Supervised Learning Program

Report On

Studies In Conceptual Sizing Of Long Range Transport Aircraft

Submitted By

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Abstract

This report studies the conceptual design phase in the Aircraft Design process. Aircraft Conceptual Design involves calculating the Gross weight of the aircraft from the given mission profile, the aerodynamic coefficients are calculated for the aircraft, a constraint diagram is prepared based on the mission profile and cost estimation, which includes Program Cost Estimation and Direct Operating Cost, is also carried out. Based on the operating constraints, the thrust to weight ratio and the wing loading are calculated. All these processes are carried out for the Boeing 787-8 Dreamliner aircraft and the codes for each module were written in Python Programming language. The data obtained using the formulae were validated against published data for the aircraft in Piano.

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1 Introduction

The Aircraft Design Process is a very big process in terms of the time required and money spent. It can broadly be divided into three stages:

- Conceptual Design
- Preliminary Design
- Detailed Design

In the conceptual stage the shape of the aircraft gets fixed. By shape, it means that the number of engines, tail shape, wing shape, jet/turboprop, gross weight, T/W, W/S etc gets fixed. In the preliminary design the wind tunnel testing is done and more detail about the aircraft is made. This stage requires a lot more analysis than the conceptual design. In the third the design gets fixed 100 % up to the nut and bolt level. This stage consumes about 90% of the labour required in the whole Aircraft Design Process.

The first stage, Conceptual Design, is very important as the aircraft shape gets fixed and in the further stages, the detailing is done. The shape of the aircraft is arrived at by doing trade studies. This arrived shape may not be optimum with respect to the requirements given. There is a scope that this process can be automated. But to do that conceptual studies must be done in detail. So, in the present report the conceptual design studies are done and are divided into the following tasks:

- Initial Sizing
- Aerodynamic Calculations
- Constraint Analysis
- Program Cost
- Direct Operating Cost

The above mentioned tasks are done for Boeing 787-8 Dreamliner.

Figure 1: *B-787-8*

B787-8 was chosen because the data is available in PIANO for comparison with our calculations and also because it is the newest passenger aircraft with the trademark Chevron Nozzles which reduces noise and is considered the best among the passenger transport aircraft.

2 Initial Sizing

To understand the process behind Initial Sizing, a tutorial was solved. The mission profile used for the analysis is as shown below.

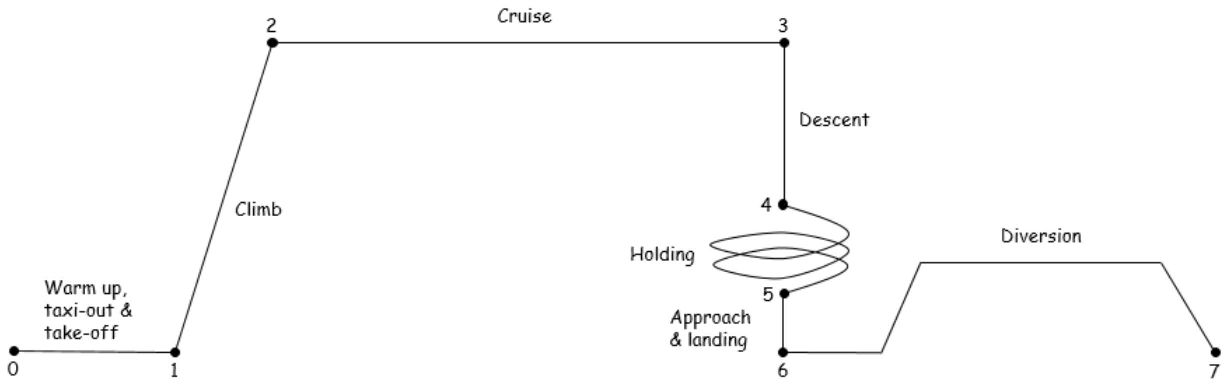

Figure 2: *Mission Profile*

Based on the mission profile, the weight fractions for each leg was calculated based on the given data and various equations. From the weight fractions, the individual Mass of fuel (since payload drop is not considered) burnt at each leg of the mission. Based on the data provided by PIANO, the error percentage was calculated. For the Design Gross Weight (W_0), an iterative process was used to calculate it based on the Empty Weight.

Take off Gross Weight of B-787-8: 218716.5 Kg

3 Drag Calculation

3.1 Different Types of Drag

Parasite Drag:

- Skin Friction – Depends in Wetted Surface Area
- Scrubbing Drag – Depends on Wetted Surface Area
- Interference Drag – Depends on Wetted Surface Area and Max C/S
- Profile Drag - Depends on Wetted Surface Area and Max C/S
- Viscous Drag – Maximum C/S
- Wave Drag – Volume distribution
- Shock Induced Separation – Depends on Max C/S and Volume distribution

Induced Drag:

- Drag due to lift – Reference Surface Area
- Trim Drag – Reference Surface Area
- Wave drag due to lift – Volume distribution and Reference Surface Area

Profile Drag: Skin Friction Drag + Form Drag

Interference Drag:
The drag due to various components inducing a change in the airflow in its surrounding which in turn affects the drag on other components. If one component results in turbulent flow over another, then skin friction drag can increase.

Trim Drag: The induced drag on the tail
Parasite Drag: A combination of form drag, skin friction drag and interference drag.

3.2 Methodology for Parasitic Drag Estimation

There are two basic techniques:

- Equivalent Skin Friction Drag
- Component Build Up Method

Equivalent Skin Friction Drag
The assumption for this is that an aircraft which is well designed will have skin friction drag as the dominant component in the parasite drag and have a small fraction of pressure drag. Equivalent skin friction coefficient is determined (C_{fe})

$C_{d0} = C_{fe}\frac{S_{wet}}{S_{ref}}$

Here, $C_{fe} = \frac{D}{qS_{wet}}$

Where D = Minimum Drag q = Dynamic Pressure and Swet is the total wetted S.A Minimum Drag is the point where Parasite drag and induced drag are equal

Component Build Up Method

- Estimates the parasite drag of each component.
- Assumes a flat plate having an equivalent area of the component.
- An estimated factor, "Q", is taken.
- Total Component Drag = Swet * Q * Cf * FF – "FF" here is Form Factor.
- The net drag coefficient is the summation of the equivalent flat plate drag coefficients for various components, the miscellaneous drag(s) coefficient(s) and Leakage and Protuberances drag coefficient.
- Flat Plate skin friction coefficient depends on Reynolds number, Mach number, skin roughness and extent of laminar flow over the surface

Component Form Drag

Due to hinges in the tail rudder/elevator, there will be a form factor 10 % higher than predicted.

Component Interference Factor (Q):

- Nacelle mounted directly on fuselage: Q = 1.5
- Nacelle mounted at a distance $<$ 1 dia: Q = 1.3
- Nacelle mounted at a distance $>$ 1 dia: Q = 1.0

Component Form Drag

Due to hinges in the tail rudder/elevator, there will be a form factor 10 % higher than predicted.

Miscellaneous Drag:

- Empirical graphs and equation used for individual components and added to get total misc. drag.
- Upsweep at the aft of fuselage produces large amounts of drag and this is prominent on transport aircrafts.
- Test data is used for landing gear.
- To account for mutual interference, a factor of 1.2 is multiplied to the drag obtained.
- If the landing gear well is open, a 7% factor of the total drag is added to account for it.
- Although ignored for initial analysis, landing gear drag is a function of lift. More the lift coefficient, lower the drag due to the landing gear.
- Induced Lift drag due to flaps are neglected.
- Parasite drag is considered.
- Empirical relation used for calculating base area drag.
- Drag due to windshield = 0.07 A_{shield}

Leakage and Protuberance Drag:

- Difficult to predict.
- Leakage drag is due to any gaps in the aircraft structure.
- Usually 2-5% of the entire drag (Transport Aircraft).

Ma = 0.85 h = 37,000 ft S_{ref} = 359.53 m^2	**Reference Value (PIANO)**	**Calculated**	**% Error***
$C_{D_0 wing}$	$4.732 \cdot 10^{-3}$ (37.1 %)	$4.976 \cdot 10^{-3}$ (38.7 %)	+ 5.2 %
$C_{D_0 wlet}$	$3.695 \cdot 10^{-5}$ (0.3 %)	$3.782 \cdot 10^{-5}$ (0.3 %)	+ 2.3 %
$C_{D_0 Hstab}$	$1.046 \cdot 10^{-3}$ (8.2 %)	$1.075 \cdot 10^{-3}$ (8.4 %)	+ 2.7 %
$C_{D_0 Vstab}$	$7.687 \cdot 10^{-4}$ (6.0 %)	$7.543 \cdot 10^{-4}$ (5.9 %)	− 1.9 %
$C_{D_0 fuse}$	$5.004 \cdot 10^{-3}$ (39.2 %)	$4.884 \cdot 10^{-3}$ (37.9 %)	− 2.4 %
$C_{D_0 nace}$	$1.186 \cdot 10^{-3}$ (9.3 %)	$1.140 \cdot 10^{-3}$ (8.9 %)	− 3.9 %
C_{D_0}	$1.277 \cdot 10^{-2}$	$1.287 \cdot 10^{-2}$	+ 0.7 %
C_{D_i}	$1.022 \cdot 10^{-2}$	$1.084 \cdot 10^{-2}$	+ 6.1 %
C_D	$2.299 \cdot 10^{-2}$	$2.371 \cdot 10^{-2}$	+ 3.1 %

* The formula used to estimate relative errors is the following: $err_x = \frac{x_{calc} - x_{ref}}{x_{ref}}$

Figure 3: *Results*

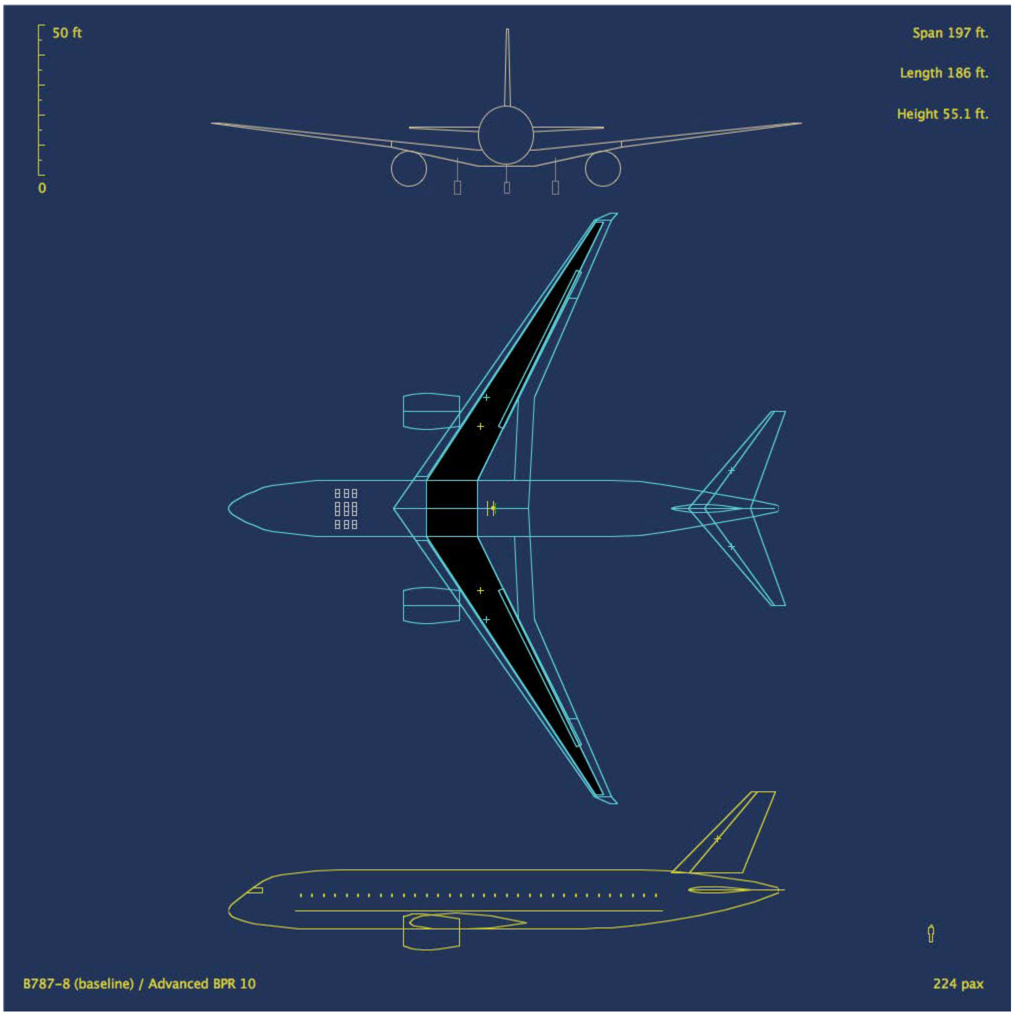

Figure 4: *Orthographic View 787-8*

4 Constraint Analysis

4.1 Brief Intro into Constraint Analysis

Designed to give an approximate Thrust and Wing loading, using predefined performance characteristics An aircraft must be designed based on various different constraints, such as Cruise Mach Number, Take off Run, Takeoff and landing stall speed etc. These constraints have very specific values which are governed by customer requirements and various regulations such as FAR – 25, FAR – 23 etc.

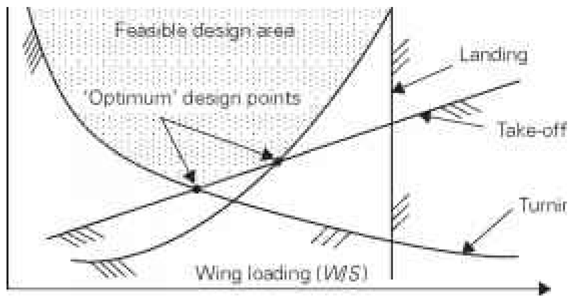

Figure 5: *Constraint Analysis*

The above image is an example of a constraint diagram. The constraint diagram, which is the graph between the Thrust to Weight ratio and the Wing Loading of an aircraft at various different conditions based on the constraint imposed upon it. This is one of the major steps in the Conceptual Design phase. It has two approaches:

1. Estimation of T/W from specific constraints
2. Estimation of W/S from various constraints

Approach 1 is preferred as there is more leeway into the design of the Thrust loading and the process is easier to implement.

4.2 Boeing 787-8 Constraint Analysis

Constraints Defined on B-787-8

Design Cruise Mach	0.9
Landing Stall Speed	52.47
Landing Ground Roll	620.8776
Take Off Stall Speed	70.9933
Second Stage Climb Gradient	0.0349
Balanced Field Length	2820.924
Missed Approach Gradient	0.021

The following were the results(graph) obtained after the constraint analysis

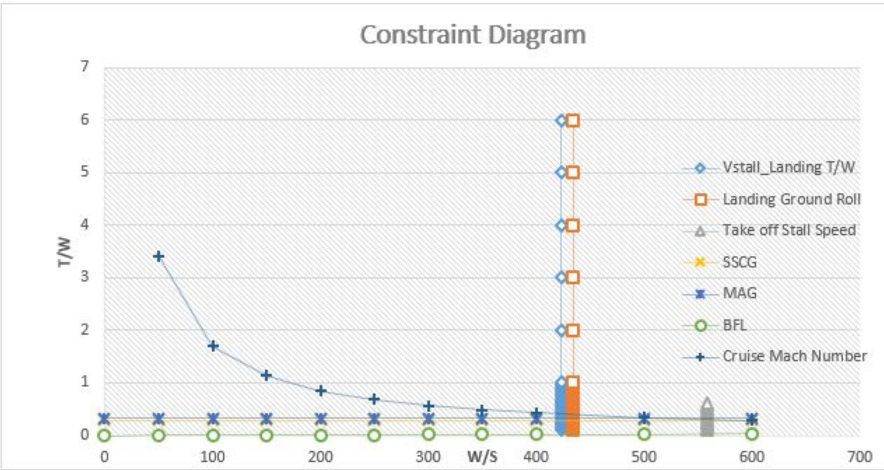

Figure 6: *Constraints Plot*

Design Point:

$\frac{T_{TO}}{W_0} = 0.4$

$\frac{W_0}{S} = 423\frac{Kg}{m^2}$

5 Program Cost

5.1 Theory

The work done in this time pertained to RDT&E (Research Development Testing and Evaluation) Cost Estimation in the development and production of an aircraft and its fleet.For this, there are various CERs (Cost Estimation Relationships).

There are various components in the RDT&E:
- Technology Research
- Design Engineering
- Prototype fabrication
- Ground and Flight testing
- Operational Stability
- Certification
- Documentation

Two basic approaches:
- Activity Based – Detailed assessment of actual task.
- CER Based – Formula based on DCR weight, Max Speed etc. One example is the Rand DAPCA IV model.

The Rand DAPCA (Development and Procurement Cost of Aircraft) IV model estimates the time required for RDT&E and production. Done by multiplying with the man-hour rates.

Other cost which are estimated directly:
- Development support
- Manufacturing material
- Flight test

Additional cost elements:
- Financing
- Profit

Engineering hours:
- Effort
- Support – Integration and Planning

Tooling hours:
- Jigs and Fixtures
- CNC machine programming
- Molds and dies etc.

Manufacturing Development Support Costs:
- Mock Up
- Structural Test rigs
- System integration test rigs

This method provides reasonable results for several class of aircrafts.

Assumptions:
- Engine cost is known.
- Manufacturing materials include almost everything except the engines and avionics.
- Avionics cost is not estimated – taken from similar aircraft or vendor quotation.

Program Cost For B-787-8: 119889.8 mil $

6 Direct Operating Cost

One of the components in the cost analysis is the Direct Operating Cost (DOC). The diagram below explains the breakup of the DOC:

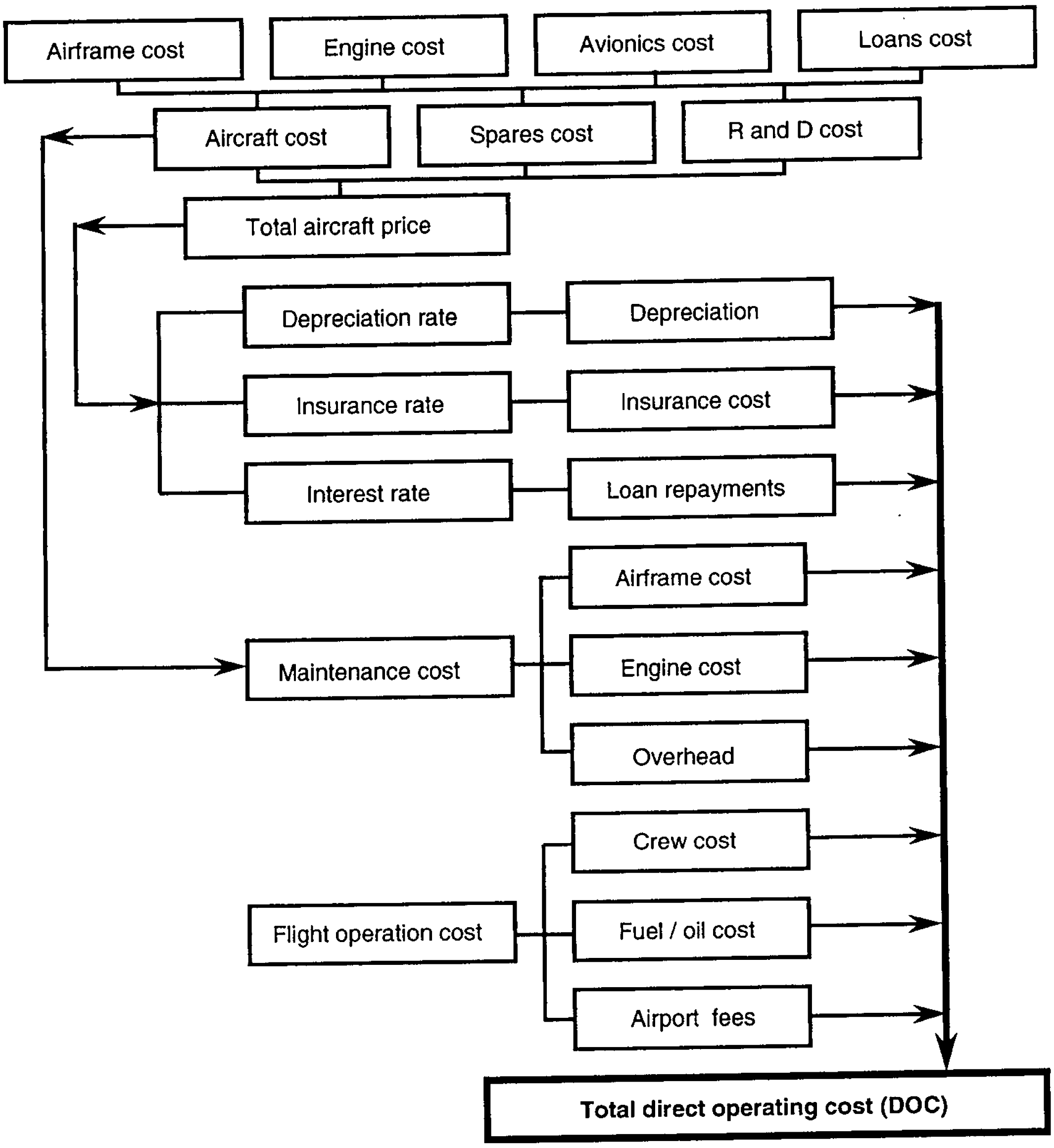

Figure 7: *DOC*

DOC	120879736.9$
DOC/Trip	2093153987$
DOC/Km	188267.1332$
DOC/pax	840.4782733$

7 Genetic Algorithm

General Genetic Algorithm was written in order to use it for optimization in conceptual design. This algorithm could be coupled with the constraint analysis with the objective function being the direct operating cost. This couldn't be done due to shortage of time.

7.1 About The Algorithm

The algorithm uses the evolution concepts. It is based on the survival of the fittest principle. It uses three main types of rules at each step to create the next generation from the current population:

Selection rules select the individuals, called parents, that contribute to the population at the next generation.

Crossover rules combine two parents to form children for the next generation.

Mutation rules apply random changes to individual parents to form children.
The algorithm generates a population of points at each iteration. The best point in the population approaches an optimal solution.

The algorithm that I wrote can work up to 3 variable functions, although it can be extended to n-variable functions easily. The code was written in Python and it was tested using standard test functions. The detailed report is given in the appendix

8 Conclusions

The aircraft conceptual design process has been studied in detail in the project. Its various sub components have been understood completely. As codes were also written for each module of the design process, therefore, the conceptual design could be done with just a change of parameters in the code. We would get faster results. Due to shortage of time the genetic algorithm could not be coupled with the conceptual design, so as an extension to this project the coupling could be done.

References

[1] Prof. Rajkumar S.Pant, *Lecture Notes On Aircraft Design*

[2] Textbook by Daniel P. Raymer, *Aircraft Design: A Conceptual Approach*

[3] https://www.sfu.ca/ ssurjano/optimization.html

Acknowledgement

I would like to express my sincere gratitude to **Prof. Rajkumar S. Pant** for his invaluable guidance, support and constant encouragement during the course of the project.His presence at tough times and prompt decisions has constantly truly inspired me in carrying out this work.
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Micky

Appendix

PIANO

Piano is an analysis tool used for preliminary design, competitor evaluation, performance studies, environmental emissions and other development tasks by airframe and engine manufacturers, aviation research establishments and governmental or decision making institutions. It has contributed to several real-world design projects, including internal Airbus conceptual studies of the UHCA (Ultra High Capacity Airliner, which led to the A380), a number of 70-100 seater designs, and at least one new mid-sized business jet currently in production. A major influence has come from engine manufacturers. Piano does not design the engine, but it is ideal for studying the application of different power-plants to both existing and projected aircraft. Consequently, engine and airframe evaluation is one the most extensive areas of usage for Piano. It has served as a 'common reference' tool between air-framers and engine makers during cooperative studies.

Some well-known organizations using PIANO:

- Textron Aviation
- Northrup Grumman
- Rolls Royce
- Airbus Industries
- Boeing
- GE Aviation and many more.

OpenVSP

It is an open source software released by NASA for conceptual aircraft design. It provides designers with a tool to make 3D models of an aircraft, which saves a lot of time. Since it's a parametric geometry modeler, it allows engineers to shape an aircraft by having control over its geometric parameters, rather than reproducing its geometry in detail. This saves a lot of time in the conceptual design process. There are various preset airfoil geometry present which expedites the process. If the 3 view of an aircraft is present, shaping the aircraft using that is easier and faster. This also helps to obtain a basic area of each component directly. Using OpenVSP various models of the B787-8 were developed, one of those are as shown below:

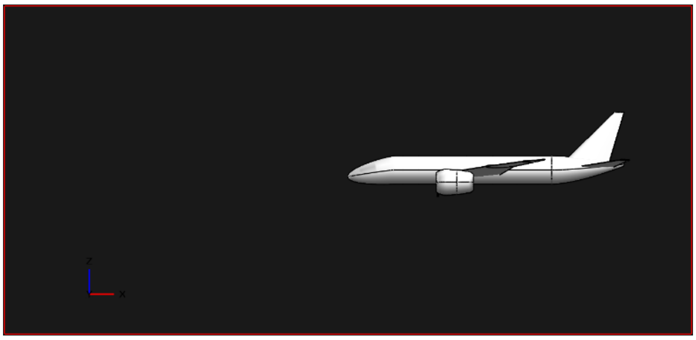

Figure 8: *Left View*

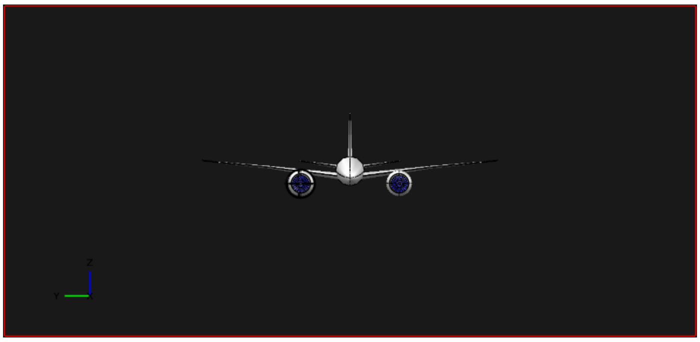

Figure 9: *Front View*

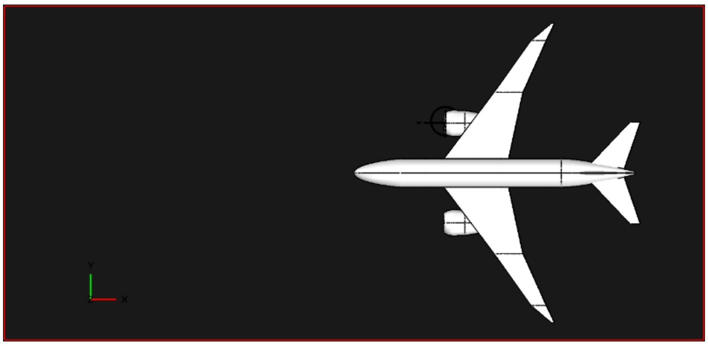

Figure 10: *Top View*

Initial Sizing

The calculated values are compared with that of PIANO values

Mission Segment		Quoted Values [kg]	Calculated Values [kg]	% Error	Remarks
0-1	Warm up, Taxi-out & Take-off	1,115 (1.3 %)	5,781.82 (7.6 %)	+ 418.6 %	Raymer assumes weight ratio of 0.97
1-2	Climb	4,322 (5.2 %)	2,804.18 (3.7 %)	- 35.1 %	Raymer assumes weight ratio of 0.985
2-3	Cruise	73,369 (88.3 %)	63,224.24 (83.4 %)	- 13.8 %	
3-4	Descent	216 (0.3 %)	0.00 (0.0 %)	- 100.0 %	Raymer ignores fuel consumption in Descent
4-5	Holding	1,642 (2.0 %)	1,399.96 (1.8 %)	- 14.7 %	L/D estimated from the aircraft equilibrium equations for level flight
5-6	Approach & landing	119.30 (0.1 %)	597.59 (0.8 %)	+ 400.9 %	Raymer assumes weight ratio of 0.995
6-7	Diversion	2,286 (2.8 %)	1,998.67 (2.6 %)	- 12.6 %	Using Diversion data
	Mission fuel	83,070	75,806.45	- 8.7 %	
	Reserve fuel	3,912	3,790.32	- 3.1 %	
	Total fuel	86,981	79,596.77	- 8.5 %	
	Design Gross Weight	216,817	192,727.23	- 11.1 %	

Figure 11: *Error Analysis*

Program Cost

The calculated values are compared with that of PIANO values

Airframe Engineering	E	DT&E	13684.7	mil $
		Production	18343.3	mil $
		Cumulative	32028.0	mil $
Development Support	D	DT&E	153.2	mil $
Flight Test Operations	F	DT&E	218.4	mil $
Tooling	T	DT&E	1621.1	mil $
		Production	4771.3	mil $
		Cumulative	6392.4	mil $
Manufacturing Labour	L	DT&E	1424.2	mil $
		Production	38925.0	mil $
		Cumulative	40349.2	mil $
Quality Control	QC	DT&E	108.2	mil $
		Production	2958.3	mil $
		Cumulative	3066.5	mil $
Manufacturing Material and Equipment	M	DT&E	420.1	mil $
		Production	27022.7	mil $
		Cumulative	27022.7	mil $
Engine	P	DT&E	714.8	mil $
		Production	4186.5	mil $
		Cumulative	4901.2	mil $
TOTAL PROGRAM COST				
		DT&E	19036.7	mil $
		Production	100853.1	mil $
		Cumulative	119889.8	mil $

Figure 12: *Program Cost*

Genetic Algorithm

The values of x are taken upto 3 decimal places

1 Ackley Function

Minima : f(x) = 0, x =(0,0,0)
Obtained :f(x) = 6.6995, x=(0.918, -1.665 ,1.436)
Details: Population size = 250
Search Region: (-32,32), (-32,32), (-32,32)
No of iterations:10000
Mutation Rate: 1.5%

2 Buckin Function N.6

Minima : f(x) =0 , x =(-10,1)
Obtained :f(x) =2.376503 , x=(-1.18847,0.014648)
Details: Population size = 150
Search Region: (-8,8), (-16,16)
No of iterations:10000
Mutation Rate: 1.5%

3 Cross In Tray Function

Minima : f(x) = -2.06261, x =(-1.3491,1.3491)
Obtained :f(x) = -2.06246, x=(-1.3662,1.3818)
Details: Population size = 150
Search Region: (-16,16), (-16,16)
No of iterations:5000

Mutation Rate: 2%

4 Drop Wave Function
Minima : f(x) = -1, x =(0,0)
Obtained :f(x) = -0.93619, x=(-0.395,0.339)
Details: Population size = 150 Search Region: (-8,8), (-8,8)
No of iterations:5000
Mutation Rate: 2%

5 Egg Holder Function
Minima : f(x) =-959.6407 , x =(512,404.239)
Obtained :f(x) = -934.94457, x=(484.899,441.131)
Details: Population size = 150
Search Region: (-512,512), (-512,512)
No of iterations:10000
Mutation Rate: 2%

6 Gramacy and Lee Function
Minima : f(x) = − , x =(−)
Obtained :f(x) = -2.2116, x=(0.165039)
Details: Population size = 70
Search Region: (-4,4)
No of iterations:1000
Mutation Rate: 2%

7 Griewank Function
Minima : f(x) =0 , x =(0,0,0)
Obtained :f(x) =5.4818 , x=(115.461,-66.492,53.961)
Details: Population size = 180
Search Region: (-1024,1024), (-1024,1024),(-1024,1024)
No of iterations:10000
Mutation Rate: 1.5%

8 Holder Table Function
Minima : f(x) =-19.2085 , x =(-8.05522,-9.66459)
Obtained :f(x) =-322.8035 , x=(-14.3447,-15.942382812)
Details: Population size = 150
Search Region: (-16,16), (-16,16)
No of iterations:5000
Mutation Rate: 2%
9 Levy Function
Minima : f(x) =0 , x =(1,1,1)
Obtained :f(x) =0.18117 , x=(1.132,0.904,-0.131)
Details: Population size = 180
Search Region: (-16,16), (-16,16), (-16,16)
No of iterations:5000
Mutation Rate: 2%

10 Levy Function N.13
Minima : f(x) =0 , x =(1,1)
Obtained :f(x) =0.15064 , x=(1.338,0.945)
Details: Population size =150
Search Region: (-16,16), (-16,16)
No of iterations:5000
Mutation Rate: 2%

11 Rastrigin Function
Minima : f(x) =0 , x =(0,0,0)
Obtained :f(x) =14.861 , x=(2.007,1.008,-0.762)
Details: Population size = 150
Search Region: (-8,8), (-8,8), (-8,8)
No of iterations:5000
Mutation Rate: 2%

12 Schaffer Function N.2
Minima : f(x) =0 , x =(0,0)
Obtained :f(x) =0.018699 , x=(3.893,1.622)
Details: Population size = 150
Search Region: (-128,128), (-128,128)
No of iterations:8000
Mutation Rate: 2%

13 Schwefel Function
Minima : f(x) =0 , x =(420.9687,420.9687)
Obtained :f(x) =0.56807 , x=(422.373,422.558)
Details: Population size =150
Search Region: (-512,512), (-512,512)
No of iterations:8000
Mutation Rate: 2%