Aircraft Design Report: UCI Jet Transport Prototype

Matthieu Lu
64487307
MAE 159
Professor Liebeck
Spring 2022

Table of Contents

List of Tables

List of Figures

1. Introduction

Aircraft can be designed with a variety of configurations. Depending on the desired performance characteristics and type of mission, configurations can look very different. From massive passenger airliners, gliders, and fighter jets, each has very different handling and performance characteristics from the other, as indicated by their very different appearances.

This report's objective is to design the airplane with the lowest operating costs for an airliner. The primary comparison will be between traditional aluminum structures versus composite structures and finding the optimal combination of sweep and aspect ratio using MATLAB.

Once these optimal parameters have been chosen and justified, the remainder of the report will detail the design process and configurations chosen for the first 3D model of the jet transport. This includes things such as the placement of various components, CG analysis, and interior layout.

2. <u>Design Aspects</u>

The objective of this report is to determine and justify the optimal aircraft design specifications for a subsonic transport aircraft. The optimal design will be based on the lowest Direct Operating Cost (DOC) possible, based on a combination of many design and extraneous factors. The base-level design requirements of this aircraft are as follows:

Number of Passengers (PAX)	200
Weight of Cargo	4000 lbs
Maximum Payload	52000 lbs
Range	4000 nautical miles
Takeoff Field Length	6000 ft
Landing Approach Speed	135 kn
Cruise Mach Number	0.82
Initial Cruise Altitude	35,000 ft

<u>Table 1:</u> Design Criteria

Aspects of aircraft design that are subject to the following analysis are as follows:

Structure Material	Aluminum, Composites, or Hybrid
Airfoil Shape	Conventional or Supercritical
Wing Aspect Ratio	6 to 14
Sweep	15 to 38 degrees
Engine Quantity, Mounting, and Type	2, 3, or 4 Engine Wing or Fuselage Mounting JT9D Advanced, JT9D, or JT8D
Interior Layout	Aisles, PAX Abreast, etc.
Risk	

<u>Table 2:</u> Modifiable Parameters

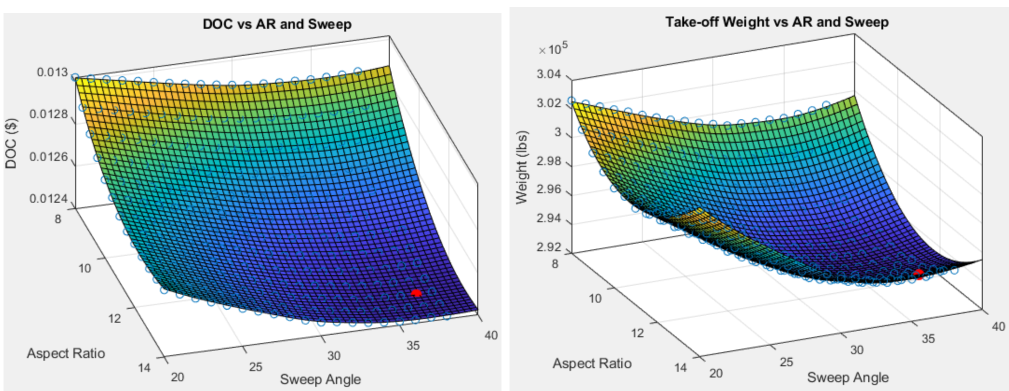
The goal of adjusting these aircraft design aspects, and of this overall report, is to identify, analyze, and select the aircraft arrangement with the lowest DOC and the most appropriate risk factor for a company looking to manufacture and sell aircraft. These justifications will be made with supporting calculations and figures, generated from both hand-written solutions, MATLAB code, and experimentally generated data.

3. Design Analysis

For the following section, the default specifications for a plot shown, unless otherwise stated/calculated for, are: AR = 8, Sweep = 35, Taper Ratio = 0.35, Supercritical Airfoil, Advanced JT9D, 2 Engine, Wing Mounted, and All-Composite, and domestic flight.

The code used to generate the plots functions primarily by generating an array of all possible sweep and aspect ratio combinations and then calculating the DOC and takeoff weight for each. The resulting plot is a 3D plot, as seen in Figures A & B. These 3D plots generated are the basis of all plots seen in the following section.

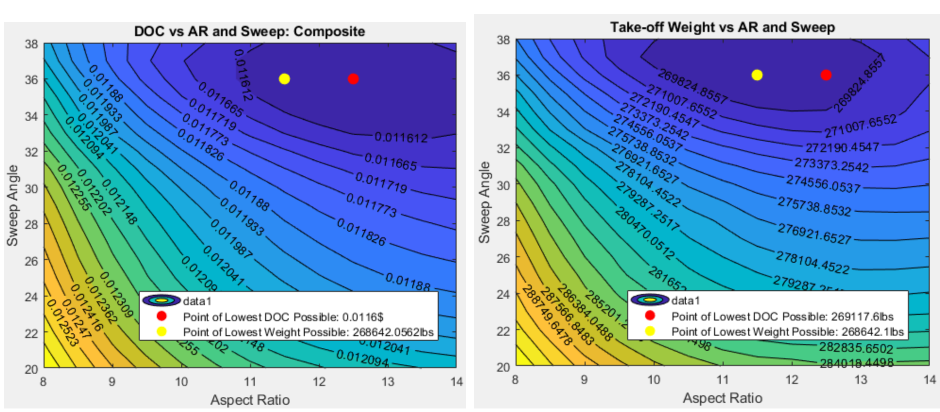
The primary focus of comparison will be between all-aluminum, composite, or a hybrid of the two technologies for the primary aerodynamic and structural components of this aircraft, and can be found in the final section of this portion of the report.



Figures A & B: An example of Generated 3D Plots

a) Overall Weight versus DOC

Weight typically correlates with DOC, though it isn't exact, typically varying within 1 aspect ratio. For this reason, optimization will be based on DOC, which is the value that directly correlates with operational costs, and is what most airlines will be focused on. Notice the offset between the minimum weight and minimum DOC points in Figures 1 and 2.



Figures 1 & 2: Correlation Between Minimum Weight and Minimum DOC

b) Cabin Configuration

Cabin configuration can be adjusted with passengers abreast and the number of aisles. The primary trend is that as the number of passengers abreast and number of aisles increases, the DOC tends to decrease. However, with decreasing passengers abreast, although the DOC is theoretically lower, the fuselage becomes uncomfortably long and causes design issues down the road.

For this reason, the configuration chosen will be a 1 aisle, 6 abreast set up, as it minimizes the length of the fuselage while also minimizing the DOC.

c) Airfoil Shape

The options for airfoil shape are conventional (NACA) airfoil shapes or supercritical airfoil shapes. Supercritical airfoils help delay shockwave formation, which allows aircraft to travel further into the transonic region without facing the performance losses due to compressibility drag. For a craft cruising at 0.82 Mach, this greatly benefits cruise performance which is reflected in Figure 3.

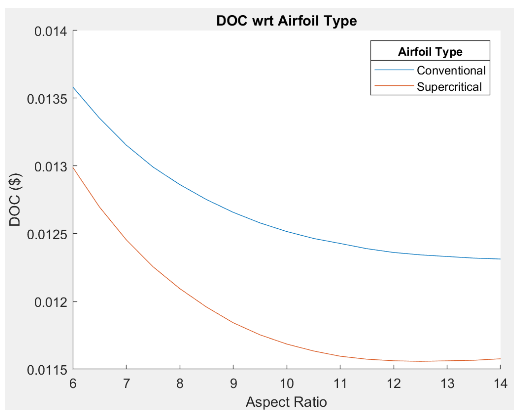
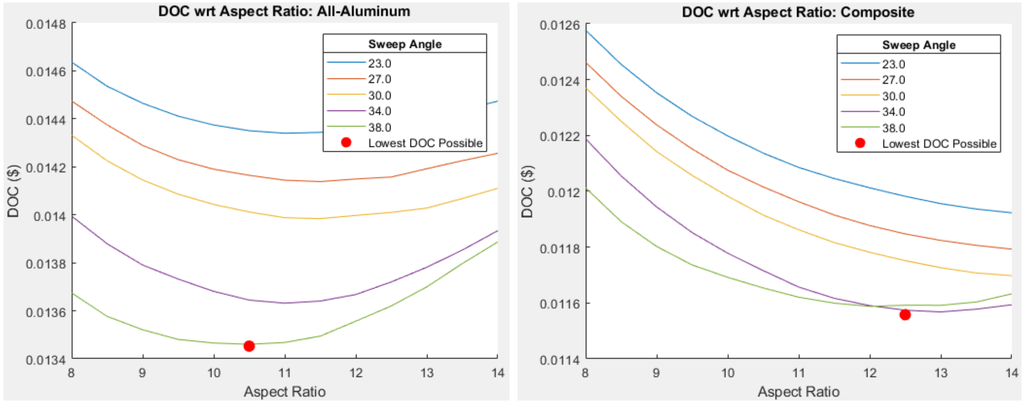


Figure 3: DOC with respect to Airfoil Type

Given the substantially lower DOC with supercritical airfoils, it will be the primary airfoil design.

d) Aspect Ratio

Aspect ratio (AR) affects the performance of a craft by directly affecting the Coefficient of Induced Drag, which can be expressed in this form: $\frac{{C_L}^2}{\pi * AR * e}$. The maximum Coefficient of Lift during both landing and takeoff are also functions of aspect ratio, specifically in this form: $cos(\Lambda)^2 * \frac{t}{c}^2 * AR$. Increasing aspect ratio lowers the coefficient of induced drag and increases the maximum coefficient of lift. However, increasing aspect ratios also affect the weight of the aircraft, specifically the wings, and this directly affects the DOC. Thus, there is an optimal aspect ratio that both maximizes flight performance and keeps the DOC to a minimum.

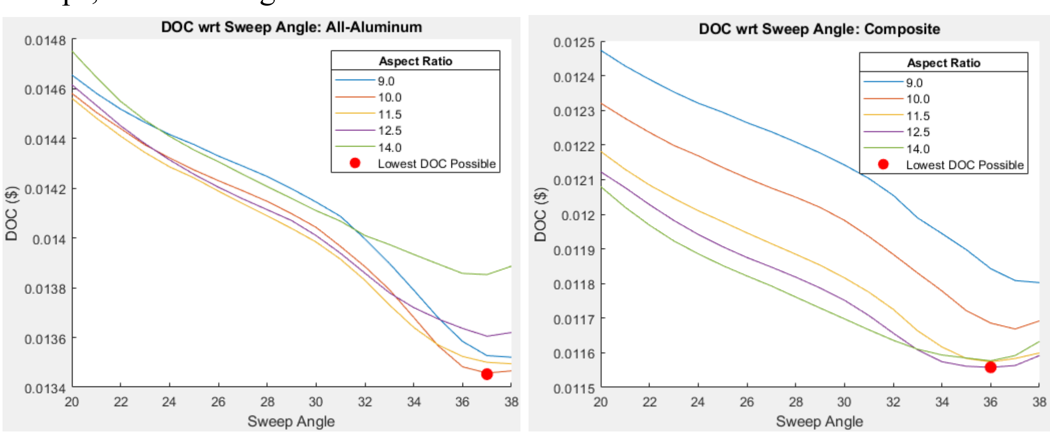


<u>Figures 4 & 5:</u> DOC with respect to Aspect Ratio

For all-aluminum structures, the optimal aspect ratio is calculated to be approximately 10.5, and for all composite structures, the optimal aspect ratio is calculated to be approximately 12.5 according to Figures 4 and 5.

e) Sweep

Sweep affects the performance of an aircraft by affecting drag characteristics and flight stability. Increasing sweep helps delay the onset of transonic drag, which is beneficial for a transport aircraft traveling at 0.82 Mach. This can be seen with effective velocity/Mach, which are functions of sweep: $M_{eff} = M * cos(\Lambda)$. However, up to a certain point, sweep begins to add too much drag, offsetting the benefits in transonic drag delays. That's why in Figures 6 and 7, you can see that at some point with extremely high sweeps, the DOC begins to increase.



<u>Figures 6 & 7:</u> DOC with respect to Sweep Angle

For all-aluminum structures, the optimal sweep is approximately 37. For all composite structures, the optimal sweep is approximately 36.

f) Engine Quantity, Mounting, and Type

The options for engines are the JT8D-9, JT9D-7, and the advanced JT9D. Each engine has its own performance characteristics, such as varying thrust levels at different altitudes, specific fuel consumptions (SFC), and maintenance costs. Varying the number of engines will also affect the SFC for takeoff and cruise.

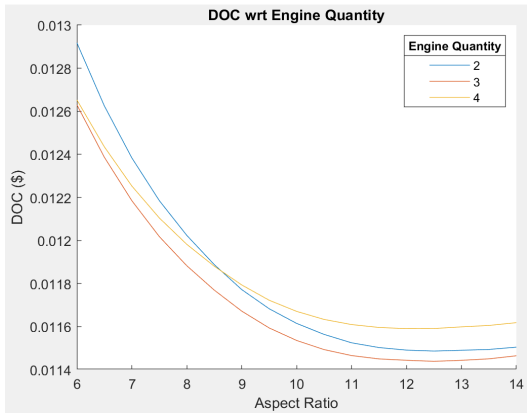
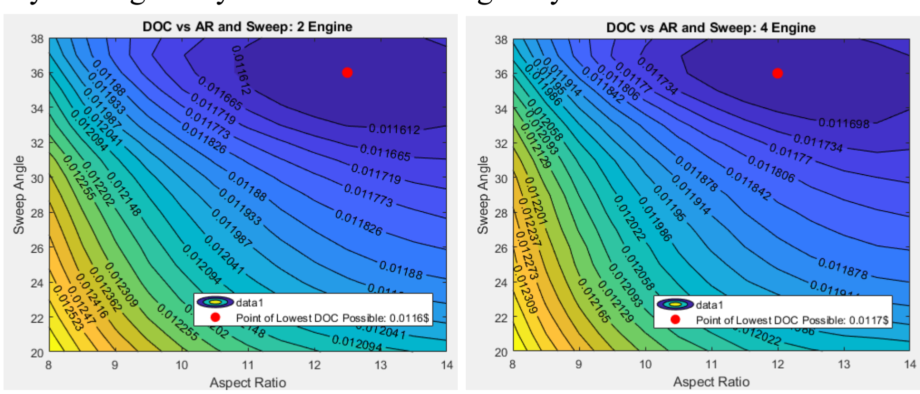


Figure 8: DOC with respect to Engine Quantity for a Given AR/Sweep

For the given sweep and a range of AR, Figure 8 depicts that, theoretically a 3 engine configuration is optimal.
However, when looking at all combinations of AR and sweep in Figures 9 and 10, typically a 2 engine layout results in a marginally lower DOC.



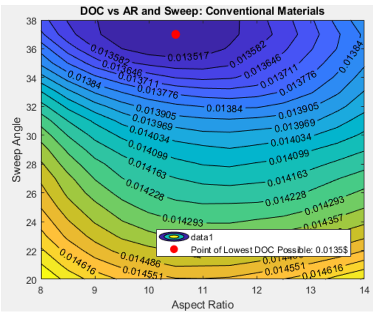
Figures 9 & 10: Minimum DOC with respect to Engine Quantity over All AR/Sweep Configurations

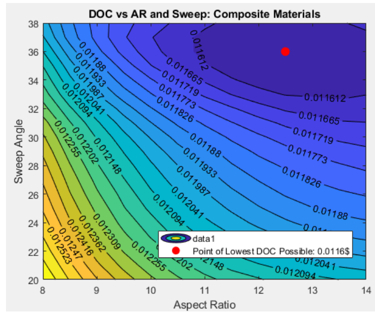
Thus 2 engines will be the selected configuration. 2 engines also add less risk for malfunction, as well as lowered maintenance costs overall, adding to the benefit of choosing this configuration. When choosing an engine, advanced JT9D engines are optimal, as they have the lowest SFC while also having the highest thrust, indicating better efficiency.

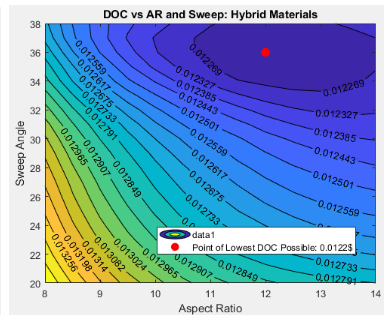
g) Structure Material

The options of structure material are aluminum, composites, or a hybrid of both. Structure material affects DOC by changing the plane's weight, with a lower weight normally desired as it lowers the thrust needed to take off and cruise.

Material is adjusted for when calculating the weight of components, where every component could be scaled down or up depending on the technology used. For hybrid structures, the fuselage will remain aluminum, and the wings/control surfaces will be composites. The configuration with the lowest DOC and risk will be chosen.







Figures 11, 12, & 13: DOC with respect to Structure Material over All AR/Sweep Configurations

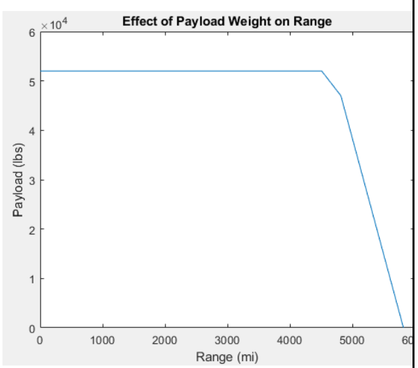
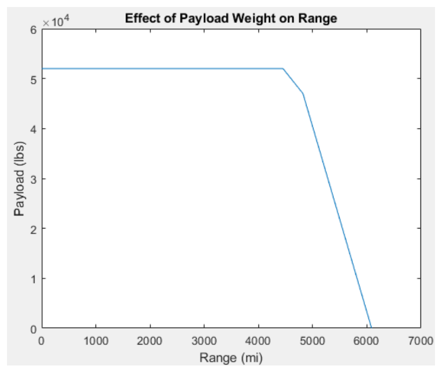
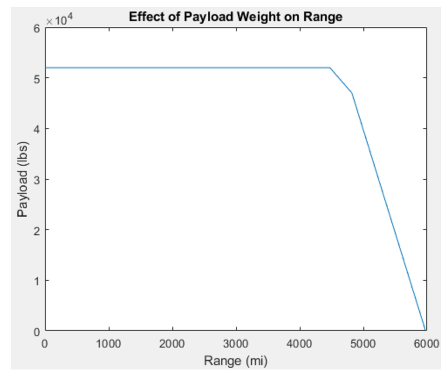
Given that the all-composite structure appears to have the lowest DOC, normally it would be selected for. However, there are currently issues regarding the reliability of manufacturing and maintenance of such full composite structures that indicate a hybrid structure would be the best compromise between the DOC of composites and the reliability of aluminum structures.

This can be best shown with the recent grounding of many Qatar Airways Airbus A350 jets due to the composite fuselages "degrading at an accelerated rate". Out of their fleet of 53 A350s, 22 are now grounded. This has led to large revenue losses for Qatar Airways, and also a hefty $600 million lawsuit for Airbus. For this reason, an all-composite structure was not selected, and instead, only the wings and tail assemblies were made of composites. As the technology improves, perhaps these issues regarding large composite assemblies will be addressed, but with the current state of manufacturing, the risk is not worth the marginal decrease in DOC.

Thus, a hybrid structure with an aluminum fuselage and all other composites will be used.

4. Summary of Analysis Results

Category	All-Aluminum	All-Composite	Hybrid
Optimal DOC	$0.0135/(PAX*mile)	$0.0116/(PAX*mile)	$0.0122/(PAX*mile)
Takeoff Weight	324,690 lbs	269,000 lbs	288,610 lbs
Wing			
Type	Supercritical	Supercritical	Supercritical
Area (ft^2)	2,046	1,686	1,821
Span (ft)	168	158	165
AR	10.5	12.5	12
Sweep	37	36	36
t/c	0.136	0.136	0.136
Taper Ratio	0.35	0.35	0.35
Fuselage			
Diameter (ft)	13.1	13.1	13.1
Length	158.5	158.5	158.5
Aisles	1	1	1
Abreast	6	6	6
Engines			
Number	2	2	2
Type	Advanced JT9D	Advanced JT9D	Advanced JT9D
Thrust (lbs)	82,465	68,326	72,790
Weight			
Payload (lbs)	47,000	47,000	47,000

Fuel (lbs)	90,829	77,447	81,619
Operation			
Type of Flight	Domestic	Domestic	Domestic
Flight Crew	2	2	2
Stewards	4	4	4
Passengers	200	200	200
Range Chart			
Range Chart (Figures 14, 15, & 16)			

<u>Table 3:</u> Final Configurations and Results for 3 Planes

5. Conclusion of Analysis

The final configuration that will be chosen will be the optimal hybrid aircraft found in the Summary section.

This conclusion takes into consideration all currently available information about the reliability of currently available components.

With the current issues with manufacturing and degradation of fully composite aircraft, it would be wise to avoid such an aircraft when considering that the craft is meant to carry many passengers domestically constantly. Having reliability issues is not optimal to the airliner nor the manufacturer when it comes to revenues and profits, and thus the design will limit the usage of composites to the wings and empennage where issues have not grounded any existing composite aircraft yet.

With regards to the engines, advanced JT9D engines are optimal. Because they have a lower SFC than both JT9D and JT8Ds, they result in lower DOCs. Because they're also the most modern and up-to-date, they are the least likely to malfunction or fault, adding to the reliability of the craft. By limiting the number of engines to only 2 as well, the risk of malfunctions or faults further decreases, as well as lowering maintenance complexity.

Overall, the selected specifications ought to balance the best of modern technology's performance and their risks in order to bring the aircraft to the lowest DOC possible to make it a viable competitor to other aircraft vying for domestic superiority with airliners.

6. Configuration Description

With optimal overall design aspects selected for the aircraft, the next sections will detail the final 3D configurations of all of the aircraft's components and will be supplemented with initial design drawings.

a) Wing and Tails

For the wings, all design aspects can be calculated using the MAC (153.3 in), y position of the MAC (394.2 in), taper ratio (0.5), aspect ratio (12), and sweep (36 degrees). A yehudi is added in order to add space for the stowaway area for the landing gear.

The fuel tank has a length of 850 inches, a base width of 118 inches, and a tip width of 62 inches. This sits between the fore and aft spars of the wing at 0.2 chord and 0.8 chord. With these dimensions, it provides 1,455,000 cubic inches of fuel, which is slightly more than the calculated required fuel volume/weight.

For the horizontal tail, a volume coefficient of 1.25 is selected, as it sits within the range for jet transports. The sweep of the horizontal tail will be the same as the one for the wings because at such a high sweep, further increasing sweep will have negligible performance gains at operating conditions at the cost of decreased performance for subsonic flight. The tail arm is 1007 inches.

For the vertical tail, a volume coefficient of 0.079 is selected as it sits within the range for jet transports. The sweep will be the same as the horizontal tail and wings as well.

b) Fuselage and Exterior Configuration

The fuselage is 1882 inches long. The nose section is 235.8 inches. The tail section is 294 inches. The diameter of the main compartment is 157 inches.

The main landing gear is located 27 inches behind the CG of the aircraft and has 2 sets of 4 56x16 wheels, each designed to support 45,000 lbs. The nose gear is located 679 inches in front of the CG and has 2 40x14 tires that each support 25,000 lbs. These allow the aircraft to support its entire load on just the main landing gears. The landing gears extend to 133 inches below the fuselage, fold back into the fuselage completely, and provide a 12.5-degree tip-back angle.

There are 5 cargo LD-W cargo containers located on board, allowing for about 400 cubic feet of cargo to be stored. 2 are forward of the plane's CG, and 3 are aft. This distribution helps push the CG of the cargo back.

c) CG Design

W_takeoff	288610	
Component	Coefficient	Weight
Wing	0.0075	25126.5786
Fuselage	1530	29367.3395
Landing Gear	0.04	11544.4
Nacelle + Pylon	0.0224	6464.864
Tails	0.0013	375.193
Power Plant	0.155	44734.55
Fixed Equipment	0.035	10101.35
Fixed Equipment		28200
Fuel	0.2828	81618.908
Passenger		43000
Cargo		4000
Total		284533.1831
(to a reference pt 120in in front of nose)	120	

Configurations	Cargo	Fuel	PAX
Design			
Empty			
Ferry			
Landing			

	Design			Empty			Ferry			Landing		
Component CG	Weight (lbs)	Length (in)	Moment	Weight (lbs)	Length (in)	Moment	Weight (lbs)	Length (in)	Moment	Weight (lbs)	Length (in)	Moment
1/4 MAC (Airplane Desired CG)		1071										
Wing	25126.5786	1109.324798	27873537	25126.5786	1109.324798	27873537	25126.5786	1071	26910566	25126.5786	1109.324798	27873537
Fuselage	29367.3395	1071	31452421	29367.3395	1071	31452421	29367.3395	1071	31452421	29367.3395	1071	31452421
Landing Gear	11544.4	1086.329919	12541027	11544.4	1086.329919	12541027	11544.4	1086.329919	12541027	11544.4	1086.329919	12541027
Nacelle + Pylon	6464.864	963.2997978	6227602	6464.864	963.2997978	6227602	6464.864	963.2997978	6227602	6464.864	963.2997978	6227602
Tails	375.193	1796.390019	673993	375.193	1796.390019	673993	375.193	1796.390019	673993	375.193	1796.390019	673993
Power Plant	44734.55	963.2997978	43092783	44734.55	963.2997978	43092783	44734.55	963.2997978	43092783	44734.55	963.2997978	43092783
Fixed Equipment	10101.35	1191	12030708	10101.35	1191	12030708	10101.35	1191	12030708	10101.35	1191	12030708
Fixed Equipment	28200	1191	33586200	28200	1191	33586200	28200	1191	33586200	28200	1191	33586200
Fuel	81618.908	1027.810789	83888794	0	1027.810789	0	81618.908	1027.810789	83888794	0	1027.810789	0
Passenger	43000	1071	46053000	0	1071	0	0	1071	0	43000	1071	46053000
Cargo	4000	1071	4284000	0	1071	0	0	1071	0	4000	1071	4284000
Sum	284533.1831		3.02E+08	155914.2751		1.67E+08	237533.1831		2.5E+08	202914.2751		2.18E+08
	Delta 1/4 MAC		-10.6524									

CG Design	1060.348
CG Empty	1074.169
CG Ferry	1054.186
CG Landin	1073.435
Forward	1052.604
Aft	1086.33

Table 4: CG Design Table

The CG calculations can be seen above, with all 4 configurations (Design, Empty, Ferry, and Landing) included. Please note the lengths are taken from a point 120 inches forward of the nose. The yellow highlighted values have adjusted CG positions in order to move the CG further rearward, resulting in a more aft wing location.

d) Interior Configuration

The interior of this plane is a 2-class layout, as this is a medium-range transport aircraft. This means that some flights will fly for several hours for trans-continental paths, allowing for some passengers to spend extra for better leg room and amenities.

There are 16 first-class seats, found in the most forward passenger compartment. It is in a 1 aisle, 4 abreast configuration with a 40-inch seat pitch.

There are 186 economy seats, found in the aft portion of the hull. It is a 1 aisle, 6 abreast configuration with a 32-inch seat pitch.

There are 6 lavatories, each one measuring 38in x 40in. They are located at the nose, over the wing, and at the tail in pairs.

There are 25 galley carts, each 12in x 34in. They are stored in groups of 4, with 5 of these storage compartments stored by the lavatories.

There is 1 Class A exit located at the nose, primarily used for boarding. There are 2 Class II exits over the wing, and easily accessible in a small resting/standing area between the lavatories and galley. There is 1 Class B exit located at the tail.

e) Selected Aircraft Configuration

Final Detailed Aircraft Configuration	
Hybrid Design	
Wing	
Planform Area (in^2)	3.15e6
Span (in)	1761.8
Aspect Ratio	12
Sweep	36
Taper Ratio	0.5
Root Chord (in)	197
MAC (in)	153.3
Dihedral	5
Horizontal Tail	
Span (in)	519.4
Aspect Ratio	3.5
Sweep	36
Taper Ratio	0.35
Root Chord (in)	220.7
MAC (in)	160.5
Tail Arm (in)	1027.2
Dihedral	5
Vertical Tail	
Span (in)	305
Aspect Ratio	1.6
Sweep	36

Taper Ratio	0.5
Root Chord (in)	502.4
MAC (in)	390.8
Tail Arm (in)	1027.2
Engine/Nacelle Specifications	
Thrust (lbs)	72,790
Inlet Diameter (in)	115
Nacelle Length (in)	292.05
Nacelle + Engine Weight (lbs)	25,600 per unit
Fuel Tank Specifications	
Tank Volume (in^3)	1455024
Landing Gear	
Nose Gear Config	2 Wheels
Nose Tire Size	40in x 14in
Main Gear Config	2x 4 Wheels
Main Gear Tire Size	56in x 16in
Aft CG Angle	18
Tip Back Angle (Lengthwise)	12.51
Tip Back Angle (Spanwise)	47.93
Landing Gear Weight (lbs)	11,544
Cargo Specifications	
Cargo Container	LD-W
Cargo Volume (in^3)	725,760
Interior Layout	
Main Door Type and Dimensions	Type A: 42in x 72in

Emergency Door Type and Dimensions	Type B: 32in x 72in 2x Type II: 20in x 44in
First Class	
Passengers	16
Seat Depth (in)	28
Seat Pitch (in)	40
Aisles	1
# of Galleys	2
# of Lavatories	2
Economy	
Passengers	186
Seat Depth (in)	25
Seat Pitch (in)	32
Aisles	1
# of Galleys	3
# of Lavatories	4

7. Drawings