robustness to Critical Technology

The technology that we recommend for immediate implementation is T32b. Technology 32b influences the out put parameters the most while also have a relatively high technology readiness level. While, it does not have the lowest research degree of difficulty out of the five technologies we suggest implementing, it will have the largest amount of value for the aircraft manufacturers. Other companies like AFRL are already creating mass manufacturing solutions for the highly loaded turbine technology. The projected impacts of adding the highly loaded turbine are increasing the bleed flow, increasing the loading on the high pressure turbine and low pressure turbine, and efficiency loss minimized remains constant through out. We created a design of experiments for this technologies properties and added several (the ones explained in step 9) terms to increase the robustness of the design. Two plots have been generated, one cash flow plot, and one aircraft price vs ROI plot.

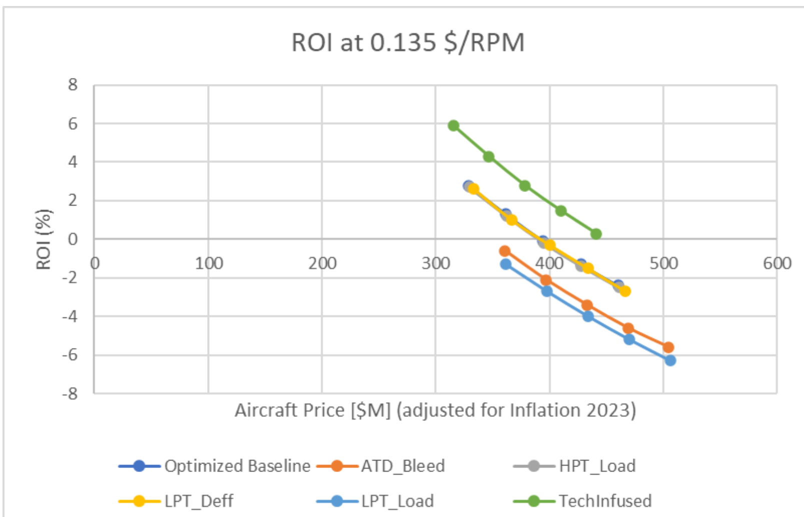


Figure 61: ROI at .135 average revenue yield per revenue passenger mile to show the effect of technology

We can see the the effects of technology inclusion and how it changes the Aircraft price vs ROI. When comparing the single technology infused aircraft and compare the ROI to the baseline we can see that ROI is much greater for the technology infused aircraft. When comparing cash flow plots we can see that the overall trend is the same and the main difference is the sunk costs.

10.4 Economic Robustness

The effect of the economic and noise variable on the outputs are shown below in the form of sensitivity plots. The DOE were run in EDS and the surrogates were created before plotting the profilers below. Only the economic outputs are affected by the noises. This is expected

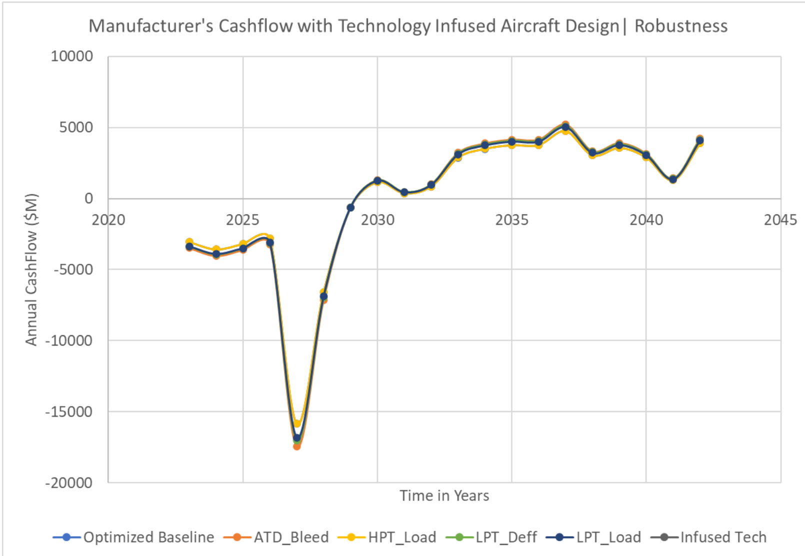
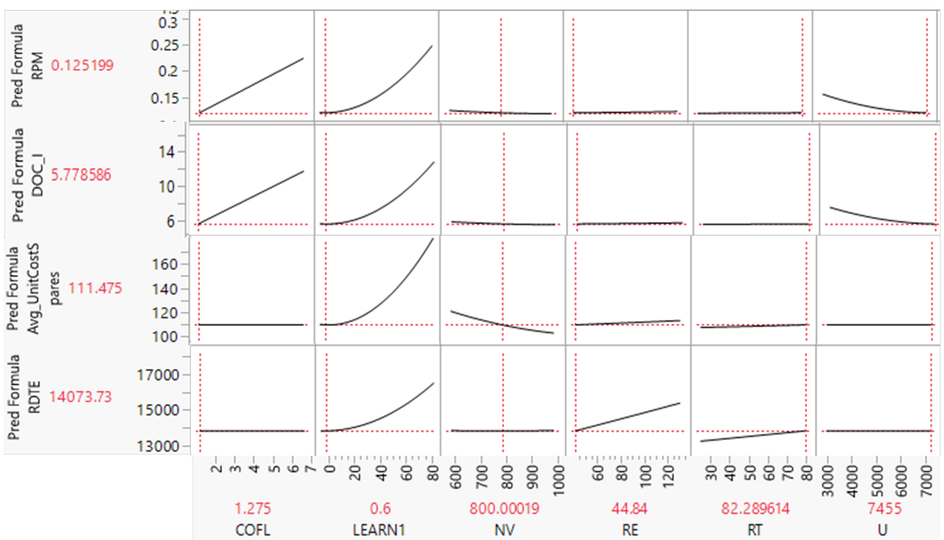


Figure 62: Cash flow comparing multiple technologies



since the performance outputs do not have any correlation with the economic noise factors. The economic outputs are susceptible to the noise variables.

10.5 Uncertainty reduction

The noise due to the economic variables is quite high. This can be observed in the distribution below.

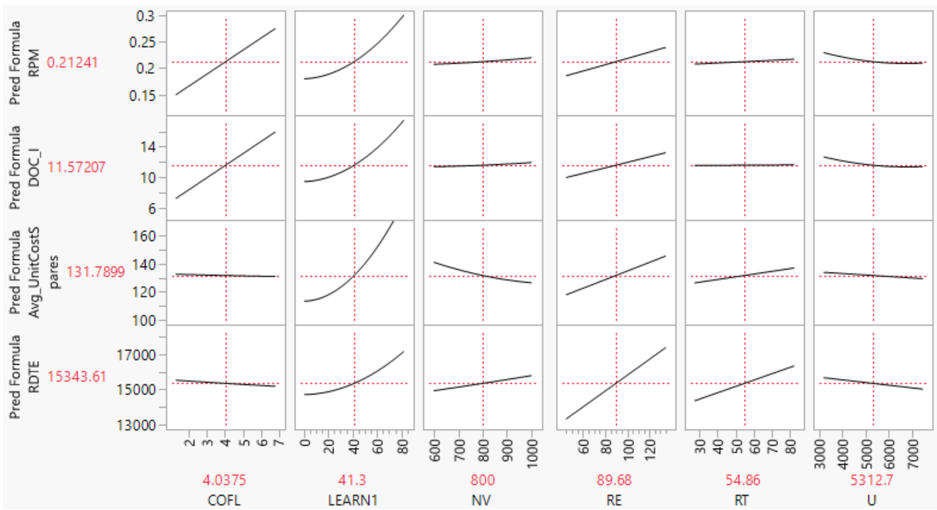


Figure 63: Profiler for Uncertainty Reduction

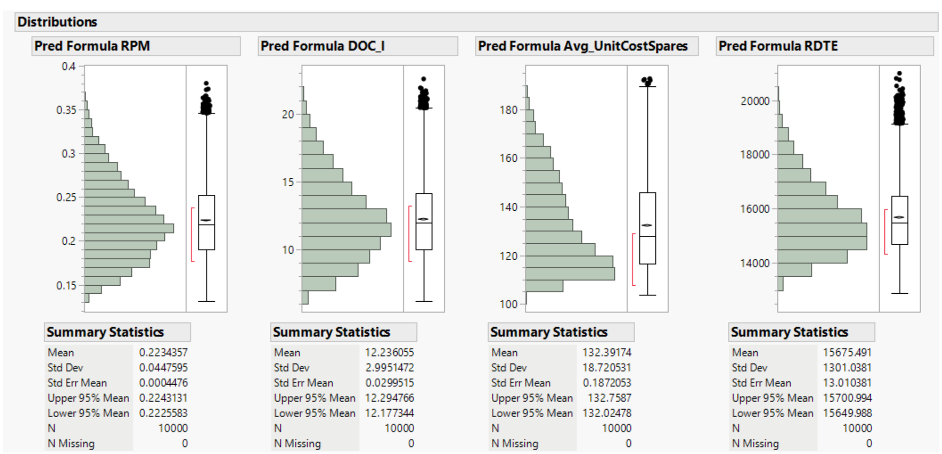


Figure 64: Skewed distribution due to noise from the wide range of variables

To reduce the uncertainty in the economic outputs we propose to reduce the range of two variables. As seen in figure 63, the economic outputs are most sensitive to the variables COFL and LEARN1. Hence these two variables are chosen. The range of LEARN1 is reduced to the range 20-40, while initially it was in the range 8.7-73.8. The COFL range is reduced from the initial range 1.8-7.7 to 3-6. This has enhanced the mean and standard deviation of our model. This can be observed in the figure 65.

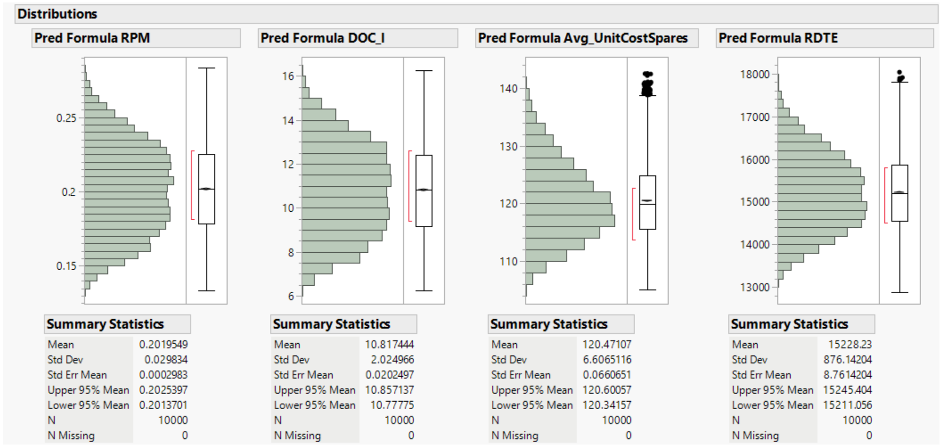


Figure 65: Symmetrical distribution due to shrinking of the range of variables

10.6 Implementation Plan

When considering infusing technologies into a new aircraft design, it is often not feasible to infuse more than one or two new technologies into a next-generation aircraft. Accordingly, we recommend a three phase approach to infusing these technologies.

1. Phase 1: Introduce T32b immediately. This technology is the perfect intersection of technology readiness, individualized sensitivity to the response variable, and only yielding medium research and development degree of difficulty.

2. Phase 2: Introduce T12 and T65 two years after the first technology infusion. This buys time for the comparatively lower technology readiness levels and research and development degrees of difficulty to reach a viable status for infusion.

3. Phase 3: Introduce T20b and T29b two years after Phase 2, four years after the initial technology introduction in phase one.

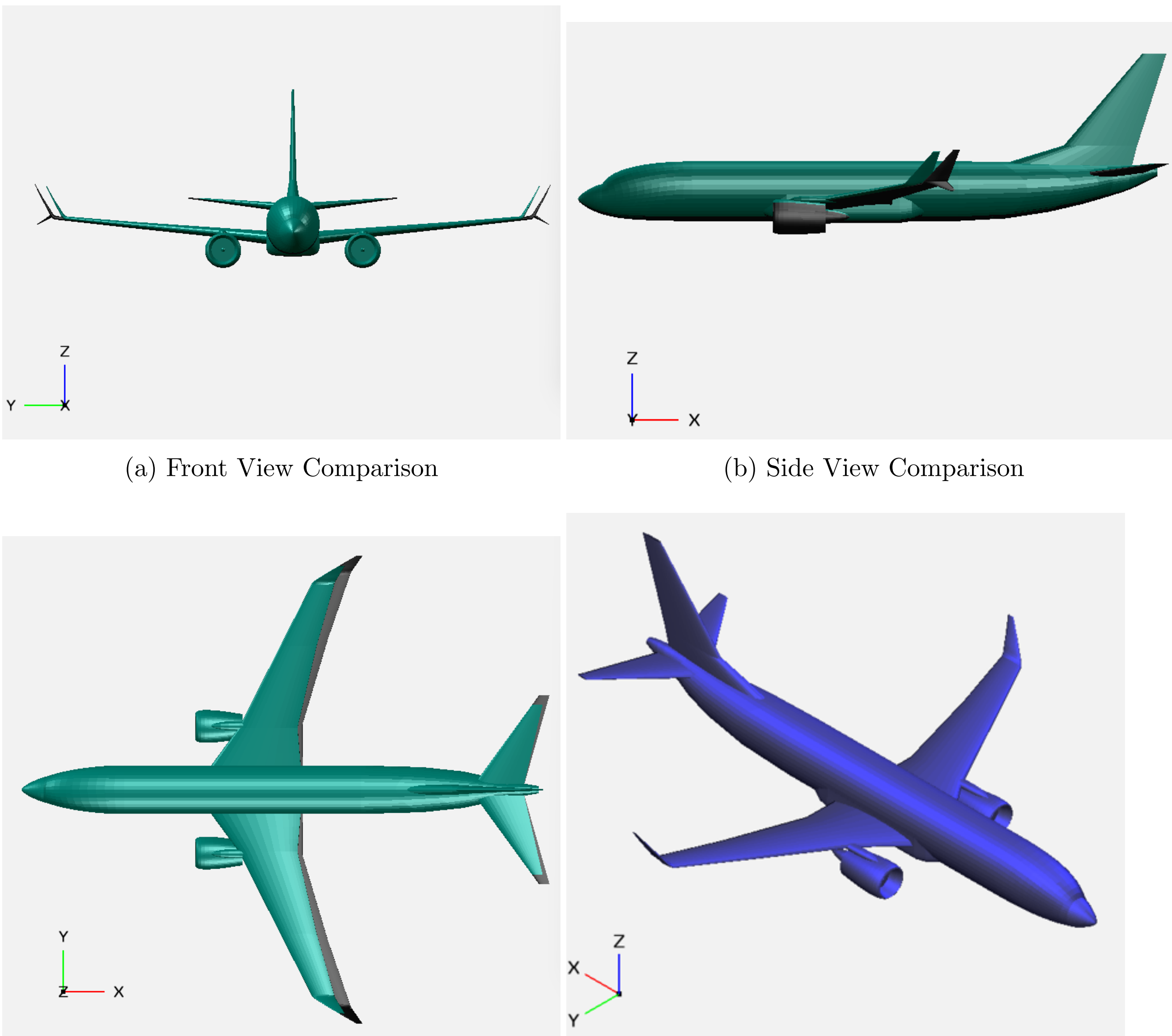
It is important to note, that if more time is needed between infusion phases then more time should be taken. The sum of the total infusion time should be no greater than 15 years, as it would ideally take less than 5 years to set up production, therefore within a twenty year time frame production has been set up, and a new technologically infused aircraft can dominate the NBA market.

10.7 Conclusion

The team has made a methodological approach towards designing an aircraft using a given baseline design of an aircraft to meet the customer requirements. This approach involves infusion of new technologies to the baseline design since it is unable to meet the requirements even after optimizing it for its best performance. The final design is shorter, lighter and more environmentally friendly than the baseline aircraft with which we started the design process.

The comparison is shown in table 16. The diagram of the final design and initial baseline design are overlaid on top of each other. The aircraft in the green color is the one with optimized along with technology infused. The one in the black is the baseline design.

At endstate, as the Research and Development team, we pose our recommendation to the decision maker to action the development of our aircraft, through our phased technology integration approach.



(a) Front View Comparison

(b) Side View Comparison

(c) Top View Comparison

(d) Isometric View of only the Final Design

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Appendices

Year	Deliveries
2023	0
2024	0
2025	0
2026	0
2027	0
2028	36
2029	36
2030	36
2031	36
2032	55.3
2033	72.1
2034	72.1
2035	72.1
2036	72.1
2037	72.1
2038	60.1
2039	60.1
2040	48
2041	36
2042	36

Table 17: A table detailing the number of deliveries of aircraft per year

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Envelope Summary Events	Status	Timestamps
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Completed	Security Checked	12/4/2023 7:55:32 PM

Payment Events	Status	Timestamps