yggdrasil

ALEX STOLL

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The right aircraft at the right time.

In the next twenty years, there will be a demand for over 19,000 single-aisle airliners, comprising 1.4 trillion dollars.[1] This demand will be driven by the urgent need for airlines to replace their legacy fleets of Boeing 737s, Airbus A320s, and McDonnell Douglas MD-80s with more economic alternatives, as well as the needs of fast-growing regions such as East and South Asia.

In the near future, this demand will be partially met by advanced derivatives of the 737 and A320, as well as new designs such as the United Aircraft MS-21. Any airliner intended to compete with these offerings must not only offer ground-breaking economics, but also must present a minimal environmental impact.

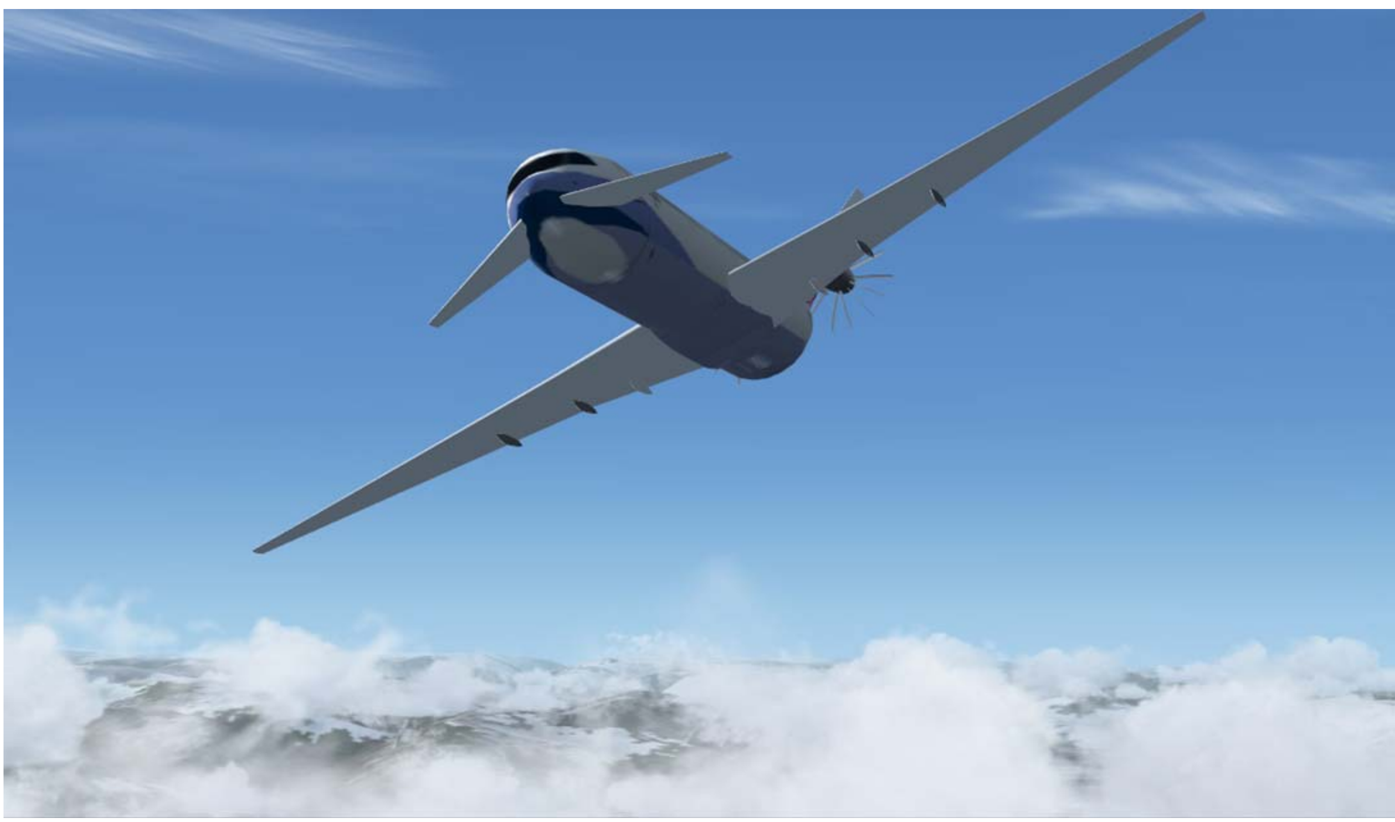
It is against this background that we offer the Yggdrasil: an innovative airliner designed from the ground up to redefine the standards of short- and medium-haul air travel. Named after the Norse mythological world tree connecting the earth to the heavens, the Yggdrasil is perfectly sized with a two-class capacity of 150 passengers and a range of at least 3,000 nautical miles. This combination of capacity and range allows the Yggdrasil to directly replace A320s and places it squarely in the middle of the 737 range.

As a next-generation airliner, the Yggdrasil is also designed to drastically reduce carbon dioxide emissions and to fully meet Stage IV noise regulations. Comfort was another prominent design point, and the Yggdrasil is designed to meet or exceed the passenger comfort levels of the aircraft it will compete against.

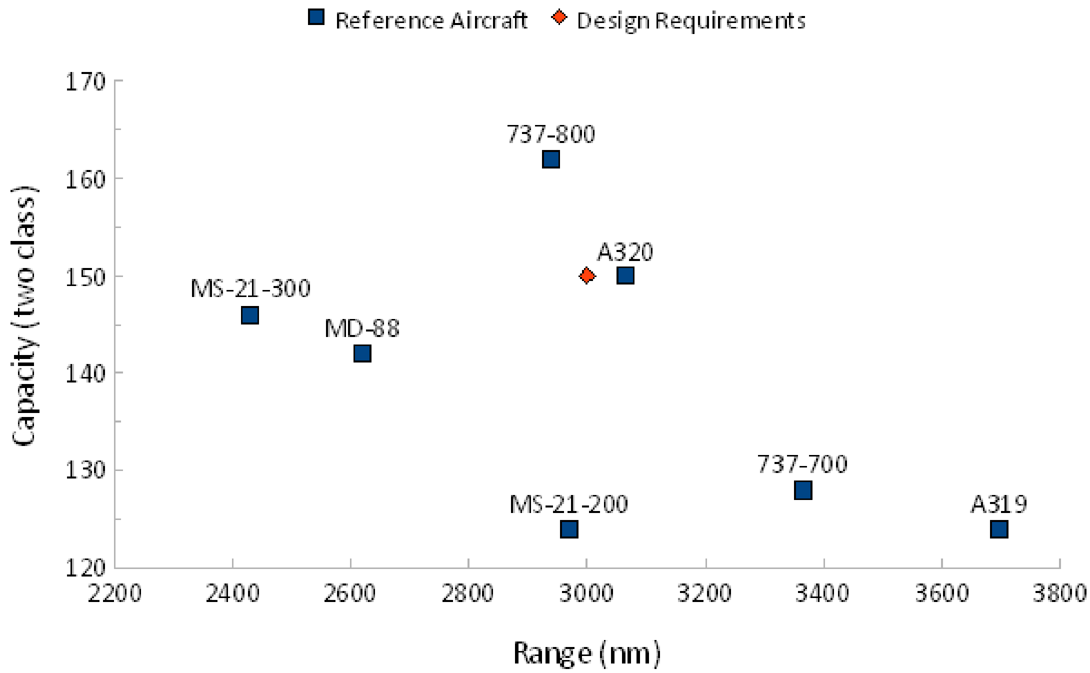
Besides offering a competitive passenger capacity, the Yggdrasil will be able to hold seven LD3 cargo containers or

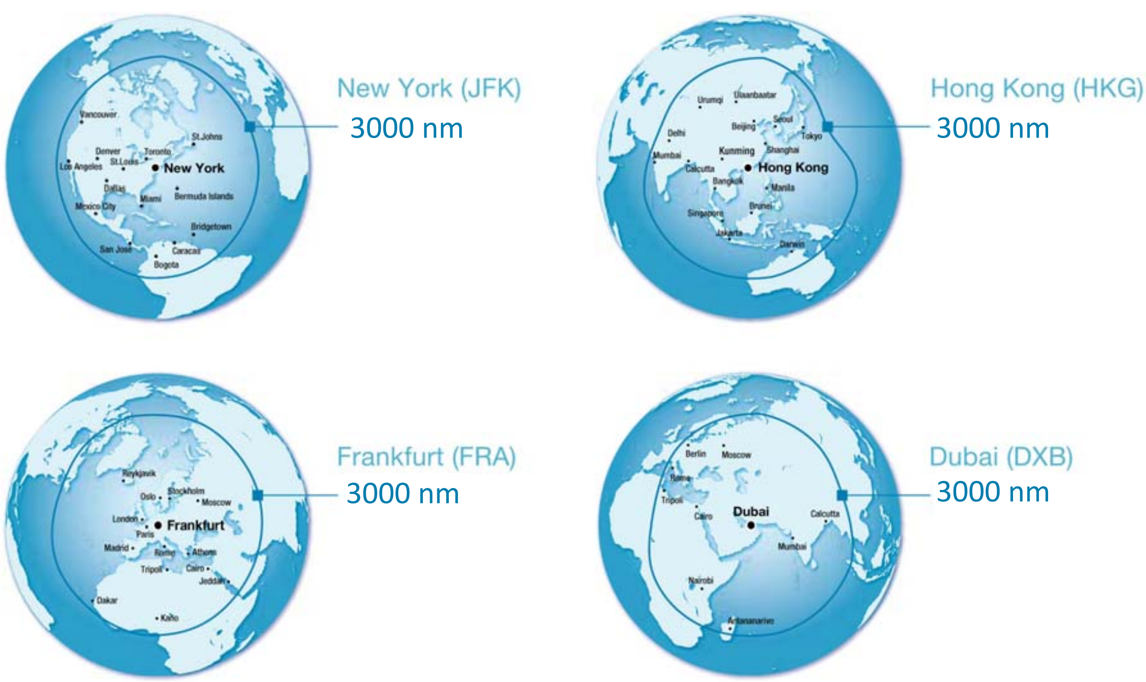
[1] Boeing Current Market Outlook 2008-2027

palletized cargo in the underbelly freight holds. The Yggdrasil's practicality doesn't end there: it is capable of operating from 7,000 foot runways at its maximum payload [2], meaning more flexibility to meet market needs. Its cruising speed of Mach 0.74 represents the ultimate combination of economy and practicality while minimizing emis-



[2] At standard sea level conditions


Reference Aircraft
Design Requirements
Capacity (two class)
Range (nm)
170
160
150
140
130
120
2200
2400
2600
2800
3000
3200
3400
3600
3800
737-800
A320
MS-21-300
MD-88
737-700
MS-21-200
A319


New York (JFK)
3000 nm
New York
Hong Kong (HKG)
3000 nm
Hong Kong
Frankfurt (FRA)
3000 nm
Frankfurt
Dubai (DXB)
3000 nm
Dubai

New from the ground up.

Unlike the modern 737, an update of a 1960s airliner, the Yggdrasil has been designed from scratch, with little heritage shared with current designs. This design process was accomplished with a combination of rational and statistical methods, as well as comparisons with existing designs.

In comparison to similar aircraft, the cruise altitude and speed were initially chosen to be 38,000 feet and Mach 0.78.

Fuselage Design

To adequately compete with aircraft such as the 737 and A320, a six-abreast (3-3) economy layout was selected for the fuselage at a comfortable 32-inch pitch, and a four-abreast (2-2) first-class layout at 36-inch pitch is also available. The baseline medium-density layouts feature 162 passengers in 27 rows of economy seating or 150 passengers in three rows of first-class (12 passengers) and 23 rows of economy

Innovative staggered seating in economy class reduces the fuselage diameter, lowering weight and parasitic drag.

(138 passengers). 179 passengers at 30-inch pitch can be accommodated in a high-density layout. The fuselage cross-section was sized to accommodate LD3 containers. The overall fuselage length and width were dictated by the cabin layout and the provisions for lavatories, galleys, closets, and flight attendant seats. Additionally, the nose and tail lengths were determined from correlations to minimize drag.

Maximum Takeoff Weight

The baseline maximum takeoff weight (MTOW) was chosen by comparison with existing aircraft in the same class, discounting 10% to account for extensive composite usage. This resulted in a value of 158,000 pounds.

Wing Design

By comparison with wing loading values for similar aircraft, a baseline wing area of 1,264 square feet was selected. Through similar comparisons, the aspect ratio was chosen to be 9.5, the wing sweep angle was chosen to be 25 degrees, the extension span and chord were chosen to be 0.286 and 0.28, respectively, and the taper ratio was chosen as 0.24. These parameters gave a wingspan of 109 feet 7 inches.

Through calculation, the optimum wing thickness was determined to be 12.3%, based on a modern supercritical airfoil. The wing was initially positioned with the 25% MAC at 60% of the fuselage constant length section, to allow for static stability with aft-mounted engines.

High Lift System

Because enough risk was being taken with other aspects of the aircraft design, a conventional leading-edge slats/double-slotted flaps configuration was selected. The slats are full-span, and the flaps cover 70% of the span and extend to 30% of the chord. This configuration gave maximum lift coefficients of 2.64 at takeoff and 2.99 at landing.

Tail and Canard Design

The V-tail/canard configuration offers many advantages over a conventional aircraft. Because, from a stability standpoint, the minimum tail size is dictated by the distance from the tail's aerodynamic center to the aircraft's center of gravity, this configuration allows the total tail/canard surface area to be smaller than an equivalent conventional aircraft, lowering weight and parasitic drag.

By employing a modern digital fly-by-wire control system, a V-tail can replace a conventional tail without a significant loss of control authority. However, the V-tail is structurally more efficient than a conventional tail, again lowering weight and parasitic drag.

The flexibility of two surfaces (canard and tail) in the design stage also aids in aircraft configuration and allows for the engines to be placed on the tail without great compromise.

The tail and canard sweep angles, aspect ratios, and thicknesses were chosen based on comparisons with horizontal tails on similar aircraft.

The total required tail vertical and horizontal surface area-moment arm products were determined through statistical methods. The relative canard and tail sizes and the V-tail dihedral were then determined to minimize total tail and canard surface area.

This process resulted in a canard with an area of 110 square feet, a sweep of 25 degrees, and an aspect ratio of 5, and a V-tail with an area of 347 square feet, a sweep of 35 degrees, a dihedral of 37.8 degrees, and an aspect ratio of 4.25. Both the tail and canard were 10% thick.

Given the locations and geometry of the tail and canard, the wing was positioned along the fuselage to provide a static stability margin of about 5%.

Engine Selection

Through comparison with similar aircraft, two engines of 23,700 pounds sea level static thrust were selected. To maximize fuel economy, these engines are modern open rotor designs. The engine dimensions and performance were estimated in comparison to existing models, namely the Progress D-27 and the General Electric GE36, resulting in an estimated dry weight of 3,870 pounds each.

The engines were mounted on the V-tails for two reasons. A rear location minimizes cabin noise; additionally, mounting the engines on the tail eliminates the need for additional engine pylons, reducing weight and drag.

Weight Estimation

Component weights were largely estimated from statistical methods, assuming the maximum high-capacity passenger load of 179. Extensive composite use allows a 15% savings in structural weight and facilitates a comfortable cabin pressure altitude of 6,000 feet. Instruments and navigational equipment were estimated to weigh 1,200 pounds, due to provisions for overwater operations. To accommodate the passenger load, seven flight attendants are employed, weighing 210 pounds each, including baggage. These calculations produced a MTOW of 149,591 pounds, a MZFW of 119,006 pounds, and an empty weight of 73,462 pounds.

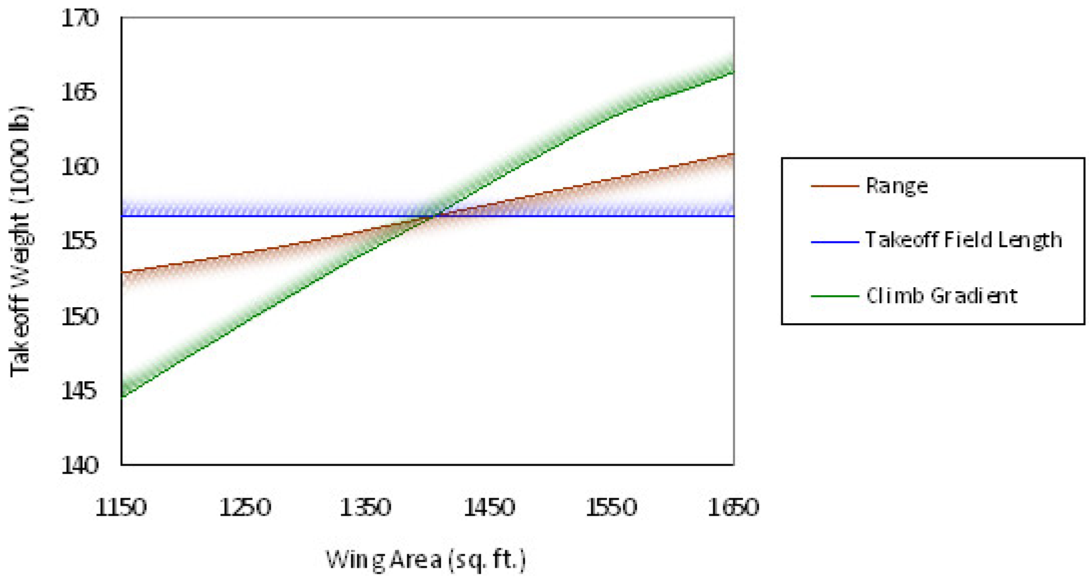
The optimal airliner.

Analysis of the baseline design at maximum capacity indicated that it would not meet certain design goals. Specifically, the estimated range was 2,605 nautical miles; the takeoff field length was 7,718 feet; the second-segment climb gradient was 2.17%; the initial drag:thrust ratio was 0.931; and the aircraft exceeded Stage IV noise regulations by 3.55 EPNdB.

These shortcomings were addressed via the optimization routines in the Program for Aircraft Synthesis Studies (PASS), using both the Java- and the MATLAB-based optimizers. However, because this program does not support three-lifting-surface aircraft, an analogue aircraft had to be designed that effectively represented the Yggdrasil with a conventional tail and no canard. This was done by shaping and sizing the analogue's tails such that both the weight and the equivalent flat plate drag projections into the horizontal and vertical planes matched between the two aircraft. Additionally, the *wother* parameter was modified to produce equal empty weights for both aircraft, and the minimum tail rotation lift coefficient margin constraint in the optimizer was modified to compensate for the lack of the canard.

Optimized values of horizontal tail-to-wing area were then translated back to the original (canard and V-tail) design; the relative V-tail and canard sizes and V-tail dihedral were then recomputed to minimize surface area.

Because environmentally-friendly aircraft are most practical at lower altitudes and slower speeds than today's airliners, the cruise altitude and speeds were reduced as inputs to the optimizer. Specifically, the cruise altitude was initially specified as 34,000 feet and the



Summary sizing plot for the optimized Yggdrasil with 179 passengers, showing the important constraints. The design is optimized to such an extent that the only feasible area is the single point determined by the intersection of the three curves.

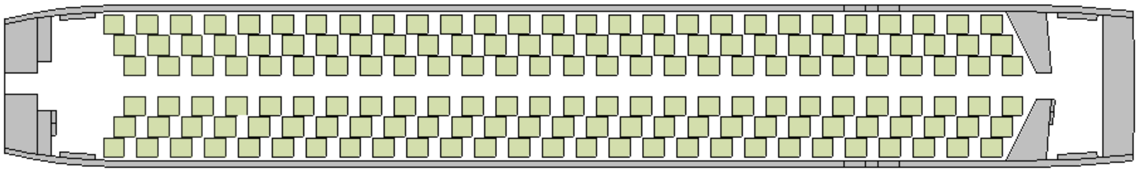
cruise speed was fixed at Mach 0.74. This allowed the optimizer to converge on a design that readily met or exceeded all of the requirements. As a result, the wing sweep was reduced to 17.7 degrees, the wing area was increased to 1406 square feet, the wing thickness was increased to 14.8%, and the wing aspect ratio was increased to 13. The relative tail sizes were also increased. This configuration resulted in a much larger canard. Because of the lower wing sweep, the tail sweep was reduced to 30 degrees. Since the optimizer tended to decrease the wing taper ratio to unreasonable values, it was fixed at 0.15. The takeoff and landing flap deflections were fixed at 20 and 40 degrees, respectively, since changing these parameters had little impact.

To maintain static stability, the wing was moved forwards on the optimized design.

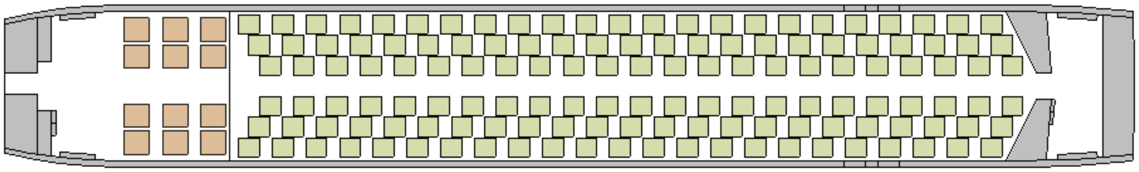
The baseline Yggdrasil (right) compared with the optimized Yggdrasil (left).

Interior layouts

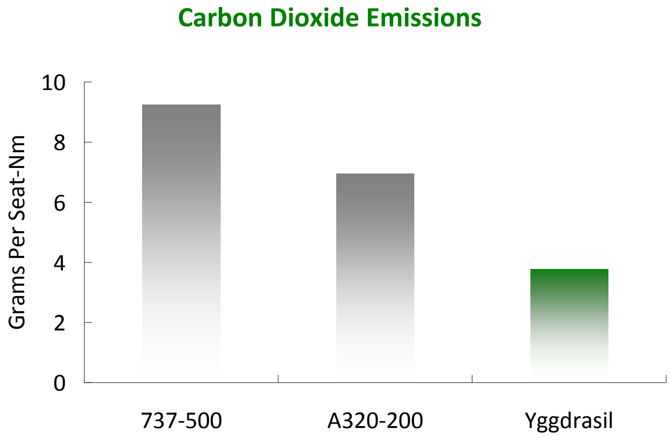
Single Class: 162 seats at 32" pitch

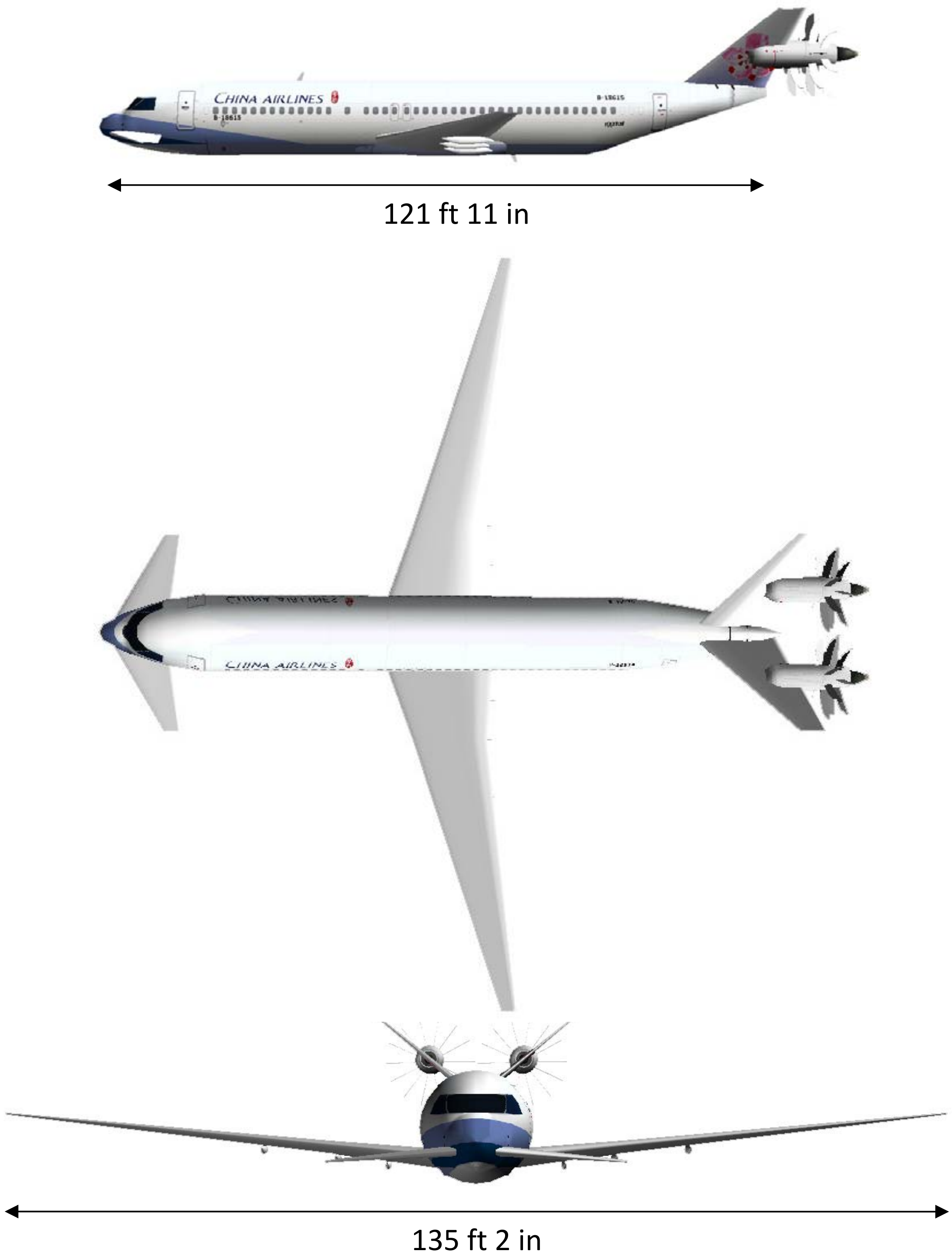


Dual Class: 150 seats (12F/138Y) at 36"/32" pitch



In addition to its low carbon dioxide emissions, the Yggdrasil meets all current emissions and noise regulations. Takeoff and landing NO_x emissions are 8.1 kilograms below regulations.




121 ft 11 in
135 ft 2 in

SPECIFICATIONS

ENGINES	
Sea Level Static Thrust (each)	22,500 lb

WEIGHTS	
Maximum Takeoff Weight	156,679 lb
Maximum Landing Weight	120,601 lb
Empty Weight	76,984 lb
Maximum Payload	38,745 lb
Maximum Fuel	36,078 lb

PERFORMANCE	
Cruise Speed	M 0.74 / 427 kts
Take Off Field Length	7,000 ft
Landing Field Length	6,620 ft
Range (150 pax. @ 205 lb)	4,809 nm
Range (179 pax. @ 205 lb)	3,000 nm
Maximum Cruising Altitude	34,700 ft
Initial Cruise L/D	16.9
Second Segment Climb Gradient	2.40%
Stage IV Noise Margin (150 pax. at max gross weight)	1.85 EPNdB
NO_x Exceedance	-8.10 kg
CO_2 (kg/passenger-km at 3,000 nm with 179 pax)	0.0378
Estimated Fare (3,000 nm with 150 pax.)	$433
Estimated Fare (3,000 nm with 179 pax.)	$387

DIMENSIONS	
Wing Reference Area	1,406 ft^2
Wingspan	135 ft 2 in
Tail Area	477 ft^2
Tail Dihedral	39.9°
Canard Area	186 ft^2
Length	121 ft 11 in
Fuselage Width	12 ft 10 in
Fuselage Height	13 ft 6 in
Cabin Width	11 ft 9 in
Aisle Width	18 in
Seat Width (Economy)	18 in
Seat Width (First Class)	22 in

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