Conceptual Design of a Long-haul Low-cost Passenger Jet

Yug V. Desai[1] and Ethan L. Williams[2]
University of South Carolina, Columbia, South Carolina, 29201, USA

There has been a significant increase in long-haul low-cost carriers (LHLC) over the past few years in the commercial aviation industry. LHLCs are carriers that promise low fares for long distance flies. The conceptual aircraft design discussed in this paper had the following param given as a starting point: A payload of 170 passengers, a range of 5100 km, a cruise altitude of 11,500 m, a cruise speed of Mach 0.82, and the take-off and landing distances of 2600 m and 1650 m, respectively. Taking all these parameters, the design was performed in five phases. In the first phase some background research was performed to gain meaningful insight about existing aircraft that address comparable requirements to perform an inside out design of a fuselage and class-I weight estimation was performed. This estimation was then applied to form preliminary and propulsion sizing param. Following this, the wing of the aircraft was designed to generate an appropriate amount of lift in all phases of flight, including the high lift requirements of Takeoff and landing phases. Class-II weight estimation was performed to be able to correctly size the empennage that accounts for center-of-gravity travel range with regards to various payload configurations. The resulting conceptual design, the AeroXpress 115, has a maximum takeoff weight of 101,274 kg. Regulations from Federal Aviation Regulations, part 25, were appropriately considered while designing the aircraft.

I. Nomenclature

LHLC	=	long-haul low-cost
LCC	=	low-cost carrier
FAR	=	federal aviation regulations
MTOW	=	maximum take-off weight
TOP	=	take off parameter
T/W	=	thrust loading
W/S	=	wing loading
T	=	thrust
L	=	lift
D	=	drag
W	=	weight
V	=	velocity
ρ	=	air density
C_L	=	lift coefficient
t/c	=	thickness to chord ratio
MAC	=	mean aerodynamic chord
LE	=	leading edge
TE	=	trailing edge
CG	=	center of gravity
n	=	load factor
X_{LeMAC}	=	leading edge mean aerodynamic chord
C_D	=	drag coefficient

II. Introduction

Cost effectiveness is a huge challenge in the aerospace industry and the companies and airlines use a lot of strategies to lower the cost passenger to increase profit margins. LCCs have had success in short haul flights using their ability to drive demand by lowering prices [1]. There is a call for exploration into extending the same business model to long-haul routes which are greater than six hours long by utilizing the newer aircraft in the family of Airbus A320, and Boeing 737 [2]. These newer aircraft offer in increased range thanks to more efficient engines such as the CFM International LEAP [3]. An aircraft fulfilling the current demands of the market was designed by the two students at the University of South Carolina as part of the aircraft design course. The course starts with a set of requirements, design param, being laid out for the students. The design param for this aircraft are shown in Table 1.

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[1] Undergraduate Student, USC Department of Mechanical Engineering, Student Member
[2] Undergraduate Student, USC Department of Mechanical Engineering, Student Member

Table 1 Aircraft design param.

Requirement type	Value	Unit
Payload	170	Passengers + luggage
Range	5100	km
Cruise altitude	11500	m
Cruise speed	0.82	Mach
Take-off distance	2600	m
Landing distance	1650	m

This aircraft was named AeroXpress 115 after its cruising altitude. Processes developed by Raymer [4], Roskam [5], Corke [6] and Torenbeek [7] were used along with FAR part 25 [8] regulations to design the aircraft. These methods will be used throughout the paper to design the aircraft.

III. Design Process

The fuselage of this aircraft was designed to house 172 passengers with 12 of them being in first class and 156 being in economy class. With a seat pitch of 85 cm (34 in) for economy class and 95 cm (38 in) for the first class, and housing 4 total lavatories and adequate galley area, the fuselage of the aircraft was designed to be 36 m long with a diameter of about 3.5 m.

A. Fuselage Design

Following an inside-out design approach for the fuselage, the outside diameter of the aircraft was determined to be 12ft (approximately 3.6m). 3-3 seating arrangement was used in economy class with 26 rows. And a 2-2 seating arrangement was used in the first class with 4 rows. 4 pairs of exit doors were used for 172 passengers (not including cabin crew) including two pairs of Type I exit doors and 2 pairs of Type-III exit doors.

Bulk storage was used to store cargo inside the belly of the narrow body aircraft. The cargo volume inside of the belly, including the area taken up by the wing box, was determined to be about 50 m^3 (approximately 13200 gallons). Taking away about 10 m^3 (approximately 2600 gallons) for wing box, 40m^3 (approximately 10500 gallons) of cargo space is available. The complete cabin layout is shown in Fig. 1 and the cross-section view of the fuselage is shown in Fig. 2.

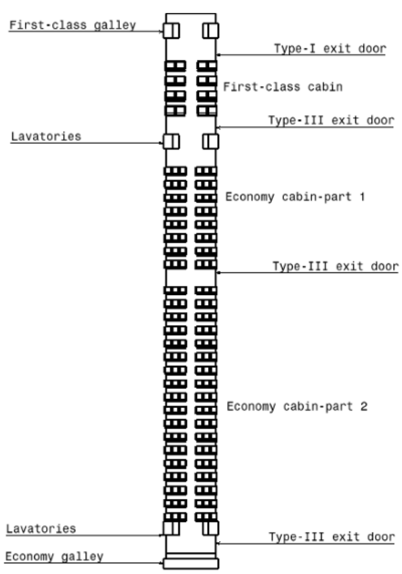

Fig. 1 Cabin layout.

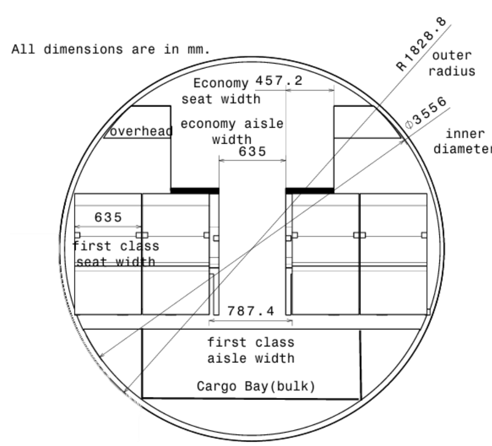

Fig. 2 Fuselage cross-section.

B. Propulsion Sizing and Design

To Determine the MTOW, the total payload of the aircraft including the cargo, carryon items, and the weights of the crew the passengers, was calculated to be 18480 kg. A trendline was plotted on the graph of empty weight vs. MTOW of the reference aircraft that are similar to the AeroXpress 115. The equation of the trendline showing empty weight as a function of MTOW and the MTOW for the given payload weight was determined to be 101274 kg.

Stall sizing was determined by using Eq. (1) at stall velocities at the highest lift coefficients for takeoff, landing, and clean configurations.

$$\frac{W}{S} = \frac{1}{2}\rho V_{stall}^{2} C_{L_{max}} \tag{1}$$

The takeoff parameter was determined to be 5106 N/m^2 for the takeoff length of 2600 m using the relationship between take off length and takeoff param of the reference aircraft. Eq. (2) was used to plot TOP on the T/W vs. W/S graph.

$$TOP = \left(\frac{W}{S}\right)_{TO} \cdot \left(\frac{W}{T}\right)_{TO} \cdot \frac{1}{Cl_{max}} \cdot \frac{1}{\sigma} \tag{2}$$

A fuel ratio of 0.84 was used to plot W/S using Eq. (3).

$$\left(\frac{W}{S}\right)_{TO} = \frac{C_{L_{max}} \cdot \rho \cdot \frac{S_{land}}{0.5915}}{2.f} \tag{3}$$

Climb performance and climb gradient requirement was plotted on the T/W vs. W/S plot using Eq. (4) and Eq. (5).

$$\underbrace{\frac{T}{W}}_{y} = \frac{c}{\sqrt{\underbrace{\frac{W}{S}}_{x}} \cdot \sqrt{\frac{2}{\rho}\frac{1}{\sqrt{3C_{D_0}\pi Ae}}}} + \frac{4C_{D_0}}{\sqrt{3C_{D_0}\pi Ae}} \tag{4}$$

$$\frac{T}{W} = \frac{c}{V} + \frac{C_D}{C_L} \tag{5}$$

The T/W vs W/S can be found in Appendix B. Design point was chosen with a value of T/W of 0.375, along with a wing loading of 3250 N/m^2. The resulting wetted area is then 305.69 m^2 (3290 ft^2), and the required take-off thrust is set at 186.28 kN (42000 lbf) per engine. Eq. (6), Eq. (7) and Eq. (8) were used to scale the size of the CFM International LEAP-1A engine to the thrust requirements of the AeroXpress 115.

$$D = D_{ref} * \left(\frac{T}{T_{ref}}\right)^{\frac{1}{2}} = 1.98 \cdot \left(\frac{186.28}{143.05}\right)^{\frac{1}{2}} = 2.259\,m \tag{6}$$

$$L = L_{ref} * \left(\frac{T}{T_{ref}}\right)^{\frac{2a-1}{2}} = 3.328 \cdot \left(\frac{186.28}{143.05}\right)^{\frac{1}{2}} = 3.798\,m \tag{7}$$

$$W = W_{ref} * \left(\frac{T}{T_{ref}}\right)^{a} = 3153 \cdot \left(\frac{186.28}{143.05}\right)^{\frac{1}{2}} = 3598.02\,kg \tag{8}$$

The size of the resulting engine is shown in Table 2.

Table 2 Engine sizing.

		CFM International LEAP-1A	New Values
T_{ref}	T-O thrust to ISA + 15°C [kN]	143.05	186.28
L_{ref}	Length (flange to flange) [m]	3.328	3.798
D_{ref}	Fan Diameter: [m]	1.98	2.259
W_{ref}	Dry Weight [kg]	3153	3598.02

C. Wing Design and High Lift Devices

Design of the wing that generates enough lift for the AeroXpress 115, and the high lift devices that help generate extra lift in the scenarios with high lift requirements such as takeoff and landing will be discussed in this sub-section.

Clean Wing Design

To initiate the wing design process, the initial step involves creating a clean wing configuration, without considerations related to fuel, landing gear, or flaps. In this phase, the wing is initially treated as if it were infinite, a fundamental step in identifying the optimal airfoil shape. Subsequently, this chosen airfoil profile is extrapolated into the creation of a three-dimensional wing design. In the first step of this process, the total lift required for the aircraft is determined. This is achieved by multiplying the aircraft's weight by a factor of 1.1. This multiplication factor accounts for several factors such as gusts and maneuvering loads. Eq. (9) was used to calculate the lift required, which resulted in 1.04 MN of lift required.

$$1.1 \cdot W_{TO} = 1.1L_{tot} = 1.1 \cdot 949481.5205 = 1044429.672\,N \tag{9}$$

The V_{cruise} and the ρ_{cruise} are established based on cruising conditions, specifically tailored for that phase of flight. The W/S denotes the average weight during the cruise, and the total $C_{L\,des}$ should be increased by 10% for the same reasons that lift was augmented in the Eq. (9), resulting in Eq. (10).

$$C_{L.des} = 1.1 \cdot \frac{2}{\rho V_{cruise}^2}\left\{\frac{1}{2}\left[\left(\frac{W}{S}\right)_{cruise,start} + \left(\frac{W}{S}\right)_{cruise,end}\right]\right\} \tag{10}$$

Eq. (10) results in the design lift coefficient of 0.281. Using the reference aircraft, the average quarter chord sweep angle of the wing was found to be approximately 25 degrees. When we evaluate the start and end conditions separately, we determine that the $C_{L,\,crStart}$ is approximately 0.311, while $C_{L,\,crEnd}$ is approximately 0.252, Currently, our aircraft employs a leading-edge sweep angle of 25 degrees. Thickness to chord ratio was determined to be 0.14 according to the trend shown in Fig. 3.

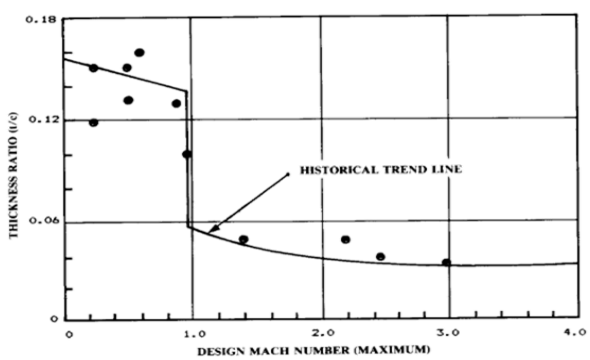

Fig. 3 Design Mach number vs thickness to chord ratio [6].

Important Wing Design param are shown in Table 3.

Table 3 Wing design param.

Parameter	Value	Unit
$W_{cruise,\,start.}$	891456	N
$W_{cruise,\,end}$	722079	N
Sweep Angle λ (LE)	25	°
S	152.85	m^2
ρ @ sea level	1.225	kg/m^3
ρ @ average cruising altitude (11500m)	0.337	kg/m^3
$V_\infty (=V_{cruise})$	247.5	m/s
$C_{L,\,des}$	0.281	none
$C_{l,\,des}$	0.342	none
t/c	0.14	none

From the wing loading in the previous section, the wing surface area can be calculated to be 152.85 m^2. With an aspect ratio of 9.75, this results in a wingspan of 38.60 m, meaning each wing from root to tip is 19.3 m. With a root chord of 6.75 m Eq. (11) can be used to calculate the taper ratio of 0.173 m.

$$A = \frac{2b}{c_R(1+\lambda)} \quad or \quad \lambda = \frac{2b}{c_R A} - 1 \tag{11}$$

This results in MAC of 4.62 m with it being location 7.38 m away from the root. According to these param shown in Table 3, the airfoil to be used for the wing was chosen to be NACA 64-314. Characteristics of the chosen airfoil shown are shown in Table 4.

Table 4 Airfoil characteristics.

Chord location of the minimum pressure	40%
Design Lift coefficient	~ 0.3
Maximum thickness	14%
Mean Line parameter	~ 1

High Lift Devices

To account for high lift coefficient requirements during takeoff and landing flaps and slates need to be added to the existing clean wing, param of flaps are shown in Table 5.

Table 5 High lift device param.

Flaps/Slats	$\Delta(C_L)_{max}$ when fully deployed	Typical Angles Deflection [Deg]		Position in chord length(x/c)	c_f/c
		Takeoff	Landing		
Flaps (TE)	1.6c'/c	50	20	0.7	0.30
Slats (LE)	0.4c'/c	40	20	0.15	0.15

After adding the high lift devices, the lift coefficient vs. angle attack graph for various phases is shown in Fig. 4.

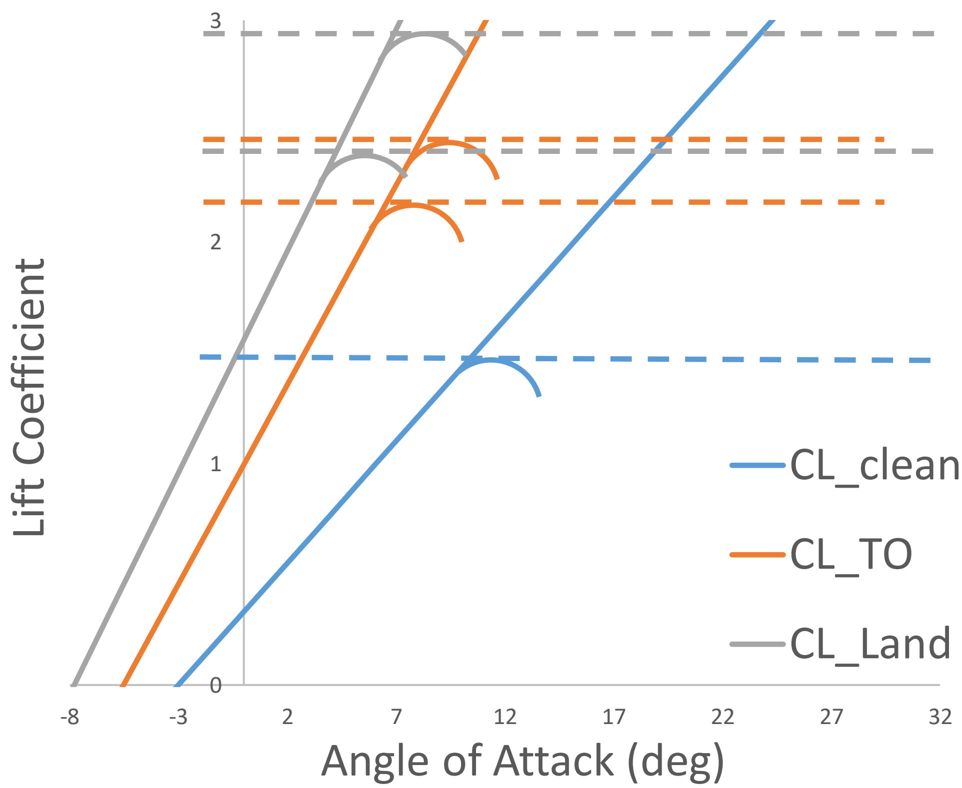

Fig. 4 Lift coefficient vs. angle of attack.

Fuel Storage

Wings will also be used for fuel storage as they have capacity to hold 11,000 kg of fuel in each wing with 11,000 kg fuel capacity inboard to yield total fuel storage capacity of 33,000 kg, enough for mission fuel requirement.

D. Weight and balance

Balancing an aircraft is necessary for a stable flight. Things to consider for a well-balanced aircraft are tailplane geometry, maneuver and gust loading, and CG estimation to yield the loading diagram (potato plot) according to various kinds of loading patterns of an aircraft.

Tailplane Design

The tailplane of the aircraft was designed in a similar fashion to the wings using V-bar method using the surface area references provide by Roskam [5]. Param of vertical and horizontal tail can be found in Table 6.

Table 6 Vertical and horizontal tail param.

Parameter	Vertical Tail	Horizontal Tail
Taper Ratio	0.3	0.4
Aspect Ratio	1.8	5
Sweep Angle (0.25c)	35-45 degrees (40)	10 Higher than Wing (31.5)

Maneuver Loading

The loading during maneuvers is specified in the Airworthiness certification specifications. For different flight conditions different requirements are set. According to the airworthiness regulations, this aircraft, a transport aircraft, falls under the FAR-25 regulations [6]. According to FAR-25, The positive limit maneuvering load factor n for any speed up to Vn may not be less than 2.1 + 24,000/ (W + 10,000) except that n may not be less than 2.5 and need not be greater than 3.8—where W is the design maximum takeoff weight. For this aircraft with a high maximum takeoff weight, the positive maneuvering load factor is determined to be 2.5. The negative limit maneuvering load factor may not be less than −1.0 at speeds up to V_C and must vary linearly with speed from the value at V_C to zero at V. This means that the maximum positive and negative load factors for the aircraft are 2.5 and -1.0 respectively.

Gust Loading

The gust at 3 velocities was evaluated: the speed at which highest lift and maximum angle of attack occurs (V_B), the V_C and the dive speed V_D The corresponding gust speeds vary with the condition and with altitude. The maximum load factor due to gust is then given by equation. The value of 1 represents the mean load factor. It is assumed that the aircraft has this load factor of one before the gust occurs. $n_{peak}= 1+\Delta n$. The value of Δn is the incremental load factor and can be obtained by Eq. (12)

$$\Delta n = \frac{\rho V C_{L_\alpha} u}{2(\frac{W}{S})} \quad (12)$$

The maneuver and gust loading diagram are shown in Fig. 5.

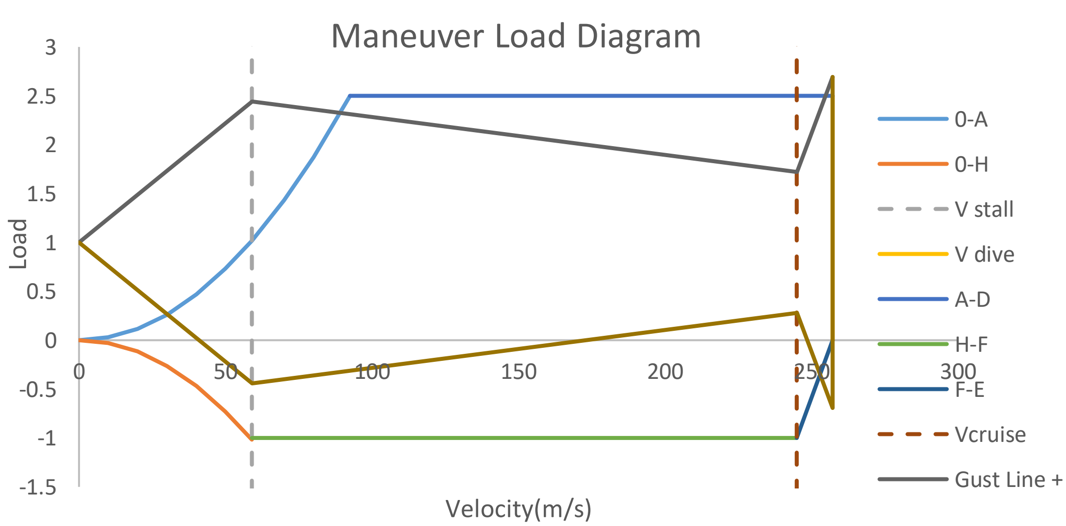

Fig. 5 Maneuver and gust loading diagram.

Weight Estimation

To determine the CG of the aircraft, its components are categorized into two groups: the fuselage and the wing group. The following tables and graphs display this breakdown, where the fuselage group's weight includes the airframe services, the fuselage landing gear, the fuselage itself, and the tail. The distance from these components to the front of the aircraft is also noted, as this is essential for locating the CG. Using the simplification that the aircraft is symmetric, and that all elements are on the longitudinal axis, together with the previously presented equation, gives us that the CG of the Fuselage Body Group is 22.14 m from the nose.

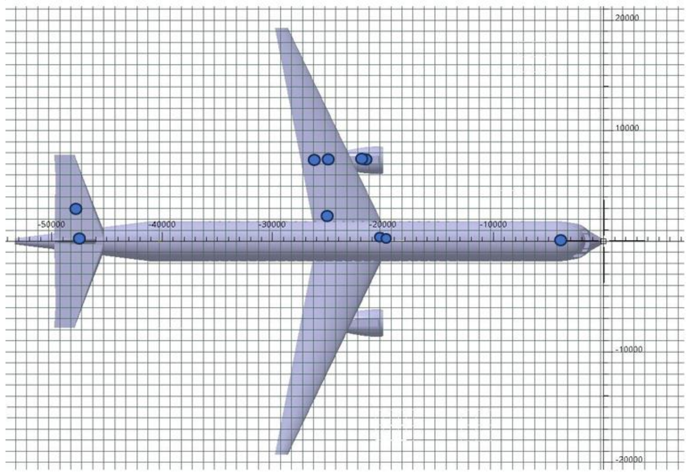

Fig. 6 Component wise CG breakdown.

As a visual aid, the body group is represented in Fig. 6, with the most contributing points on the aircraft. Moving on to the second group, known as the wing group, it comprises the wing structure, propulsion, nacelles, and main landing gear. The collective mass of the wing group amounts to 28,144 kg, with detailed breakdowns of the individual components of the fuselage wing group provided in Table 7.

Table 7 Component wise CG locations.

Fuselage Group	**Weight [kg]**	**X_{front}[m]**
Fuselage	6,857	20
Airframe Services	14,569	20
Horizontal Tail	1,421	47
Vertical Tail	873	46
Nose Landing Gear	570	4
Wing Group	**Weight [kg]**	**X_{front}[m]**
Wing (6)	11,798	25
Propulsion (7)	9,103	22
Main Landing Gear (8)	3,405	26
Nacelle (9)	2,210	21.5
Surface Controls (10)	1,437	26

The Center of Gravity of the entire aircraft is determined to be situated at 23.7 m from the nose of the aircraft. Further examination from the drawings reveals that the X_{LeMAC} measures 22.5 m from the front of the nose. Subsequently, the ratio between the leading edge of the MAC and the length of the nose. Subsequently, the ratio between the leading edge of the MAC and the length of the fuselage $\frac{X_{LeMAC}}{L_{fuse}}$ computes to 0.61. Expressing the CG position in terms of X_{LeMAC}, the CG for the empty weight is positioned with 26.58% MAC beyond the X_{LeMAC}, or alternatively, at 26.58% of X_{LeMAC} /MAC. This, with the previously derived empty weight of 52,723 kg through the Class II method, serves as the initial reference point for the Loading Diagram.

Loading Diagram

In this section, the shift in the aircraft's center of gravity resulting from the loading of passengers (including pilots), luggage, and fuel will be analyzed. Pilots are accounted for within the passenger count. The sequence of loading contributions includes bulk cargo, window-seat passengers, middle-seat passengers, aisle seat passengers, and fueling from the wing tanks.

Starting from the previously established baseline, weight per row of the aircraft: 180 kg for two passengers and cargo for two bays in bulk, will be incrementally added. For simplicity and comprehensive overview, the aircraft will be loaded in its full economy configuration, accommodating 170 passengers, and holding bulk cargo in two bays (front and back). In a similar method as the one described above for each fuselage or wing element, the weight is added, and the new CG position is calculated iteratively for the different steps in the loading process. Minimum and maximum locations of the CG are shown in Fig. 7.

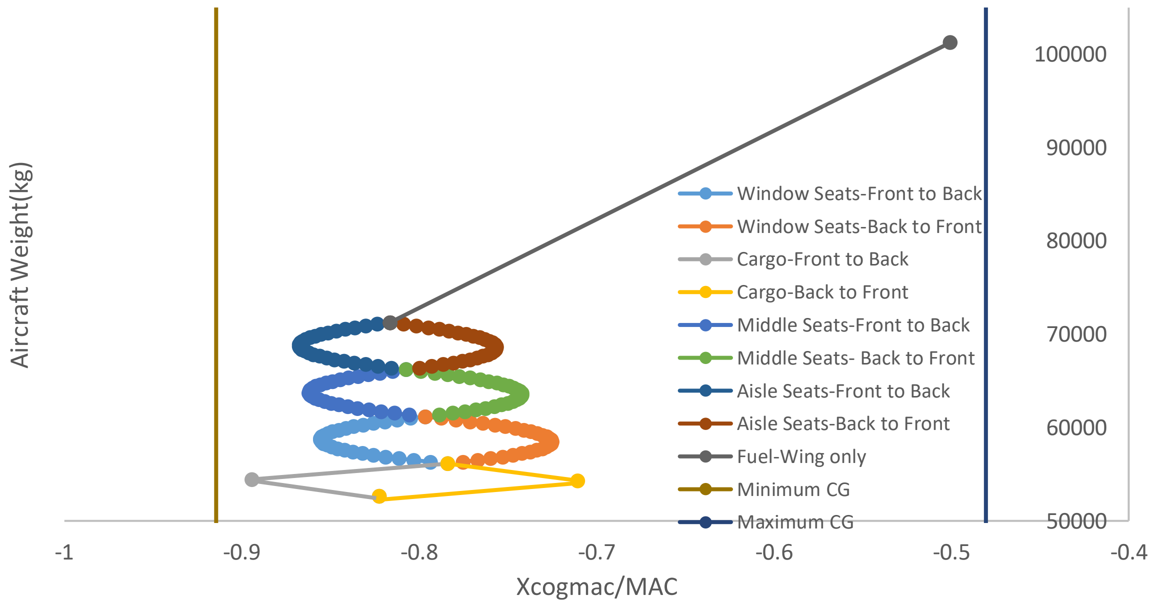

Fig. 7 The loading diagram.

IV. Component-wise Drag Estimation

Drag contribution from each component will be discussed in this section. All the drag contributions will be combined and plotted to generate the drag polar of the aircraft. Component wise zero lift drags are shown in

Component	C_{D0}
Wing	0.01886
Fuselage	0.02360
Horizontal Tail	0.01324
Vertical Tail	0.01236
Nacelles	0.00234
Pylons	0.00198
Windshield	0.02093
Trim	0.00402

Table 8. Drag Polar of the total and component-wise drag incrementally added is shown in Fig. 8.

Component	C_{D0}
Wing	0.01886
Fuselage	0.02360
Horizontal Tail	0.01324
Vertical Tail	0.01236
Nacelles	0.00234
Pylons	0.00198
Windshield	0.02093
Trim	0.00402

Table 8 Component wise zero lift drag.

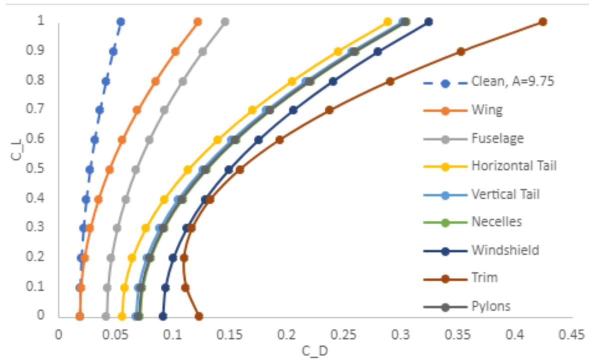

Fig. 8 Component-wise drag polar.

V. Conclusion

In conclusion, the conceptual design of the AeroXpress 115 showcases a systematic and detailed approach to meet the demands of the growing long-haul low-cost carrier segment. The thoughtful consideration given to fuselage configuration, propulsion sizing, wing design, weight distribution, and regulatory adherence highlights a dedication to safety, efficiency, and economic feasibility. Featuring elements like the CFM International LEAP-1A engine and the NACAS 64-314 airfoil, alongside the integration of high lift devices and innovative fuel storage solutions, the AeroXpress 115 emerges as a competitive player in the evolving aviation landscape. This conceptual design lays a robust foundation for subsequent refinement, testing, and the eventual realization of the AeroXpress 115, making significant contributions to the advancement of long-haul low-cost air travel.

Appendix A Technical Drawings (Dimensions in mm)

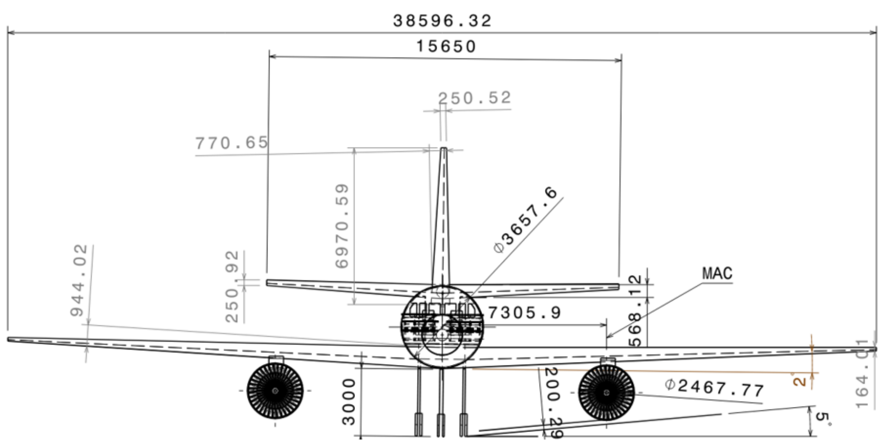

Fig. 9 Front View

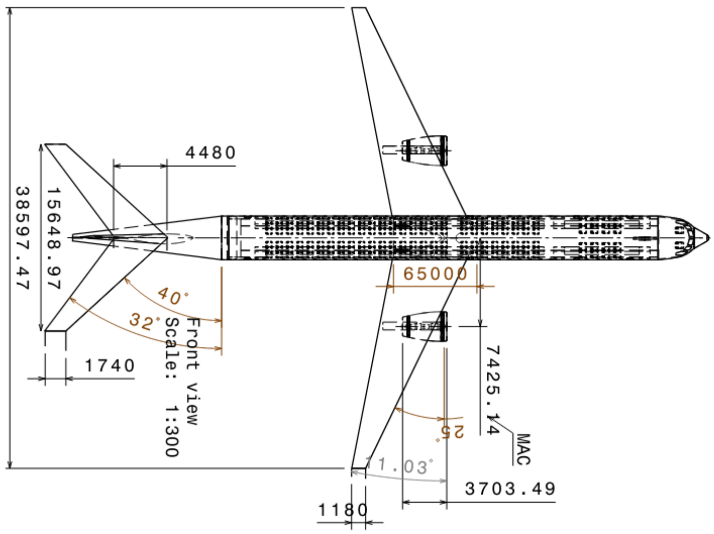

Fig. 10 Top View

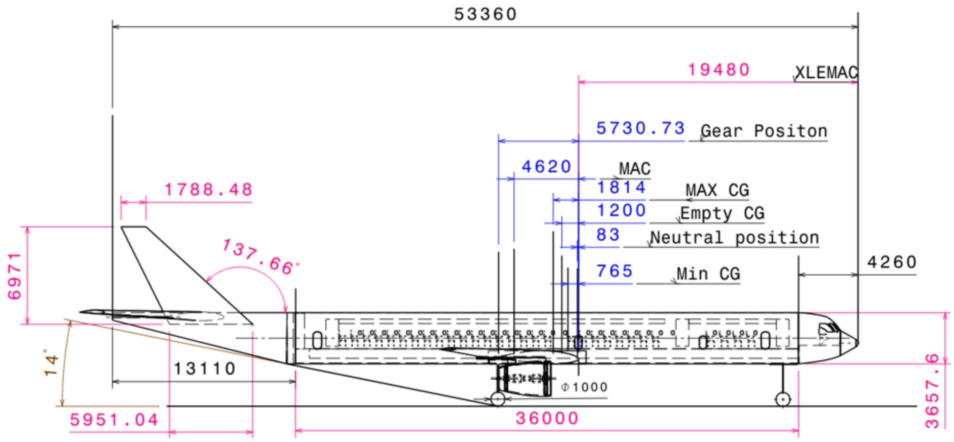

Fig. 11 Side View

Appendix B T/W vs. W/S chart

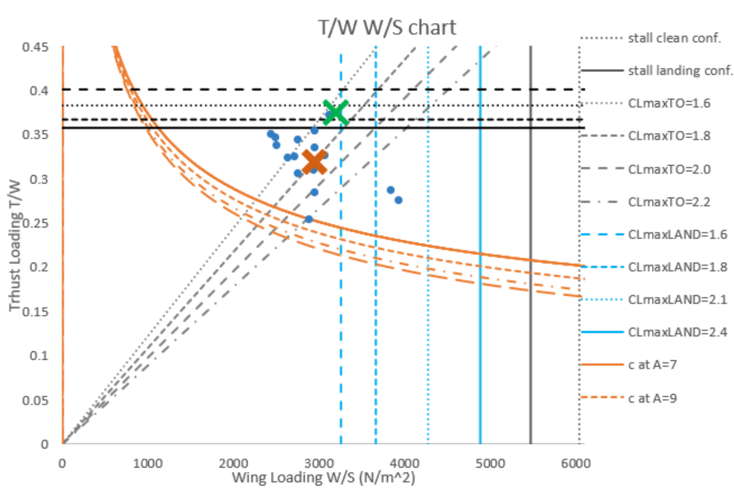

Fig. 12 T/W vs W/S chart

Appendix C Aircraft Parameter Table

	Parameter		Value	Unit
Aircraft Wing Geometry				
b	Wingspan		38.6	m
S	Wing area		152.86	m^2
A	Aspect ratio		9.75	
L	Wing sweep angle		25	Deg
X_{LeMAC}	Leading Edge Mean Aerodynamic Chord		22.5	m
F_l	Fuselage length		36	m
Weights and Loadings				
MTOW	Maximum take-off weight		101,274	kg
W/S	(maximum) Wing loading		3,250	N/m^2
Flight Parameter				
h_{cruise}	Cruise altitude		11,500	m
V_{cruise}	Cruise speed		0.82	Mach
$C_{Lcruise}$	Cruise lift coefficient		0.342	-
C_{Lmax}	Maximum lift coefficient (take-off)		2.5	-
s_{TO}	Take-off distance		2600	m
s_L	Landing distance		1650	m

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