MAE 159 Midterm Airplane Design Final Report

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June 4th, 2021

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Contents

1 Introduction

This report consists of a study on the cost and performance optimization for two subsoinc commercial transport aircraft with a design range of 7400 nautical miles. One aircraft must meet the design range without any stops and the other aircraft is designed to make one stop in transit. These aircraft will herein be referred to as the non-stop and one-stop aircraft respectively. In this report, the reader will find a summary of the methods used and the data generated from an iterative python script which uses standard, well-defined aircraft design methods to exactly meet the design specifications on each iteration. Various parameters, including the aspect ratio, the airfoil type, the wing sweep angle, and the seating configuration, were systematically varied to determine the optimum design parameters for each aircraft. After optimization of the basic aircraft properties, the aircraft was configured with detailed interior and exterior arrangements. The conclusion of this report provides customer recommendations and a fuel burn analysis.

2 Design Specifications

As mentioned prior, two aircraft with distinct given design requirements, were considered in this design study. Both aircraft are required to carry 225 passengers and complete a 7400 nautical mile journey. The complete set of given design specifications are listed in tables 1 below. For both aircraft, takeoff conditions were assumed to be at sea level on a hot day with an air temperature of $84°F$.

Non-stop Aircraft	
Design Specification:	**Parameter Value:**
Number of Passengers	225
Weight of Cargo	6,000 lbs
Still Air Range	7,400 nmi
Takeoff Field Length	10,500 ft
Landing Approach Speed	140 kts
Fuel Destination Payload	35%
Cruise Mach Number	0.85
Initial Cruise Altitude	35,000 ft

One-stop Aircraft	
Design Specification:	**Parameter Value:**
Number of Passengers	225
Weight of Cargo	3,000 lbs
Still Air Range	3,700 nmi
Takeoff Field Length	6,000 ft
Landing Approach Speed	130 kts
Fuel Destination Payload	0%
Cruise Mach Number	0.80
Initial Cruise Altitude	35,000 ft

Table 1: Given Design Specifications.

3 Design Analysis

The object of this section is to perform an analysis for both aircraft to determine the optimized specifications for the given design parameters. An iterative python script was developed with user-selectable design parameters to make calculations of direct operating cost (DOC), weight, drag, and other aircraft performance characteristics easy, fast, and repeatable.

3.1 Direct Operating Cost versus Aspect Ratio and Wing Sweep Angle

The aspect ratio describes the ratio of the aircraft's wingspan to its mean aerodynamic chord length. A small aspect ratio describes a short and wide wing whereas a larger aspect ratio describes a long and narrow wing planform (1). The wing aspect ratio is an important factor in determining the available lift of the aircraft, the weight of the aircraft, and the induced drag during flight. For a typical jet transport aircraft, Schaufele gives an aspect ratio range of 7.0 to 9.5 (3), as such, this formed the basis for design selection. Aspect ratios in steps of 0.1 were considered from 6.0 to 12.0 during this study. The method for comparison will be the resulting DOC per passenger, per mile. Figure 1 shows the aspect ratio versus the DOC with curves of fixed sweep angle for both the short range and long range aircraft. A total of 1800 discrete aircraft designs were considered. The plots in 1 show every 5 degrees of wing sweep angle from 10 to 40 degrees, along with the optimized wing sweep angle, which varied for both aircraft. These designs also consider two JT9D engines with one aisle, six abreast for the seating configuration.

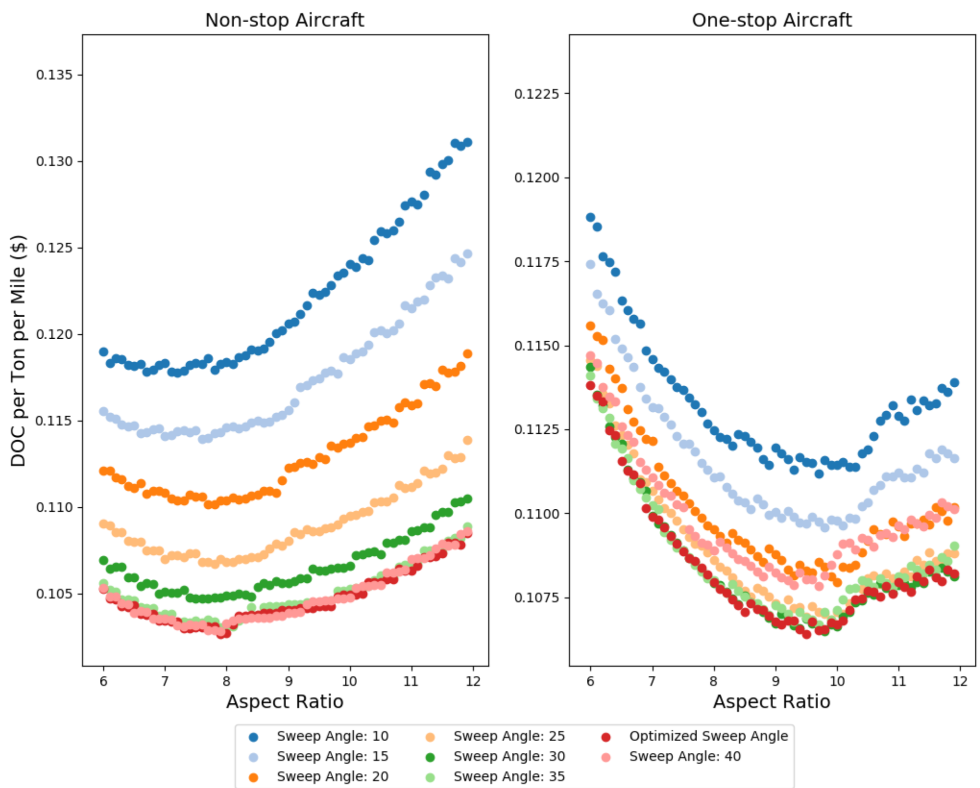

Figure 1: Direct operating cost, per ton, per mile plotted against aspect ratio for the non-stop and one-stop aircraft at different wing sweep angles.

From figure 1, the optimized aspect ratio can be determined by finding the range at which the minimum value occurs. Although 1800 designs were considered, the sweep angle curves are only plotted for every 5 degrees and for the optimum angle, to allow the figure to be more discernable. From this analysis, it is evident that for the non-stop aircraft, the optimized aspect ratio is 7.9 with a wing sweep angle of 37 degrees. For the one-stop aircraft, the optimized aspect ratio is 9.5 with a wing sweep angle of 31 degrees. This corresponds to a direct operating cost, per ton, per mile of $0.1064 and $0.1026 for the one-stop and nonstop aircraft respectively. The rest of the sections within section 3 will be based off of the control values found in this section of the report, using conventional technology and a seating configuration of one aisle and six seats abreast.

3.2 Weight versus Aspect Ratio and Wing Sweep Angle

Now that the most efficient plane in terms of cost to operate has been found, it is of interest to look at the weight of each discrete aircraft design generated in section 3.1. Figure 2 plots the takeoff weight of the aircraft in pounds versus the aspect ratio using fixed lines of sweep angle, using the same plotting scheme as the previous section. The plots in this figure show a much more dramatic divergence from the optimum value than the direct operating cost plots. The minimum weight values occur near the range of aspect ratios for the lowest direct operating cost.

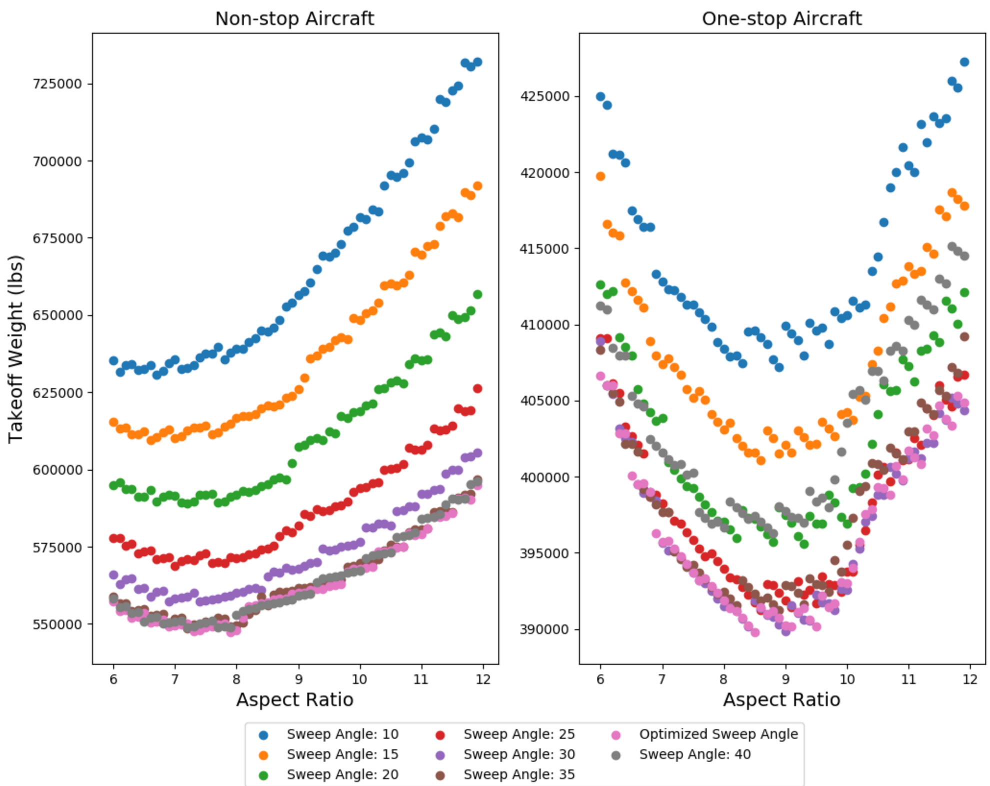

Figure 2: Aircraft takeoff weight plotted against sweep angle for the non-stop and one-stop aircraft at the optimized aspect ratios.

3.3 Advanced Technology

Modern technology and manufacturing advancements has allowed for the use of more exotic design decisions that previous heritage aircraft could not take advantage of. Regarding airfoil selection, the advent of supercritical airfoils has been cited to improve aircraft fuel efficiency and thus lower the direct operating cost of the aircraft. The Boeing 757 and 767, developed during the 1980s were some of the first commercial aircraft to use this technology (2). However, these airfoils types are comprised of more complicated compound curves which presents added complexity in the manufacturing process, driving up initial cost of the aircraft. The initial airframe cost increase was not considered in this study.

The second advanced technology considering during the design process herein was the implementation of composites materials for the airframe. Airframes have typically been composed of various aluminum alloys which presents a strong yet lightweight option. However, recent advancements in materials engineering has allowed for reliable implementation of composite layups, which are lighter and stronger than the aluminum alternative. However, the process to form structures from composites is complicated and if not performed properly, the composite structures may exhibit delamination. Performing the process correctly is expensive and time consuming, thus driving up the initial procurement costs of the aircraft using this technology.

Again, this effect was omitted in this study. Figure 3 plots the takeoff weight of the aircraft with different technologies. Dropping the weight of the aircraft drops the DOC, thus combination with the lowest weight presents the best option.

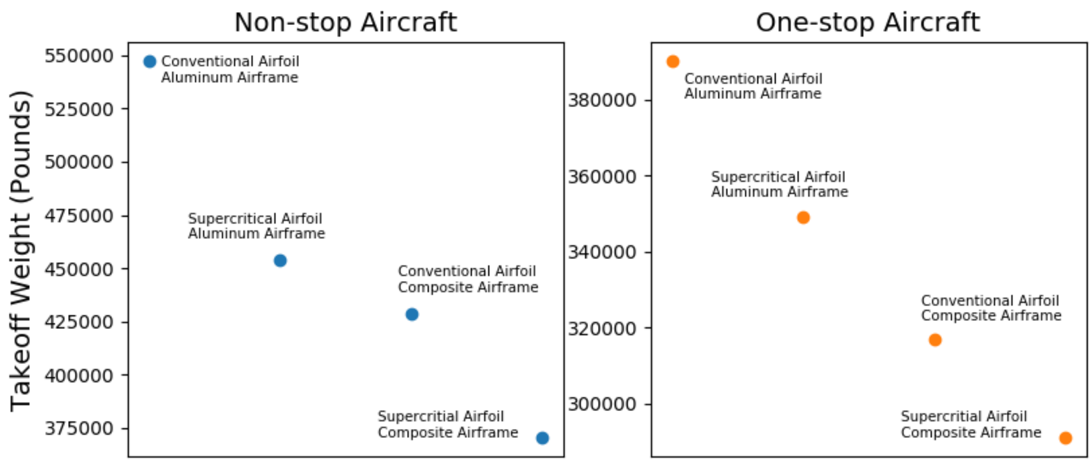

Figure 3: Takeoff Weight for the optimal aircraft configuration using different technologies.

It is clear that both technologies, supercritical airfoils and composite structures, reduce the direct operating cost. Although using a supercritical airfoil may produce a different optimized aspect ratio and sweep angle, these effects were not considered in this study.

3.4 Aircraft Seat Configuration

The aircraft seat configuration can also be varied in the number of aisles that run the length of the fuselage, and the number of seats abreast. In this case, the main metric of comparison will be the direct operating cost. For this study, the optimized aspect ratio and both supercritical airfoil technology and composite technology has been applied to the aircraft design. In the previous sections, the standard configuration of one aisle and six passengers abreast was considered. These results are plotted in figure 4.

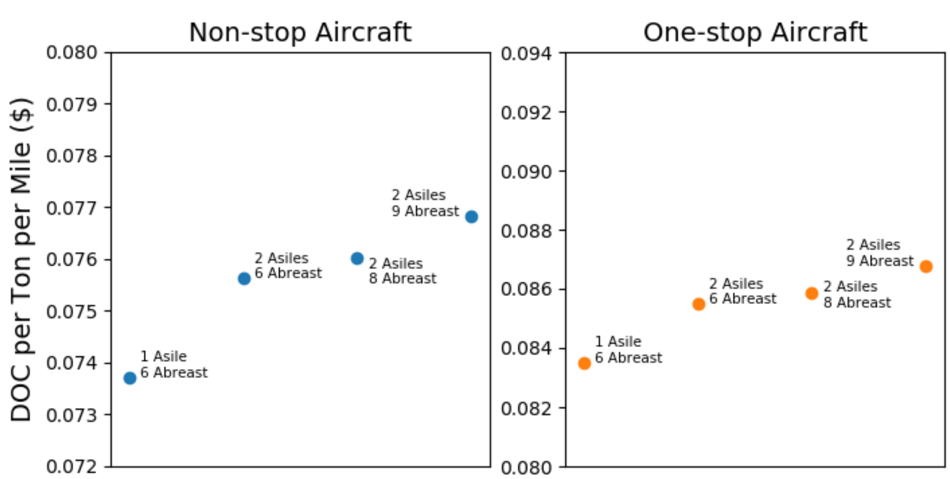

Figure 4: Direct operating cost, per ton, per mile for the optimal aircraft configuration using different seating configurations.

From this study, it is evident that when holding the number of aisles constant, increasing the number of passengers abreast leads to a higher direct operating cost. Additionally, it is clear that the one aisle, six abreast configuration had a lower direct operating cost for both aircraft than any of the two aisle configurations. However, with a two aisle configuration, passengers are able to load and unload from the aircraft more quickly, significantly reducing the down time required when at the airports. For aircraft that may be making shorter flights, such as the one-stop aircraft in this study, it may be more beneficial to use the two-aisle configuration despite the higher direct operating cost found in this study. The increased loading and unloading efficiency was not taken into account in the direct operating cost estimation used in this study.

3.5 Number of Engines

The final design consideration was the number of engines. Figure 5 plots the direct operating cost for a 1 aisle, 6 abreast airplane using the optimized aspect ratio and wing sweep angle, with both advanced technologies applied. It is clear from the plot that increasing the number of engines dropped the direct operating cost; for the nonstop aircraft, the optimum number of engines was three in terms of the direct operating cost. However, the final engine count chosen was two for both aircraft as the effects of initial procurement and maintenance costs, were not considered in the direct operating cost calculation.

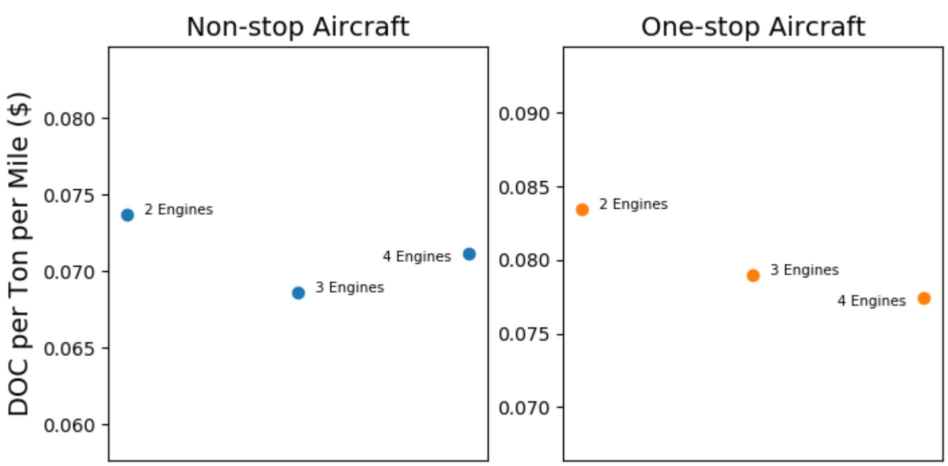

Figure 5: Direct operating cost, per ton, per mile for the optimal aircraft configuration, using 1 aisle and 6 abreast, with different engine count.

3.6 Final Aircraft Design Specifications

The table below lists the final optimized specifications of the non-stop and one-stop aircraft, as derived from the Python script.

Non-stop Aircraft	
Specification:	**Optimized Value:**
Sweep	37 deg
Aspect Ratio	7.9
Airfoil Type	Supercritical
Wing Area	2567 ft^2
Wing Span	142 ft
Number of Aisles	1
Number of Seats Abreast	6
Fuselage Diameter	14.4 ft
Fuselage Length	191 ft
Number of Engines	2
Structure Type	Composite
Takeoff Weight	393945 lbs
Fuel Weight	168068 lbs
DOC	0.078 $/ton/mile

One-stop Aircraft	
Specification:	**Optimized Value:**
Sweep	31 deg
Aspect Ratio	9.5
Airfoil Type	Supercritical
Wing Area	2224 ft^2
Wing Span	145 ft
Number of Aisles	2
Number of Seats Abreast	6
Fuselage Diameter	14.7 ft
Fuselage Length	174 ft
Number of Engines	2
Structure Type	Composite
Takeoff Weight	241715 lbs
Fuel Weight	64047 lbs
DOC	0.068 $/ton/mile

Table 2: Final aircraft sizing specifications.

4 Summary and Conclusion

This section will summarize the results of the non-stop and one-stop aircraft design studies discussed in detail in the previous sections herein. Recommendations shall be made as to which aircraft may suit a given customer's needs the best.

4.1 Payload Range

This section shows the payload range chart. This chart plots the range each optimized aircraft can fly given varying payloads.

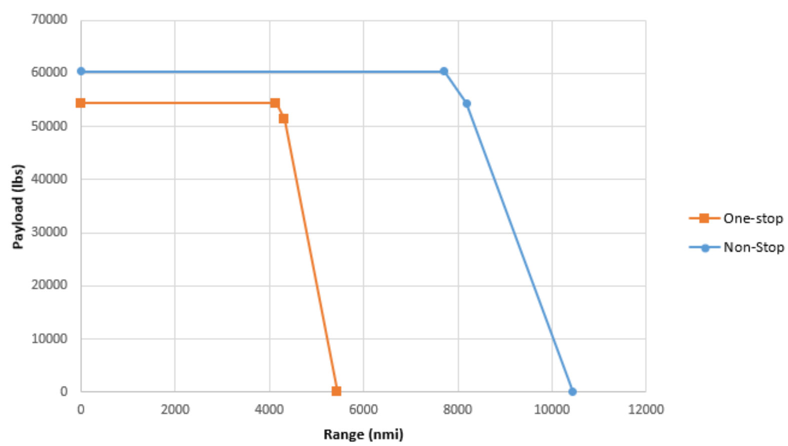

Figure 6: Payload range plotted against the range.

4.2 Aircraft Configuration Descriptions

The previous sections of the report have found the optimized specifications of a short haul and long haul aircraft able to meet a 7400 nautical mile design range, with one stop and non stop flights respectively.

These specifications are listed in table 2 above. This section contains a table with the configuration selections and dimensions such as galley size, seat size, window size, and more important interior and exterior component dimensions. A three-dimensional model of the airplane and corresponding two-dimensional drawings were created using SolidWorks. Detailed drawings are shown in the last section of the report.

Final Detailed Configuration		
Parameter	Non-Stop Aircraft	One-Stop Aircraft
Main Wing		
Sweep (deg)	37	31
Taper Ratio	0.35	0.35
Aspect Ratio	7.9	9.5
Planform Area (ft^2)	2567	2224
Span (ft)	142	145
Root Chord (ft)	26.8	22.7
MAC (ft)	14.5	12.3
Wing Dihedral (deg)	6	6
Horizontal Tail		
Sweep (deg)	42	36
Taper Ratio	0.35	0.35
Aspect Ratio	4	4
Planform Area (ft^2)	395	351
Span (ft)	39.8	37.5
Root Chord (ft)	14.7	13.9
MAC (ft)	8	7.5
Wing Dihedral (deg)	9.6	9
Vertical Tail		
Sweep (deg)	42	36
Taper Ratio	0.5	0.5
Aspect Ratio	1.6	1.6
Planform Area (ft^2)	281	301
Span (ft)	21.2	22
Root Chord (ft)	17.7	18.3
MAC (ft)	5.9	6.1

Final Detailed Configuration		
Parameter	Non-Stop Aircraft	One-Stop Aircraft
Engine/Nacelle		
Inlet Diameter (ft)	9.6	7.6
Length (ft)	23	18.2
Fuel Tank		
Tank Volume (ft^3)	1677	1276
Span Wise/Spar Location (ft)	0.2 / 0.8	0.2 / 0.7
Landing Gear		
Nose Gear Tire Size	44 x 14	40 x 14
Main Gear Tire Size	56 x 16	44 x 16
Aft CG Angle (deg)	21.9	22.5
Tip Back Angle (deg)	19.4	19.4
Cargo		
Cargo Container	LD-W	LD-W
Number of Containers	6	3
Total Cargo Volume (ft^3)	502	251

Final Detailed Configuration		
Parameter	Non-Stop Aircraft	One-Stop Aircraft
Interior		
Passenger Mix (1st class/Business/Economy)	12 / 42 / 171	18 / X / 207
Seat Pitch (in) (1st class/Business/Economy)	60 / 38 / 32	40 / X / 32
Seat Depth (in) (1st class/Business/Economy)	28 / 25 / 25	28 / X / 25
Seat Recline (in) (1st class/Business/Economy)	43 / 36 / 32	36 / X / 32
Bulkhead to Seat Nose (in) (1st class/Business/Economy)	24 / 20 / 18	22 / X / 20
Aisle Width (in) (1st class/Business/Economy)	25 / 20 / 18	10 / X / 15
Number of Galley Carts (1st class/Business/Economy)	4 / 9 / 13	5 / X / 16
Galley Size (in)	15 x 36	15 x 36
Number of Lavs (1st class/Business/Economy)	1 / 1 / 3	1 / X / 4
Lav Size (in)	38 x 40	38 x 40
Entry Door Size (in)	A: 42w x 72h	A: 42w x 72h
Emergency Door Size (in)	I: 24w x 48h	I: 24w x 48h

Figure 7: Configuration Parameters

4.3 Recommendations

The final aircraft design specifications were chosen based on optimizing the minimum direct operating cost, providing appealing options for the customers needs, and creating a safe aircraft. Both aircraft utilized two engines. The one-stop aircraft utilized only a two aisle, six abreast seating configuration while the non-stop aircraft used a one aisle, six abreast seating configuration. The two aisle configuration was chosen for the smaller airplane for its ability to load and unload passengers more quickly, thus decreasing the idle time at airports and increasing the maximum number of flights than may be conducted on a given day, which could reduce the DOC.

The one-stop flight presents the better option over the non-stop flight. Not only does the one-stop flight have a shorter operating cost per ton, per mile; but, the one-stop flight also uses less fuel (when doubled) than the non-stop flight. The fuel burn for the non-stop aircraft was 168,068 pounds while two one-stop flights to achieve the 7,400 nmi range only used 128,094. In total, the one-stop aircraft saves roughly 24% fuel, and thus carbon emissions, compared to the non-stop aircraft. The one-stop flight presents the superior option to the non-stop aircraft in all considerations - cost to the airline, cost to the passenger, and cost to the environment.

5 References

1. Hall, Nancy. (2018). Wing Geometry Definitions. NASA Glenn Research Center.
2. Roeseler, W. G., et al. (2007). Composite Structures: The First 100 Years. 16TH INTERNATIONAL CONFERENCE ON COMPOSITE MATERIALS.
3. Schaufele, R. D. (2007). The Elements of Aircraft Preliminary Design. Santa Ana, CA: ARIES Publication.
4. Shevell, R. S. (1983). Fundamentals of flight. Englewood Cliffs, NJ: Prentice-Hall.

6 Configurations

The following pages show a three-view, layout of passenger arrangement, and a wing-tail diagram for both optimized aircraft. The drawings are presented on size B paper and all dimensions are shown to the nearest tenth of an inch.