AVDASI 4 - GROUP 2F
FINAL ENGINEERING DEFINITION REPORT

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SUMMARY

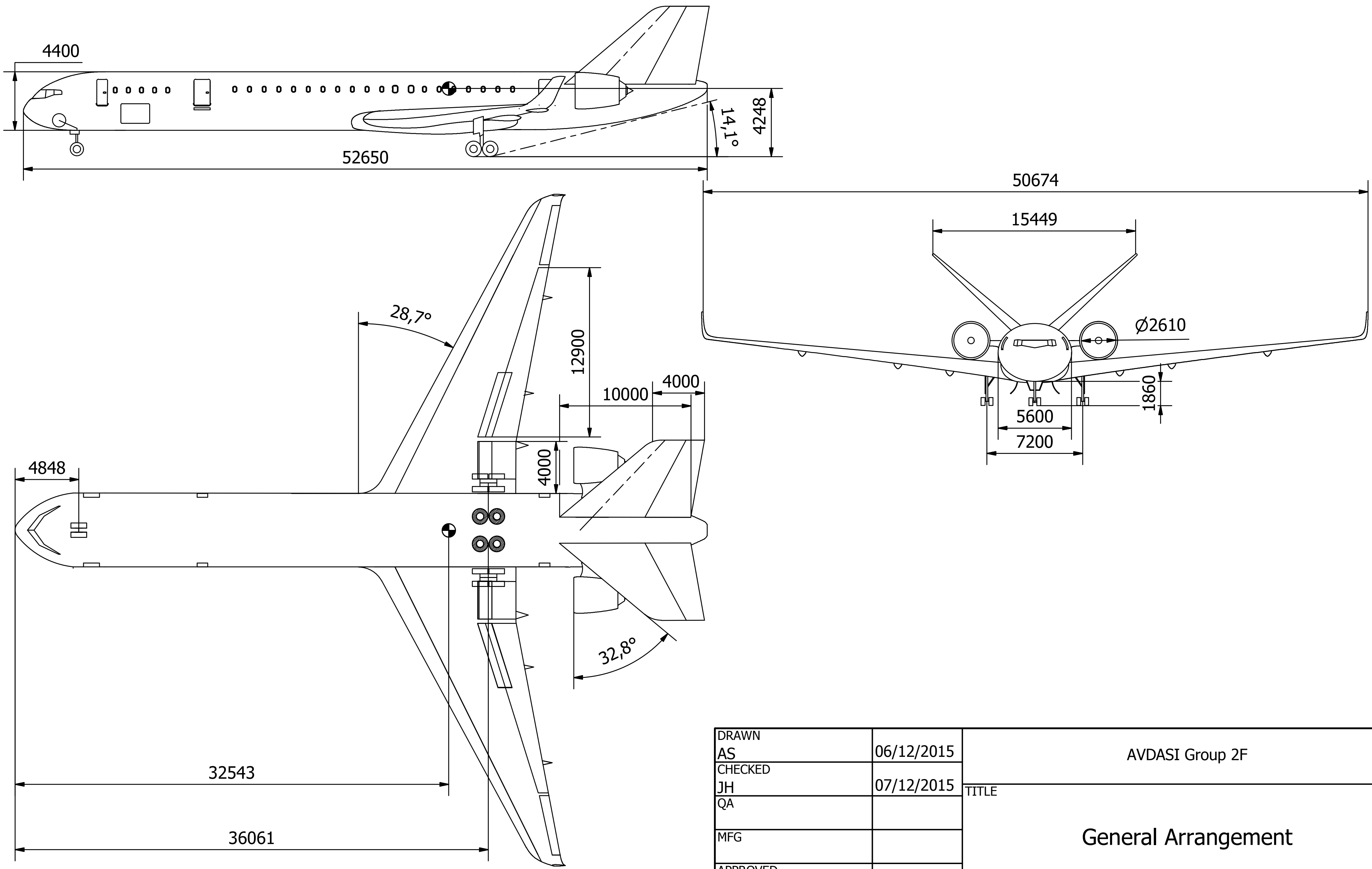
This report details the design of a 'Middle of the Market' airliner with a PAX capacity of 225 passengers and a range of 4500nm. The specification detailed the need for an aircraft with a range of 3500-5000nm and PAX capacity 200-250PAX in order to fill the gap in the Boeing product line between the B737-MAX and the B787 with an EIS of 2025. The key design drivers to achieve were high utilization and a 15% reduction in aircraft Direct Operating Costs (DOCs).

An ***Elliptical fuselage****,* ***V-Tail****,* ***Rear Engine*** *aircraft was chosen as the final concept to support the aims of increasing utilization, minimizing structural mass and improving the aerodynamics of the aircraft. The final aircraft design achieved a DOC reduction of 11%. However, this was due to the reduced development costs of producing a predominately composite aircraft for EIS 2025 compared to the 2010 'state of art' in the form of a scaled down B787. The selection of a rear engine configuration was justified due to the potential this offers within emerging markets when considering un-developed airports. However, the V-Tail was shown to be 'performance neutral' and the Elliptical fuselage was found to have a detrimental impact on the aircraft performance.*

CONTENTS

NOMENCLATURE

ACN – Airport Compatibility Number
CS – Certification Specification (CS.25)
DOC – Direct Operating Cost
ECN – Engineering Change Notice
EIS – Entry Into Service
ETOPS –Extended range Twin engine OPerationS
FC – First Class
FDR – Final Design Review
FOD – Foreign Object Debris/Damage
GA – General Arrangement
ICAO – International Civil Aviation Organisation
HoQ – House of Quality
MSP – Manufacturer's Study Price
MTOW – Maximum Take Off Weight
NRC – Non Recurring Cost
OEI – One Engine Inoperative
PAX - Passengers
PDR – Preliminary Design Review
RC – Recurring Costs
ToS – Trade-off Study
YC – Economy Class

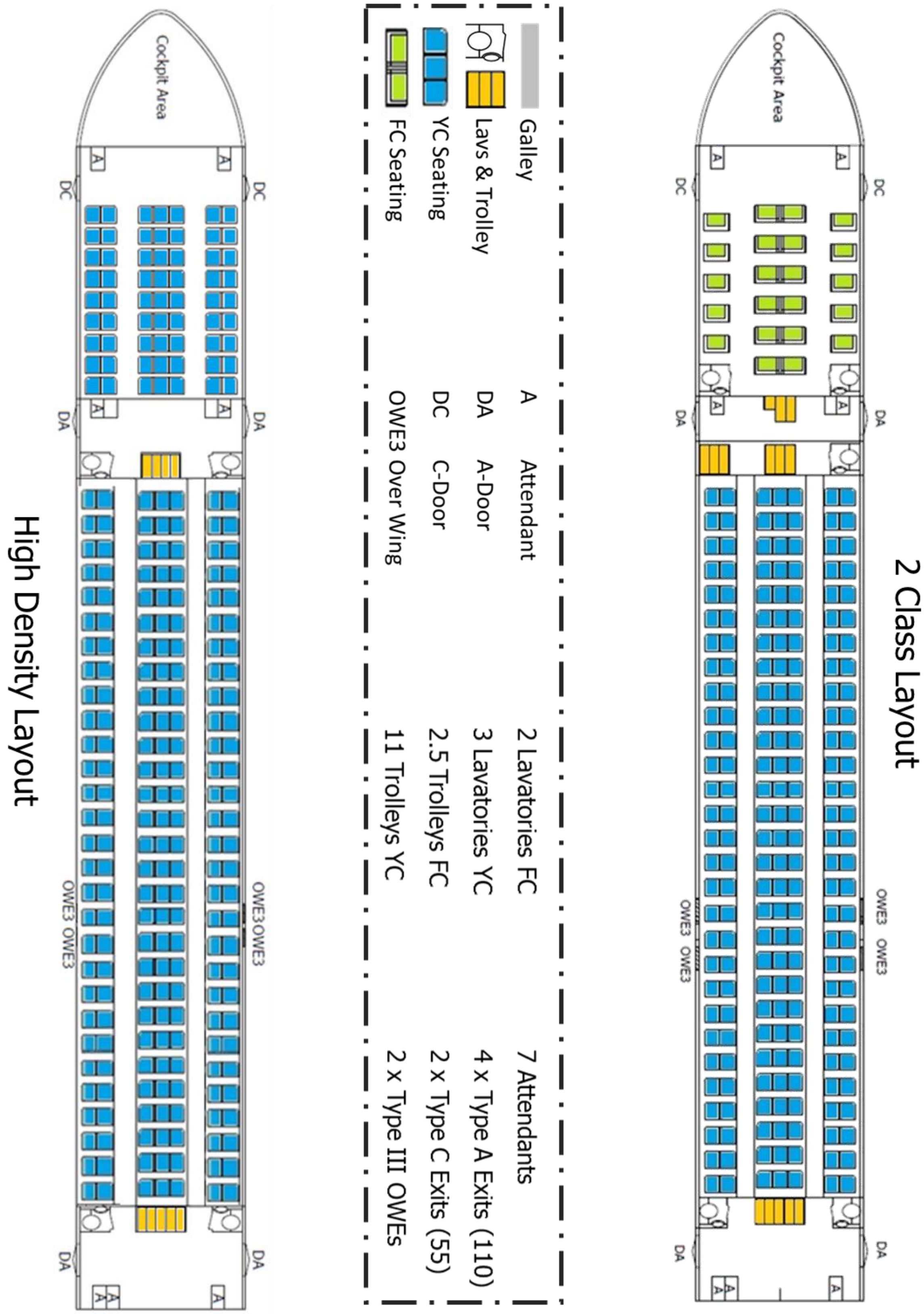


DRAWN AS	06/12/2015	AVDASI Group 2F
CHECKED JH	07/12/2015	TITLE General Arrangement
QA		
MFG		
APPROVED JH	07/12/2015	
ALL DIMS IN MM AND °		SIZE A3 — DWG NO GA_Wide_Group2F_REV7 — REV 07
		SCALE 1/270 — SHEET 1 OF 1

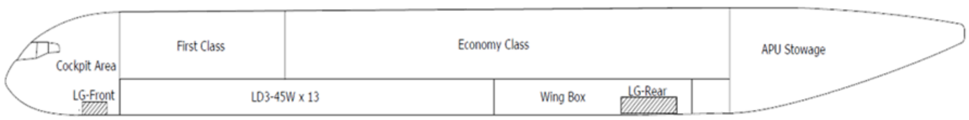
oVal Concept FEDR Aircraft Data Sheet

Item	Value	Units	Additional Comments
PAX Capacity	225	PAX	2 - Class (22 FC, 203 YC)
Design Mission Range	4500	nm	
Configuration: Rear Engine, V-Tail, Elliptical Fuselage, Low Wing			
Maximum Take-Off Weight	175060	kg	
Operators Weight Empty	102177	kg	
Fuel for design mission	42435	kg	Design Mission: 2- Class configuration over 4500nm route.
Payload for design mission	23730	kg	
Maximum Landing Weight	148800	kg	
Maximum Zero Fuel Weight	130924	kg	
Maximum Fuel Capacity	57519	kg	With additional belly-tank.
Cruise Mach No	0.84		
VCr/MCr (VCr in kts CAS)	350 / 0.88	kts CAS / -	Structural Design Speed.
Initial Cruise Altitude	35000	ft	
L/D (start of Cruise)	19.96		
Take-Off Field Length	1700	m	Appropriate to Market Condition.
Landing Field Length	1661	m	
Approach Speed	140	kts	
Fuselage Length	52.65	m	
Fuselage Width	5.6	m	
Fuselage Height	4.4	m	
Wing Area	274	m^2	
Span	50	m	
Aspect Ratio	8.35		
Thickness of Wing @ outer wing (t/c)	10		
Taper Ratio	0.205		
Mean Aerodynamic Chord	7.66	m	
Sweep @ 1/4 Chord	24.63	degs	
High Lift System (trailing edge)	Single Slotted Fowler Flaps (1 Inboard, 1 Outboard per wing)		
High Lift System (leading edge)	No Leading Edge High Lift System Fitted		
CLmax	2.49		High Lift System Deployed
Distance of wing LE at root from nose	27.35	m	
Distance of wing MAC from fuselage centreline	9.72	m	
Tailplane Area	148	m^2	
Span	10.534	m	
Aspect Ratio	1.5		
1/4 Chord MAC (wing) to 1/4 Chord MAC (tailplane)	14.004	m	
Fin Area	148	m^2	V-Tail configuration. Therefore, 'fin' properties are identical to 'tail' properties.
Span	10.534	m	
Aspect Ratio	1.5		
1/4 Chord MAC (wing) to 1/4 Chord MAC (fin)	14.004	m	
Number of Engines	2		
Engine position (wing/fuselage/other)	Rear Fuselage		
Engine Type	High Bypass Turbofan		UB455 Engine
Sea Level Static Thrust (per Engine)	62112	lb	
Thrust at Initial Cruise Altitude (per Engine)	10613	lb	
Engine Fan Diameter	2.66	m	
sfc at cruise	0.442	lbm/hr/lbf	
Main Landing Gear Tyre Size	46 x 18 x R20	inches	
Main Landing Gear Geometry for ACN	8,600	mm	Outer Main Landing Gear Track
ACN	51.3		
Height of Fuselage Datum above Ground	1.86	m	
CG range at MTOW	28	% MAC	
Aircraft NRC	14700	Million $	
Aircraft RC	84.3	Million $	
Manufacture's Study Price	170	Million $	
Engine Price (per engine)	21	Million $	
Aircraft DOC	53154	$/trip	based on 1000nm trip with std pax P/L
Turnaround time	30	mins	Based on durations from Boeing 767-200 Airport Compatibility Guide
Refuel time (Full wing tanks)	18	mins	
Trim Tank yes/no	No	kg	
Electric flight control architecture	Conventional fly-by-wire flight control architecture to fit into existing Boeing design philosophy. 3 Primary Flight Control Computers (PFCs) running the same software on dissimilar hardware for 3 similar lanes per computer.		
Electric flight control actuation	Primary control surfaces (ailerons and ruddervators) actuated by Electohydrostatic Actuators (EHAs). Secondary control surfaces (flaps and spoilers) actuated by Electromechanical Actuators (EMAs).		
Electronic Flight Instrument System architecture	"All glass" flight deck with an option for Enhanced Vision System (EVS) with Head-Up Displays.		
Nav-Flight Management System architecture	RNP-01 or better FANS compatible 4D navigation system.		
Electrical Power System architecture	Electrical system to provide cabin pressurisation, control surface actuation, fuel pumping, landing gear retraction and braking services in addition to avionics electrical supply. **Peak demand estimated to be 1.3MW**. 2 Variable Frequency Generators per engine. 1 gas-turbine APU and Lithium-Polymer batteries available for ground-power.		
Hydraulic System architecture	Hydraulic system replaced with electrical system (control surface actuation, landing gear retraction).		
Fuel System tank arrangement	1 x 29m^3 fuel tank **per wing**. 1 x belly fuel tank of 16m^3. Electrically-driven fuel pumps in pairs for redundancy. Wing-tip surge/vent tanks fitted and wing-tip fuel jettison capability. Engine cross-feed and fuel transfer between tanks available.		

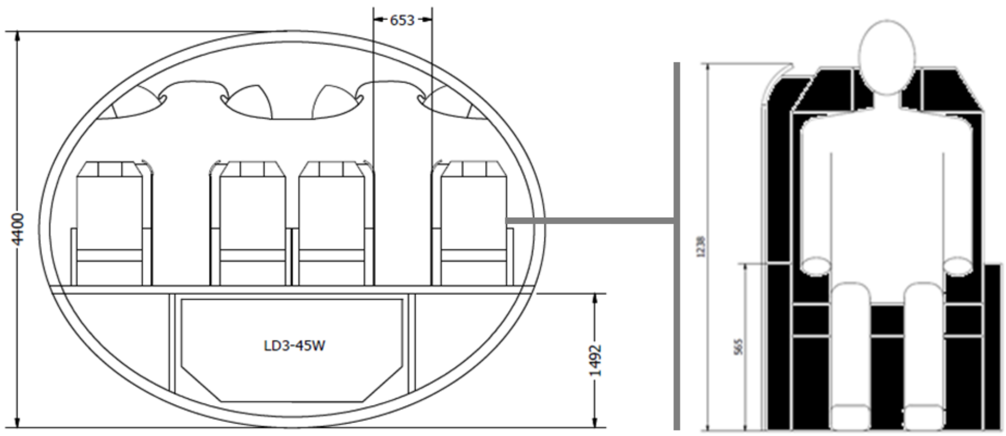
3. oVal CONCEPT SEAT LAYOUT



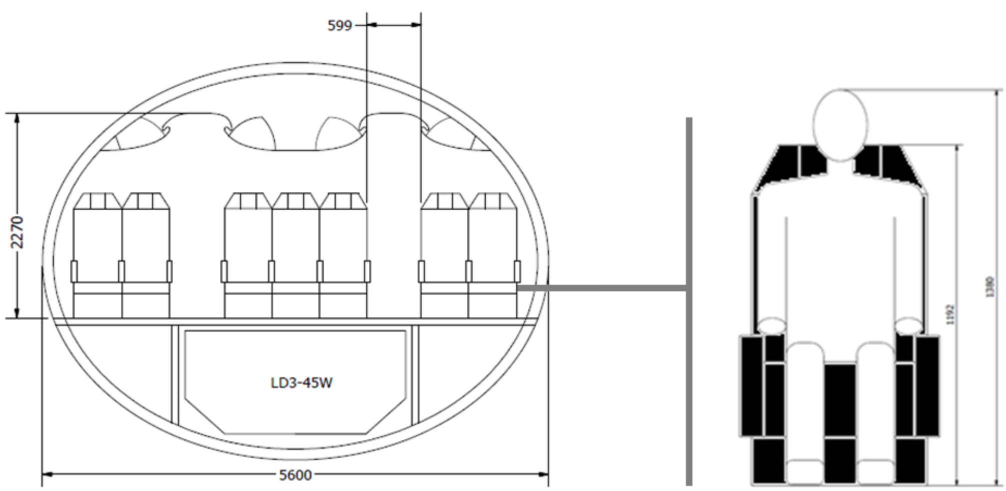
4. oVal CONCEPT CABIN LAYOUT



General Layout



First Class Layout



Economy Class Layout

Parameters	FC	YC
Seat Pitch	653	599
Seat Width	810	560
Aisle Width	653	599
Aisle Standing Height	2270	2270
Hold Height	1204	

5. INTRODUCTION

Within the aerospace industry the ‘middle of the market’ aircraft concept provides a distinct opportunity to develop a new generation of civil transport aircraft. Defined by the project specification as an aircraft with a 200-250 PAX capacity and a 3500-5000nm range, the ‘middle of the market’ concept is aimed at filling the gap in the Boeing product family between the Boeing 737MAX and B787. This gap has been created by the retirement of the Boeing 757 and 767 families and therefore the threat is present of Boeing losing their market share to Airbus’ A321LR and A330neo products. However, the ‘middle of the market’ definition also encompasses the needs of emerging and expanding airline markets across the globe.

The aim of this project was to develop and design a concept aircraft to satisfy the needs of the ‘middle of the market’. This report details the final aircraft design of a rear-engine, V-tail configuration with an elliptical fuselage cross section. A novel aircraft configuration was selected with the hope of to achieving a 15% reduction on aircraft DOCs compared to the 2010 state of the art. Following a description of the final design, the risks and challenges facing the future development of the concept are discussed.

6. CONCEPT SELECTION AND JUSTIFICATION

This section of the report identifies the key steps taken to perform concept selection up to the PDR. Due to the ‘middle of the market’ project specification, the concept down selection was performed by combining market analysis with qualitative trade-off studies based upon the aircraft specification.

6.1. Market Analysis

In order to initiate the process of concept selection, the range and PAX capacity of the aircraft had to be defined using market analysis. The project specification required that the aircraft should be proposed as a ‘middle of the market’ concept and therefore have a range of 3500-5000nm and a PAX capacity of 200-250 (2-Class) [1]. The market analysis was based on existing Boeing 757 and 767 routes. Whilst the aircraft concept is anticipated to replace the current global Boing 757 and 767 fleets, the age of these aircraft has resulted in the majority of operators replacing their B757/767 fleets by 2017 with Airbus ‘neo’ products. Therefore, emerging markets and developing routes beyond the normal routes that the B757 and B767 fleets are operated on were also considered. It was found that the Asia-Pacific market is expected to have strong growth in Indonesia, India and China due to the expanding middle classes for whom air travel for business and leisure will become more attractive In order to relate this market analysis to the specification, desirable routes (shown in ***Table 1***) were then established based upon the initial market analysis considering ***Existing B757/767 Routes, Emerging Markets*** *and* ***Existing Hubs.***

Table 1: Desirable routes for the ‘middle of the market’ concept.

Hub/Operation	Routes [Length (nm)]	Justification
London Heathrow (LHR)	Europe – East Coast America [3750nm]	Existing B757/B767 Operations
Domestic USA	3500nm Required (Aircraft Optimised for 1000nm)	Existing B757/B767 Operations
Jakarta	Indonesia – China [2900nm] Indonesia – Sydney [3000nm] Indonesia – Dubai [3600nm]	Emerging International and Domestic Market
Beijing	China – Dubai [3200nm]	Emerging International and Domestic Market
Dubai	Dubai – Europe [3000nm] (LHR)	Established Market
Delhi	Delhi – Europe [3650nm] (LHR)	Emerging International and Domestic Market

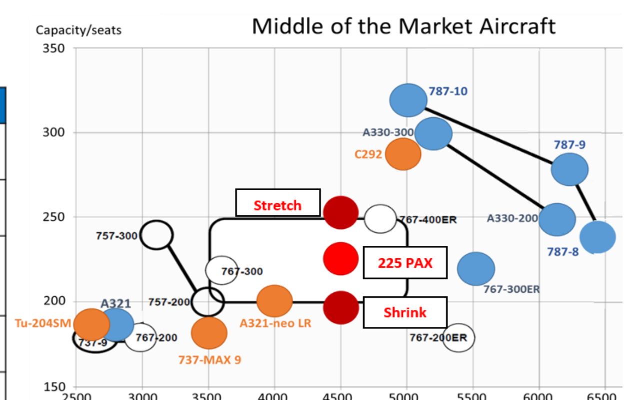


Figure 1: Market position of the proposed concept family.

Each of the desirable routes in ***Table 1*** required a maximum still air range of 3750nm. However, in order for the aircraft operate safely and reliably on 3750nm routes, current wind data [2] and a 10% safety factor were applied resulting in a final required range of **4500nm**. This range provides a competitive edge over the A321 LR as well enabling cargo operations between the world's major cargo hubs (Anchorage, Memphis, Hong Kong [3]).

The PAX capacity of the concept was defined by the total market coverage of the aircraft family (nominal, shrink and stretch variants) and the competitive impact this would have on existing and proposed aircraft. The PAX capacity of the nominal aircraft was selected to be **225 passengers** (2-Class). This positioned the aircraft in the centre of the 'middle of the market' design space and enables the shrink variant (200 PAX) to directly compete with A321 neo LR, whilst the stretch variant (250 PAX) will compete with the A330 on shorter and lower density routes. This market position is shown on ***Figure 1***.

6.2. Requirements Analysis

Following market analysis, the requirements within the project specification were comprehensively analysed and classified as 'Hard' or 'Soft'. These requirements are summarised in ***Table 2*** and mostly focused on the technical performance of the aircraft. In addition, the specification provided a requirement concerning the economic performance of the aircraft. The concept was to achieve a **15% DOC reduction** compared to the 2010 state of the art (a scaled down B787). Key design drivers were also stated in the specification and are listed in ***Table 3***. In order to assess the importance of theses design drivers, a DOC study on the B767-200 was performed. As shown by ***Figure 2***, fuel costs provide the greatest contribution to the aircraft DOCs. Therefore, the '*low fuel burn*' design driver was considered the most effective way of satisfying the 15% DOC reduction requirement. In addition, aircraft operating costs far exceed the initial aircraft investment costs and therefore the '*low investment costs*' design driver was considered to be less important than the 'high utilisation' or the '*high operational reliability*' design drivers. Ranking these design drivers enabled the decision making required during concept down selection to be referred back to the design drivers with ease. The key design characteristics of the aircraft were therefore the weight and aerodynamic efficiency as these directly affects the fuel consumption.

Requirement item	Unit	Specification	Type
Passenger capacity(2 Class)	-	200-250	Soft
Design range	nm	3500-5000	Soft
Design Cruise Speed	Mach	0.82-0.86	soft
Time to climb(1,500ft to ICA at ISA)	Mins	<30	Hard
Take off Field Length	m	1800	Hard
Landing Field Length	m	1350	Hard
Turn-Around Time	Mins	30	Soft
Airport compatibility	-	ICAO 'D'	Hard
Family Variants	-	+/-20% PAX	Soft
Expected Entry to Service(EIS)	-	2025	Soft
Initial Cruise Altitude	ft	35000	Hard
ETOPS	Mins	180	Hard
Evacuation	-	-	Hard

Table 2: Hard and Soft Requirements

Design Driver	Ranking
Aim: Minimise Direct Operating Cost (DOC) ***(Target 15% reduction on 2010 baseline)***	
Low Fuel Burn	1
High Utilisation	2
Low Investment Costs	3
Low Maintenance Costs	2
Aim: Achieve High Operational Reliability	
High Operational Availability	2
Ability to Fix Operational Interrupts Quickly	2

Table 3: Design Driver Ranking

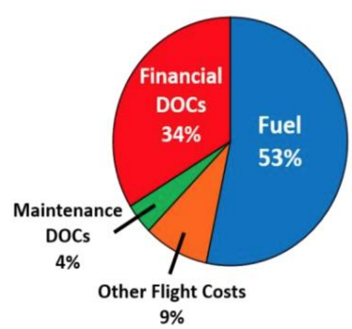


Figure 2: B767-200 DOC Breakdown

6.3. Concept Down-Selection Process and Trade-Off Study

The overall concept down-selection process is shown in ***Figure 3***. The process was initiated by conducting preliminary concept research which enabled unsuitable concepts to be rejected. This was followed by a formal quantitative trade-off study. Lastly, the finalised concept and configuration were identified.

Figure 3: Concept down-selection Trade-off Study Process.

The preliminary concepts and configurations researched by the team were as follows:

- Blended Wing Body
- Lifting Body
- Box Wing
- Delta Wing
- Conventional High Wing Aircraft
- Conventional Low Wing Aircraft
- Conventional Rear Engine Aircraft
- *Span Loader (i.e. PAX Cabin within the wing box)*
- *Canard Control Configuration*

It should be noted that span loader concept was rejected at this stage due to its application only being suitable for larger capacity aircraft. In addition, the canard research area was also rejected as the manoeuvrability which canards offer is not a desirable quality of a civil aircraft. Therefore, the remaining 7 concepts were selected for further down selection studies. Whilst the advantages and disadvantages of each of these concepts had been identified during the preliminary concept research, a formalised method was required in order to relate these qualitative attributes back to the specification requirements and design divers.

Therefore, to support the decision making required for concept down-selection, a Trade-off Study (ToS) method was developed for assessing concepts with respect to specification and design drivers identified during requirements analysis.

As each potential aircraft concept can be uniquely defined in terms of its engineering characteristics (e.g. engine position, aerodynamic performance enhancements, estimated concept weight etc.) a House of Quality (HoQ) [4] was used to further understand how these unique concept characteristics impact the specification requirements and design drivers. This enabled ToS criteria which directly assessed the concepts against the project specification requirements and design drivers to be developed. The HoQ working process can be visualised as shown in ***Figure 4***.

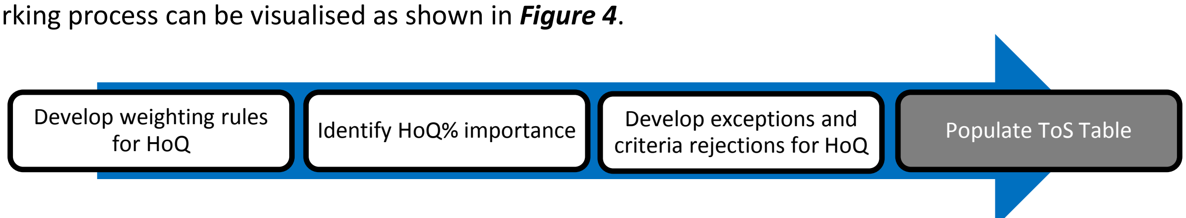


Figure 4: House of Quality Process and Application of HoQ Importance

A HoQ study identifies the importance of each engineering characteristic based on combing the specification requirements and design drivers ranking developed during requirements analysis and the scale of impact each characteristic has on each requirement/design driver. ***Table 4*** shows the engineering characteristics assessed using the HoQ. Engineering characteristics to be used as criteria within the ToS were required to have a HoQ %importance of greater than 5% in order to prevent engineering characteristics with little impact on the concept satisfying the project specification driving the design. Key observations and reasoning made during the HoQ study were collated and indentifed to further explain the HoQ % importance allocated:

Table 4: HoQ Importance Ranking

Engineering Characteristic	HoQ % Importance
Engine Location	14%
Structural Efficiency	13.6%
Wing Position	11.6%
Fuselage Configuration	11.1%
Aerodynamic Efficiency	9.1%
Weight	7.5%
Configuration and Location of Landing Gear	7.5%
Control Sys. Complexity	6.8%
Configuration and Location of High-Lift Devices	6.7%
Tail Configuration	4.3%
Fuel Sys. Complexity	2.7%
Actuation Sys. Complexity	2.6%
Environ. Sys. Complexity	2.6%

1) **Engine Location, Wing Position, Structural Complexity and Fuselage Configuration** have the greatest impact on satisfying the customer requirements based upon the House of Quality Importance score. Therefore, the trade-off study should be focused on assessing these areas.
2) **Weight** - Whilst weight received a low overall score, it should be noted that aircraft weight is the greatest driver of Direct Operating Costs due to fuel burn. Therefore, structural mass should carry the maximum weighting within the trade-off study**.** The low overall score demonstrated here is a limitation of the HoQ weighting process.
3) **Aerodynamics** should carry a significant weighting in the ToS due to its link to aircraft fuel burn.
4) **Landing Gear Configuration and Location** should carry a significant weighting within the trade-off study based upon the House of Quality Importance score.

To ensure the ToS could be conducted as objectively as possible, criteria weighting rules shown in ***Figure 5*** were developed based on each design drivers' importance. Objectivity and engineering bias had to be removed from the process to ensure validity of the down selection process. This was especially important as a ToS was the only approach available to the team to perform down selection due to the lack of data available on novel aircraft concepts. The population of the trade-off study was performed by scoring each concepts against criteria on a scale of -5 (Major performance reduction) to +5 (Major performance improvement) with respect to a baseline (selected as the conventional low wing aircraft concept).

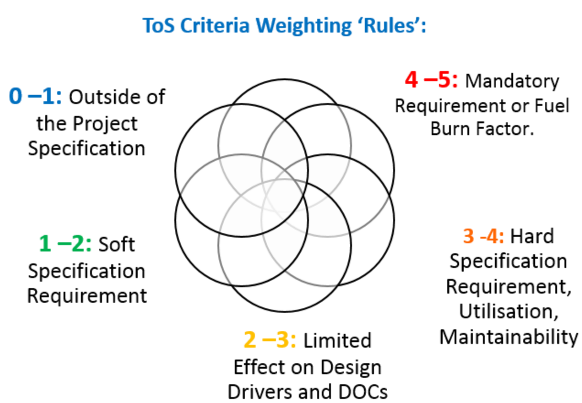


Figure 5: Rules used to develop the weightings for the trade-off study criteria based upon specification requirements and design drivers.

6.4. Trade-off Study Results and Concept Selection

The populated ToS table (***Table 5***) shows that the Rear Engine (low wing), Box Wing, and High Wing concepts had larger normalised scores than baseline. Therefore, these three concepts were passed through the down-selection process and were compared qualitatively against the requirements and design drivers. This allowed the selection of final concept to be based upon engineering judgement supported by the trade-off study results

Table 5: The fully-populated trade-off study table used for concept down selection. Concepts with a larger score than the baseline are highlighted in green.

		Baseline	Concept #1	Concept #2	Concept #3	Concept #4	Concept #5	Concept #6
Trade-Off Criteria	**Weighting**	**Conventional**	**Blended Wing Body**	**Lifting Body**	**Box Wing**	**Delta Wing**	**High Wing**	**Rear Engine**
Engineering Characteristics								
Weight	5	0	5	-2	0	0	-2	-2
Aerodynamic Efficiency	4.5	0	4	4	5	-4	0	2
Structural Complexity	4.5	0	1	-2	4	1	-1	-1
Control Complexity	3	0	-2	-1	-4	-2	1	0
Integration of high lift devices	2	0	-4	0	-3	-4	0	2
Landing Gear Integration	3	0	5	4	4	3	4	4
Engine Integration	2.5	0	2	-2	-2	-2	-2	-2
Regulatory Requirements								
Evacuation	5	0	-5	0	0	-1	0	2
Exterior Noise	5	0	4	-2	2	-2	0	0
Operational Criteria								
Airport Compatibility	4	0	-2	0	2	-1	4	3
Maintainability (Airframe + Engine)	4	0	-2	-2	-3	-2	-2	-1
Additional Cargo Capacity	0.5	0	1	2	1	0	2	0
Passenger Comfort (Interior Nosie)	2	0	-2	1	2	-3	-2	-1
Concept Versatility								
Air Freight Capability	1	0	4	3	-1	-2	4	4
Charter / Low Cost Operations	1	0	-4	0	5	-3	4	4
Compatibility with Family Concept	3	0	-4	-2	-4	-4	0	-1
Risk-Based Criteria								
Technological Risk	3	0	-4	-3	-4	-1	0	0
Disruptive Nature	1.5	0	-4	-1	-2	0	0	0
Ease of Manufacture	1.5	0	-5	-3	-3	2	-1	-1
NORMALISED RESULTS		**0.50**	**0.48**	**0.45**	**0.52**	**0.37**	**0.51**	**0.54**

Firstly, the Box wing concept had the potential to reduce DOCs due to its aerodynamic benefits and low induced drag. However, there are technical risks associated leading to a significant structural weight penalty. In addition, it also contains potentially significant economic risks due to the large concept development costs and large investment costs from customers due to the additional pilot training and infrastructure modification required to permit the concept to operate. Therefore the combined technical and economic risks outweigh the benefit, and the concept was rejected.

The rear engine allows a 'clean' wing design and short landing gear. The clean wing design enables a reduction in drag which lowers fuel burn and hence DOCs. The short landing gear design encourages increased utilisation by reducing turn-around times through the use of integrated air stairs. Shorter landing gear also contribute to DOC savings through reduced weight. The rear mounted engine concept also enables a smaller vertical fin to be designed due to smaller yawing moment during one engine inoperative (OEI) conditions. This would potentially reduce aircraft DOCs through reduced surface area drag and structural mass of the tail. Whilst engine maintenance accessibility is a drawback, as is engine ingestion of the wake produced by the wing and complex empennage engine pylon structure required, FOD ingestion on ground is reduced which enhances the concept's potential operational availability and reliability.

When assessing the high wing conventional concept aircraft, the utilisation benefits are similar to the rear engine configuration. However, passenger comfort is impacted by the engine noise adjacent to the cabin along with the need to carry the wing box through the cabin, reducing the overhead luggage volume available. This could be mitigated with a fairing above the fuselage; however this would be significantly larger than an underbody fairing, increasing overall aircraft drag and reducing vertical tail plane effectiveness. In addition, regulatory concerns regarding engine disk burst are significant due to the 'cabin-level' positioning of the engines.

In order to select the final concept, the advantages and disadvantages of the high wing and rear engine concepts were related back to the key design drivers of minimum direct operating costs and high utilisation. Although both of these could be satisfied to a similar extent each concept, a final section of low wing rear engine was made due to the passenger comfort issues which are inherent to the high-wing concept. Whilst there are noise concerns for the rear-engine aircraft, these are localised to the rear PAX cabin/empennage of the aircraft whereas high-wing noise impacts a larger cabin section.

6.5. Finalised Concept and Configuration

Following the selection of a rear-engine concept, the aircraft configuration could then be defined. For this concept, the tail and fuselage cross section were the two elements of the aircraft configuration which could be modified with a view to supporting the specification design drivers, specifically the reduction in aircraft DOCs.

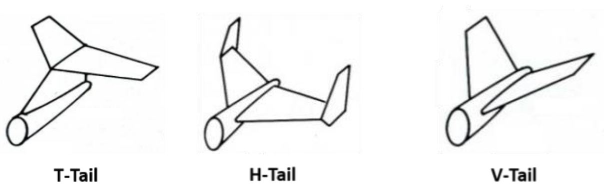


Figure 6: The tail configurations investigated.

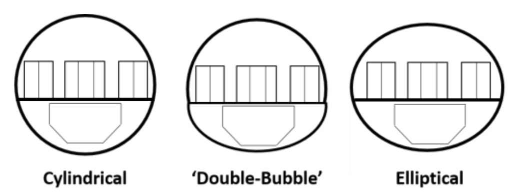


Figure 7: The fuselage configurations investigated

Firstly, various tail configurations (T-Tail, H-Tail and V-Tail – ***Figure 6***) were considered to qualitatively identify if any marginal performance gains could be achieved through selecting an un-conventional (i.e. T-tail) configuration. A V-Tail was selected due to the potential weight saving which could arise from removing a surface and control system, translating into lower fuel burn and therefore reduced DOCs.

Conventional (circular), 'Double-Bubble' and elliptical fuselage cross sections (***Figure 7***) were also investigated and assessed. An elliptical fuselage was chosen to optimise the internal volume of the fuselage and make improved use of the aisle width (Circular fuselages typically have 'excess' space around the hold cargo containers). In addition, an elliptical cross section could potentially reduce the frontal area over a circular fuselage, therefore reducing profile drag. This would result in a reduced fuel burn and therefore supports the aim of reducing aircraft DOCs. The double-bubble cross section was not selected due to the challenge of maintaining the structural integrity of the joint between the two cylindrical 'bubbles' at the floor beam under pressurisation. This would have represented a significant risk, especially considering that composite materials will be required for fuselage due the 6,000ft cabin pressurisation altitude at a ceiling of 41,000ft [1].

Therefore, the final configuration selected to satisfy the project specification was a **low wing, rear engine aircraft** with a **V-tail** and an **elliptical fuselage**. This configuration was then named the '**oVal**' concept to encompass the novel V-tail and elliptical fuselage of the aircraft. A summary of the justification supporting the down-selection of the final concept and configuration is shown overleaf in ***Figure 8.***

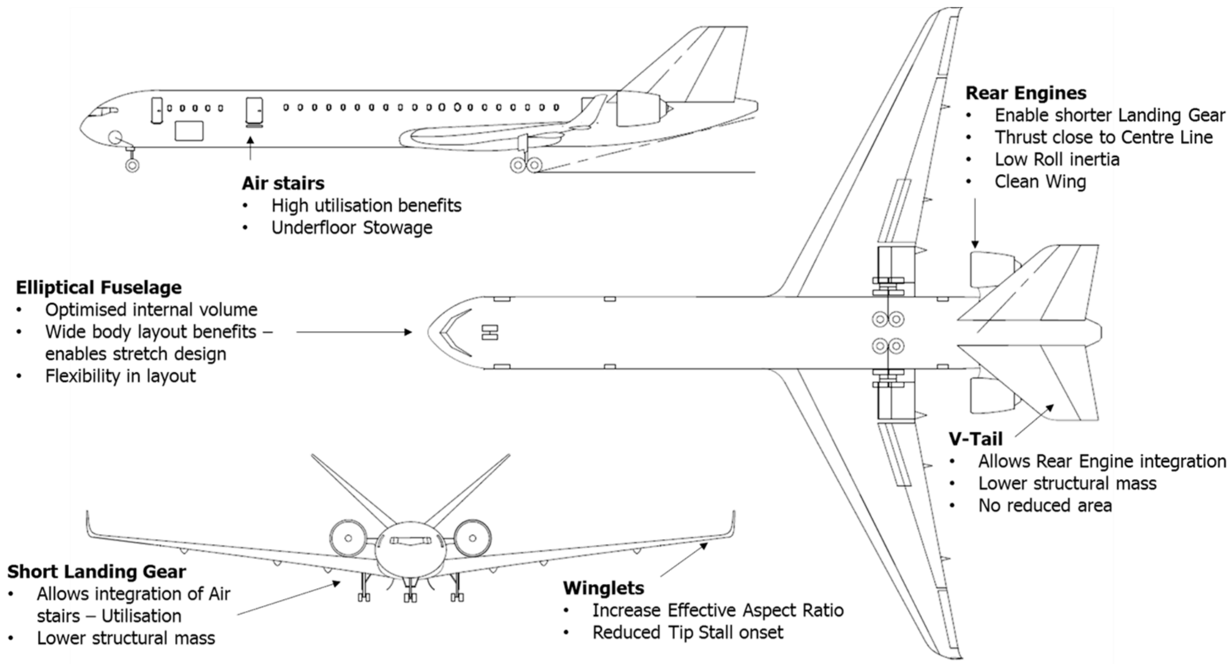


Figure 8: 3-Way view showing the final 'oVal' concept and configuration selection. The annotations provide an overview of the justification for selecting this aircraft concept.

7. DESCRIPTION OF FINAL DESIGN

This section of the report aims to communicate the key aspects of the final design through a review of each of the technical specialisms required to design the aircraft. The aircraft was designed across 3 design loops, the final of which focused on detail design elements such as the aircraft systems.

7.1. Aircraft Architecture and Systems Integration

The cabin was sized around the 2-class configuration with 22FC and 203YC and a high-density configuration was deigned at 259 PAX in order to specify evacuation requirements. For the 2-class configuration a 4-abreast 1-2-1 FC and 7-abreast -3-2 YC layout was chosen to maximise internal capacity by minimising aisle widths whilst maintaining airline convention. The economy 7-abreast configuration results in only 1 'excuse-me' seat, a selling point for airlines on the longer routes capable with this aircraft. The fuselage cross section is 5600mm wide by 4400mm deep permitting LD3-45W containers to be used.

The passenger cabin was sized considering all of the cabin layout requirements stated in the specification.

7.2. Aerodynamics

The critical sizing case for the wing area was cruising at 39000ft, due to the high weight of the aircraft resulting in a wing area of 274m^2. The wing has a sc20610 supercritical aerofoil section, with low transonic wave drag due to the thin aerofoil section used. The wing span of the aircraft was limited to 50m to satisfy ICAO Category D requirements. Due to this wingspan limitation, 3m winglets were added to improve lift induced drag effects. For the nominal aircraft, only trailing edge single-slotted fowler flaps are required to achieve the required maximum lift coefficient. The wing aerodynamics were modelled using AVL and profile drag for the aircraft was estimated using empirical calculations from Jenkinson [5].

7.3. Wing Structural Design

The wing torque box configuration was designed as a conventional stiffened-skin structure in order to de-risk the overall aircraft structure due to the novel elliptical fuselage, V-tail and rear-engine pylon structural elements present within the design. In order to enable a 'common' wing structure across the oVal concept family, the structure was sized to sustain ultimate loadings based on the MTOW of the 'stretch' oVal variant (195,000kg). The wing is to be manufactured using Carbon Fibre Reinforced Polymer composites for the primary structural elements. The mass of the complete composite wing structure was calculated to be 14,800kg and provides a mass saving of 991kg when compared to an Aluminium Alloy structure. This results in a $200 per trip (1000nm DOC mission) saving due to the use of a composite wing structure.

7.4. Fuselage and Empennage Structural Design

The elliptical fuselage structure was also designed to be a conventional stiffened-skin structure. Carbon Fibre reinforced composites were required to sustain the cabin pressurisation of 6000ft at the aircraft ceiling, especially considering the elliptical fuselage cross section. In order to support the fuselage skins under pressurisation, the fuselage floor beam was required to be a primary structure element. The final mass of the fuselage was 22,000kg. The empennage structure required careful design to safely integrate the engines and V-tail. The engines are supported by two carbon fibre composite pylon beams; one attached to the aft pressure bulkhead and the other attached to a solid fuselage bulkhead at the rear of the PAX cabin. The structural design was based on the B727 to reduce certification risk [6].

7.5. Weight, Balance, Stability and Flight Control

The current MTOW of the oVal concept is 175 tonnes and was calculated by combining the guidance provided within the Airbus specification [1], empirical estimates from Toreenbeek [7] and the calculated airframe masses from the structural specialists. The mass of the aircraft had increased by 25 tonnes from the PDR estimate due to several over conservative mass estimates from the structural group due to the use of a 'black metal' approximation for composite materials. A critical success of the oVal design is achieving no restrictions for the standard aircraft loading procedure (window-aisle-middle) in both the two class and high density seating arrangements. This is a common challenge with rear engine aircraft, and was achieved by using aft wing and therefore aft landing gear position on the aircraft. The V-tail of the aircraft was sized using conventional methods to determine the appropriate projected horizontal and vertical tail plane areas for the longitudinal and lateral requirements. These resulted in a 16% static margin and a 19% manoeuvre margin. The Ruddervator area of 25.9m^2 was sized by trial and error, due a lack of existing design data, in order to meet the take-off rotation and engine out requirements.

7.6. Landing Gear

The landing gear was sized to optimise the landing gear height to achieve high utilisation, resulting in the key challenge of achieving a stable landing gear track of 7.2m whilst minimising the length of the landing gear. The resulting landing gear configuration was a 2 x 4-wheel bogie main landing gear (MLG) with a 2 wheel nose landing gear (NLG). The landing gear integrates into the fuselage immediately aft of the wingbox. The landing gear was sized to achieve ICAO D airport compatibility and an ACN of 50.3 to provide comparable pavement loading to the B767-200 [1]. In addition, other load case requirements such as, dynamic loading 10 ft/s at maximum landing weight (MLW) and 0.5g turning case (CS25.473 and CS25.495 respectively[8]) were investigated. The tyre diameters are 46 inch and 40 inch for the MLG and NLG respectively. The landing gear weight was estimated using Currey's [9] method and was found to be 6,293kg for main landing gear and 1,100kg for nose landing gear.

7.7. Operational Performance and Propulsion

The engine sizing was based on satisfying the initial cruise altitude with 300ft/min climb rate and FAR 25 requirements. The critical sizing case was the FAR 25.121(OEI) second segment climb, resulting in a thrust to weight ratio of 0.321. To achieve the FAR requirements the sea level static thrust of the UBB-45 turbofan engine was 62,113lb. This resulted in a specific fuel consumption of the engine of 0.442 lbm/hr/lbf which translates into design mission fuel burn of 42,500kg. The engine was mounted to the rear fuselage using the twin-beam pylon structure. The oVal concept was designed to comply with International Civil Aviation Organisation (ICAO) noise limit for approach (95.8EPNdB), side-line (97.5EPNdB) and flyover (92.1EPNdB).

7.8. Avionics, Fuel and Power Systems

The avionics suite of the oVal concept consists of a fly-by-wire and fail-operational Automatic Flight Control System (AFCS) with full envelope protection. This configuration of the AFCS ensures that the oVal concept's avionic suite is consistent with the modern Boeing product range (e.g. B777 [10]). An "all-glass" flight deck using Head-Up Displays shall be used to enhance the human-machine interface.

The oVal concept replaces conventional pneumatic and hydraulic systems with an all-electric architecture (***Figure 9***) to allow 'Bleedless' operation of the UBB-45 engine and to potentially reduce the mass and maintenance burden of the aircraft's systems. A peak electrical demand of 1.3 MW was identified through combining the B787 electrical cabin pressurisation demand (1.4MW) [11] and the A330 mechanical pumping demand (hydraulics, engine fuel and oil supply – 0.34MW) [12]. These demands were then scaled by a factor of 75% (the ratio of the oVal concept's MTOW and the B787/A330 MTOWs). Electrical generation shall be provided by the B787 architecture of 2 variable-frequency direct drive generators per engine, 1 gas-turbine APU and Lithium-polymer batteries [11]. Electrical flight control actuation and landing gear retraction will be achieved using Electro Hydrostatic and Electro Mechanical actuators.

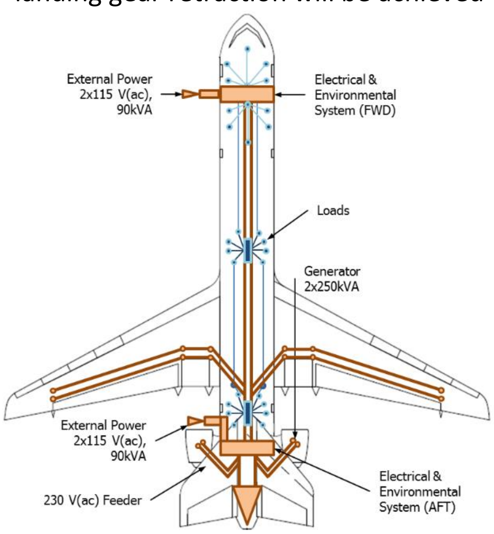


Figure 9: oVal electrical architecture.

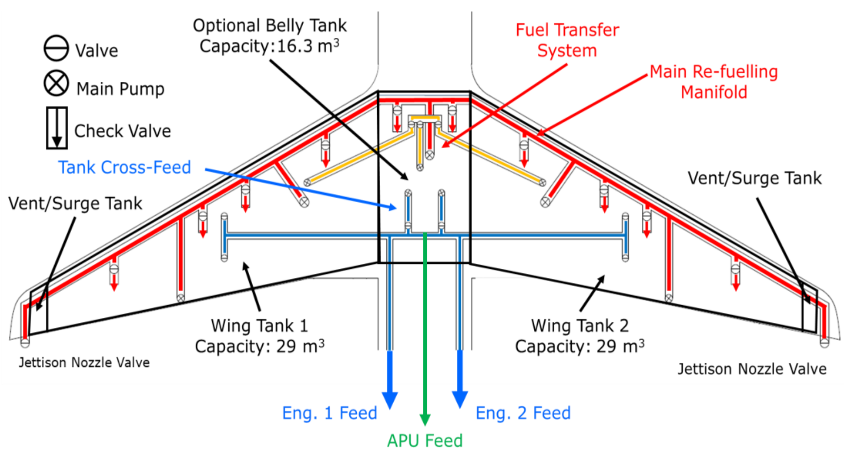


Figure 10: Wing fuel tank architecture.

The oVal concept's fuel system consists of 1 'wet-wing' fuel tank per wing. A 16 m^3 belly tank is also fitted to permit extended range operations and to enable a common wing to be used across the oVal concept family. Within the empennage, duplicated electrically-pumped engine fuel feeds have been used to minimise the risk of fuel supply loss in the event of an engine disk-burst (***Figure 10*** and ***Figure 11***).

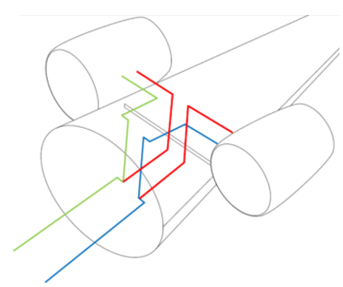


Figure 11: Empennage fuel feeds.

8. AIRCRAFT CHARACTERISTICS vs. SPECIFICATION

8.1. Specification Verification

Table 6: The verification matrix used to identify whether the final oVal concept satisfied the project specification.

Specification [3] item	Requirement classification	Required value	Oval value	Spec. Satisfied?	Reference
Passenger Capacity (2 – Class)	Hard	200-250	225	**Y**	A
Design Range	Hard	3500-5000nm	4500	**Y**	B
Design Cruise Speed	Hard	0.82-0.86	0.84	**Y**	C
Time To Climb (1500ft to ICA at ISA)	Hard	<=30 mins	28 mins	**Y**	D
Maximum Cruise Altitude	Hard	41000ft	41000ft	**Y**	E
Approach Speed	Hard	<=140kts CAS	140knts CAS	**Y**	F
T/O Field Length (MTOW, S-L, ISA+15)	Hard	1800m	1700m	**Y**	G
Landing Field Length	Hard	1350m	1661m	**N**	H
One Engine Inoperative Altitude	Soft	-	16500ft	**Y**	I
VMO/MMO	Hard	360kts / M_{CR} + 0.04	360kts / 0.88	**Y**	J
Equivalent Cabin Altitude (at 41000ft)	Hard	6000ft	6000ft	**Y**	K
Turn-Around Time	Soft	30 mins	30 mins	**Y**	L
Airport compatibility limits	Soft	ICAO D	ICAO D	**Y**	M
ACN (Flexible B)	Soft	< 60.0	50.3	**Y**	N
DOC target	Soft	-15%	-11%	**N**	O
ETOPS capability (at EIS)	Hard	180 mins	180 mins	**Y**	P

Table 6 displays the oVal concept's fulfilment of the various 'hard' and 'soft' requirements identified from the specification during requirements analysis. The aircraft successfully satisfies 15 of the 17 requirements. It should be noted however, that the 'hard' Landing Field Length requirement is not currently satisfied due to the omission of certain aircraft features (*detailed below*) in the calculation procedure. It is therefore fully expected that this requirement will be achieved in practice, resulting in the overall aim of a 15% DOC reduction being the only requirement not currently fulfilled by the oVal concept. A comparison between the oVal concept characteristics and the specification requirements is detailed below displaying how each requirement is satisfied by the aircraft:

A. The passenger capacity of 225 was chosen based on the market research done prior to the aircraft design which placed the aircraft in a unique position in the market, allowing a competitive market placement for the shrink and stretch variants.

B. The design range was also chosen based on prior market analysis which suggested 3750nm was the required range in order to fly transatlantic as well as reach most of the South East Asia Pacific market from China. However, when factoring in wind data, a range of 4500nm was selected in order to meet the 3750nm still air range.

C. The design cruise speed of 0.84 was selected as a compromise between; reducing the required wing area to minimise lift induced drag, minimise flight time to decrease the overall amount of fuel burnt and preventing the large onset of wave drag from flying too quickly. It was found that the reduction in block time was not significant enough to influence the decision on design cruise speed.

D. Time to climb was met due to the engine providing enough thrust for an average climb rate of 1210ft/min which produced a time to climb of 27.7mins.

E. Maximum cruise altitude can be achieved by increasing the cruise time at the initial cruise altitude to burn fuel before reaching the ceiling or it can be reached with a lower fuel load and payload.

F. Single-slotted fowler flaps were employed in order to meet the approach speed case on landing, using a C_{LMAX} of 2.49.

G. Take-off field length is achieved due to the take off static 62,000 lb static thrust of each engine exceeding the aircraft drag in take-off configuration allowing a take-off field length of 1700m.

H. Landing field length was not achieved in the current design due to the landing calculations not considering the use of spoilers or thrust reversers on the aircraft. In addition, a very conservative estimate of the co-efficient of friction equal to 0.3 was used for the runway, meaning if the friction was relaxed to an upper bound of 0.5, the aircraft would have met the landing requirements.

I. The critical engine sizing case was from FAR 25.121(OEI) second segment climb which gave a thrust to weight ratio of 0.321 and setting the thrust at 62,00lb per engine produced the OEI altitude at 16500ft.

J. The engine is capable of providing sufficient thrust to ensure that both the maximum operating speed of 360kts and the maximum operating Mach number of 0.88 (M_{cr}+0.04) are achievable.

K. The equivalent cabin altitude requirement is satisfied by the oVal aircraft, although it should be noted that this is based upon the pressurisation of a circular fuselage. Crude initial calculations assessing the effect of the elliptical shape have been conducted and suggest that the cabin pressurisation requirement can still be fulfilled by the elliptical fuselage, although considerable additional structural support will be required to mitigate the larger pressurisation loads.

L. It is expected that a turnaround time of 30 minutes or less can be achieved [13], with the aircraft benefitting from the high utilisation associated with a rear-engine configuration and the integrated airstairs that allow for quick passenger loading/unloading.

M. A wingspan of 50m ensures that the aircraft satisfies the ICAO code D requirement of a wingspan between 36m-52m.

N. An Aircraft Classification Number (ACN) of 50.3 was achieved for a flexible pavement of medium strength (class B), fulfilling the requirement of being less than 60. The ACN of an aircraft is mainly dependent upon the mass per MLG tyre, as such, an 8 MLG tyre configuration was chosen. The resultant mass per tyre value is 21882.5kg which constitutes the above mentioned ACN value of 50.3, once tyre spacing and tyre pressure considerations are made.

O. A DOC target of 15% savings was set in the specification and current estimates suggest the oVal aircraft can achieve savings of 11%. This value is highly subjective to change due to the many simplifications and assumptions made throughout the design process. Estimations have generally been conservative throughout, implying that the savings are more likely to increase following further detailed design.

P. The ETOPS certification standard of being able to fly any route that falls within 180 minutes of single-engine flight time to the nearest airport was deemed to be satisfied. The rear-engine configuration of the aircraft proves to be beneficial in the case of an engine out, due to the reduced yawing moment produced by the thrust imbalance, suggesting that the ETOPS performance will be superior to a conventional counterpart aircraft. The specified ETOPS level of 180 minutes is notably greater than the 120 minutes that is generally seen as being sufficient for Transatlantic flight, ensuring that the aircraft can safely travel to the majority of worldwide destinations.

Q. The expected 2025 entry to service requirement is expected to fulfilled, assuming that there are no considerable delays during the manufacture and assembly of the aircraft. The maturity levels of the various technological aspects of the aircraft are all sufficiently high enough to assume that they will not hinder the progress of the development of the aircraft (see ***Section*** **9**).

8.2. Satisfaction of Regulatory Requirements - Evacuation

The passenger capacity of 259 (in High Density) drove the placement and sizing of the emergency exits: 4 type A exits at 110 rating, 2 type C exist at 55 rating and two pairs of type III over wing exits at 35 rating allows this. The furthest distance between emergency exists 54.2 ft (from second set of doors to the over-wing exits) and therefore is within the 60ft requirement. ***Figure 12*** shows the positioning of the emergency evacuation slides. The slide sizing was driven by slide spacing and inlet clearance at the rear engine.

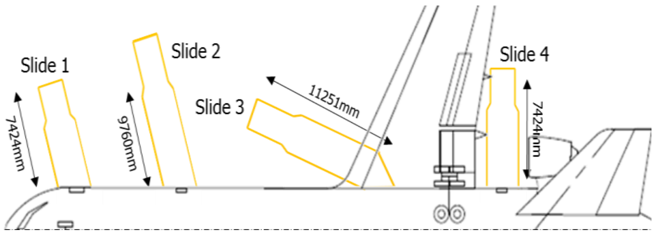


Figure 12: Emergency evacuation slide positions.

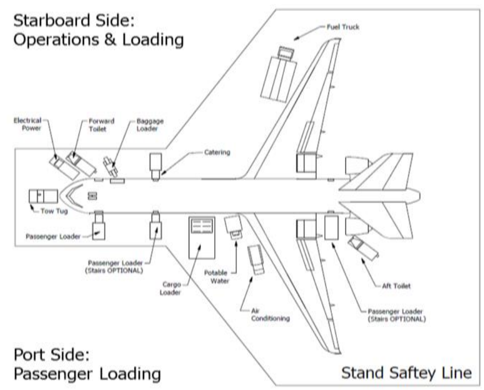


Figure 13: oVal concept ground loading.

8.3. Satisfaction of Design Drivers – High Utilisation

Due to the oVal's rear engine configuration, it is believed that a turn-around time of 30 minutes can be achieved, based upon the B767 ground handling manual [13]. Whilst this time is rarely achieved in-service, the design team are confident that the oVal concept could regularly achieve a turn-around time of 30 minutes. This is due to the integrated airstairs enabling the loading/unloading of PAX as soon of the aircraft arrives on stand without waiting for jetways or ground-based airstairs. This configuration will be particularly attractive to cost/charter operators, or airlines which operate into airports with developing infrastructures in expanding markets. In addition, the galley areas within the cabin have been grouped at the large 'A' class doors between the FC and YC cabin sections. This enables the galleys and interior to be serviced using only one door during the turnaround (***Figure 13***). These features support the 'high utilisation 'design driver'.

9. TECHNOLOGY AND RISK ANALYSIS

9.1. Risk Analysis

A risk analysis was conducted in each of the technical specialist areas as well as on the project/design overall. A standard if/then approach was taken in order to quantify the likelihood and severity of impact of the risk. The matrix in ***Table 7*** was then used to order the rank the risks. A summary of the risks is provided in ***Table 8***.

		Severity				
		Very Low	Low	Medium	High	Very High
Likelihood	Very High	L	M	H	VH	VH
	High	VL	L	M	H	VH
	Medium	VL	L	M	H	H
	Low	VL	L	L	M	H
	Very Low	VL	VL	L	M	M

Table 7: Likelihood vs Severity Risk Matrix

Table 8: Summary of oVal concept risks.

Risk			LLH	SEV	Risk Level
#	If	Then			
1	The composite engine pylon is not certifiable under current safe life fatigue regulations.	The aircraft will not be certified to fly.	M	VH	H
2	The electrical system is not certifiable under current hydraulic/electric system regulations.	The aircraft will not be certified to fly.	L	VH	H
3	The Flight Control System is not certifiable as it implements new control laws to account for the V-tail aerodynamics.	The aircraft will not be certified to fly.	L	VH	H
4	The fuselage structure is unable to retain the elliptical shape under pressurisation.	The fuselage will need to be redesigned and reinforced resulting in a significant weight and cost penalty.	M	H	H
5	The landing field length calculation has not taken into account the effect of spoilers or thrust reversers.	The landing field length requirement will not be met.	H	M	M
6	The V-tail performance is incorrectly predicted using current analysis methods.	The V-tail will need to be increased in size incurring a weight, cost and drag penalty.	M	M	M
7	The empennage is susceptible to acoustic fatigue from the engines.	The empennage structure will have a reduced fatigue life.	H	M	M
8	The engine disk burst failure case takes out both the V-tail planes and control surfaces.	The aircraft will suffer loss of control.	VL	VH	M
9	The aircraft design scales poorly for the stretch and shrink variants.	The stretch and shrink aircraft will require significant redesign and analysis resulting in increased development costs and/or the aircraft will be inefficient to operate.	H	L	L
10	Acquisition of titanium proves difficult due to economic or political factors.	The cost of titanium and the aircraft cost per unit will increase.	L	M	L
11	The empirical weight estimation methods are incorrect for novel and advanced aspects of the aircraft's design.	The aircraft will have been sized to the wrong weight and be inefficient in flight.	L	M	L
12	The landing gear is oversized due to an overestimation of 25% for loading.	The landing gear and aircraft will be heavier than necessary.	M	L	L
13	Crude analysis methods have resulted in incorrect design features of the aircraft (such as landing gear position).	The aircraft will not perform as expected.	L	M	L

9.2. Discussion, Mitigation and Technological Challenges

In a number of significant cases, the action required to mitigate risks also coincides with the areas of technological development that would be required for the successful implementation of the design. A number of risks and challenges during the design have been due to the novel and unconventional aspects of the aircraft, specifically the rear engines, V-tail and elliptical fuselage. Risks 1, 4, 7 and 11 could be mitigated by developing increased knowledge of the behaviour and certification requirements of composite materials. By tailoring the properties of the composites to the novel aspects of the structure, and with increased certainty in their use, it would be expected that as time progressed, the risk associated with the composites and the novel structural aspects would be mitigated. It would also be anticipated that the use of composites would be able to provide a net weight saving on the aircraft as a whole.

The electrical and control systems of the aircraft are also the cause of a number of risks. For the EIS of 2025 it would be expected that aircraft would be more electric, and therefore environmentally friendly, than the 2010 state of the art. The electrical system of the design has therefore been designed by scaling Boeing 787 with added systems (flight control surfaces and landing gear actuation) also being powered electronically. The current estimated peak demand of the electrical system is comparable with the B787, however this value may increase in order to provide redundant electrical supply to the flight control system. This will present a certification and technological development risk. In addition, more complex flight control laws would also be required for V-Tail, therefore requiring a significant amount of development and testing. The electrical and control systems would therefore be required to be developed so that this scaling was achievable and certifiable, in order to mitigate risks 2 and 3.

A number of risks are also due to the fidelity of the design available at this stage. In particular, risks 5, 9 and 13 all arise due to the crude methods of analysis which have currently been used to date. These risks would need to be monitored as the design progressed and more refined analysis methods were used. In addition to increasing the fidelity of analyses, new analysis methods such as those applied on the V-tail would require validation in order to ensure that performance was as predicted, mitigating risk 6. Further studies in each of the areas above would also need to be carried out with the other family variants of the oVal concept in order to further mitigate risk

9.3. Aircraft Materials Breakdown

Composite materials represent a significant area of applying state of the art technology to the oVal concept. ***Figure 14*** shows the distribution of materials across the structure. Both the fuselage and the wing structure will feature predominately carbon fibre reinforced composite in the primary structure (e.g. wing and fuselage skins). The V-tail will also be of composite construction. Glass fibre reinforced composite will be used in areas of the aircraft that require increased impact resistance such as the leading edges of the wing. The engine pylons are also of carbon fibre composite construction, and therefore as Identified above pose a certification risk. However, with the B787 and A350 in revenue service with composite primary structures, it is expected that this risk will reduce in the decade leading up EIS. Titanium alloy is also used on the structure for carrying concentrated loads, such as the landing gear mounts, wing-fuselage joint and lug mounts of the engine pylons.

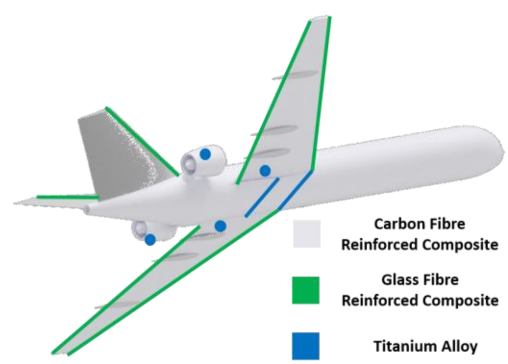


Figure 14: oVal concept materials breakdown.

10. ECONOMIC ANLYSIS AND COMPETITIVE POSITION

This section of the report provides an overview of the economic performance of the aircraft through assessing the oVal concept against its financial impact on the operator and manufacturer and analysing the market coverage offered by the oVal concept family.

10.1. Costs to the Operator

One measure of the effectiveness of a new aircraft is the costs of its operation. The target for the oVal was to save 15% of the direct operating costs against the state of the art in 2010 at its entry into service in 2025, for a 1000nm trip. The benchmark for comparison was taken to be a scaled down Boeing 787-8 with Rolls Royce Trent 1000 engines which was 'entering production' in 2010, described here as the 'Boeing 787-MIN'. The final design was found to save 11% of the direct operating costs

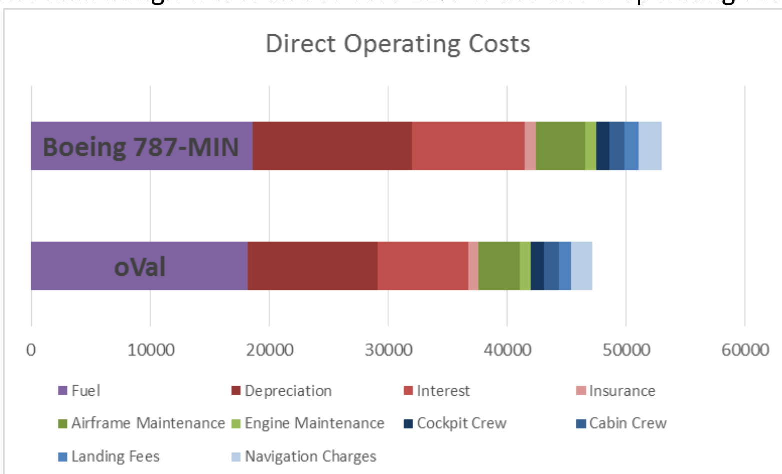


Figure 15: A comparison of DOCs between the B787-MIN and the oVal concept.

Figure 15 shows the differences between the direct operating costs (DOCs) of the B787-MIN and the oVal final design. The costs of the fuel for the 1000nm trip are in purple. It is clear that there is very little difference between the two aircraft and the oVal only achieves a 2% saving over the 787-MIN. This is due to weight of oVal design being heavier than what might be expected from a composite aircraft, as the analysis techniques used in the structural design were not refined enough to fully utilise the potential benefit of composite materials. The flying costs (excluding fuel), shown in blue, and the maintenance costs, shown in green are both a small fraction of the overall DOCs. The oVal makes savings in both, costing 6% less in flying costs and 12% in maintenance costs. The latter is largely driven by the relatively simple engine characteristics yielded by the performance analysis.

The biggest contribution to the 11% DOC saving is the financial costs of depreciation, interest on loans and insurance. These are all calculated using functions of the manufacturer's study price (MSP), for which the oVal's value of $170 million is significantly less than the 787-MIN at $212 million. This saving is largely driven by the fact that in 2010, the state of the art for primarily composite wide body airliners was in its infancy with Boeing's 787 Dreamliner programme being the first to enter production. This meant that due to a relative lack of experience in designing, manufacturing and certifying composite airframes, the development and production costs were high. For the oVal concept, the expected entry into service date of 2025 means that the industry will have had 15 years of producing and operating composite wide body airliners and as such the manufacturer's study price is expected to be lower than that of a B787.

10.2. Costs to the Manufacturer

Developing a new aircraft programme of the magnitude that the oVal would warrant represents a vast expense to the manufacturer. Using Roskam's [14] method for estimating the aircraft costs, the non-recurring costs (NRCs) were found to be $14.7 billion. The recurring costs (RCs) for delivery of one aircraft were found to be $84 million. This value was calculated for a production volume of 700 aircraft. In reality, the recurring costs of an aircraft will vary with the number produced. As the manufacturer delivers more aircraft, there is a learning curve, which is driven by a greater knowledge of the processes required to manufacture aircraft after more have been made. This results in more efficient and therefore cheaper manufacture. Roskam's method uses this concept.

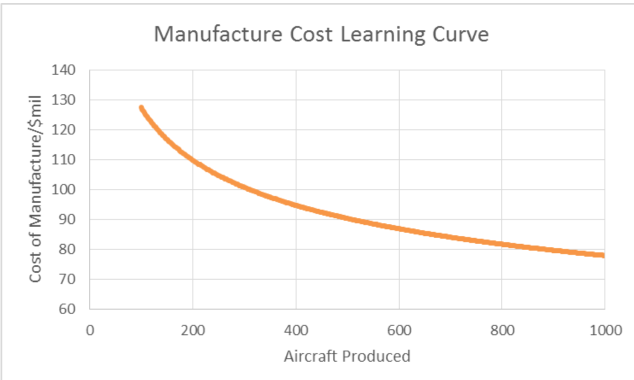


Figure 16: Manufacturing 'Learning Curve'.

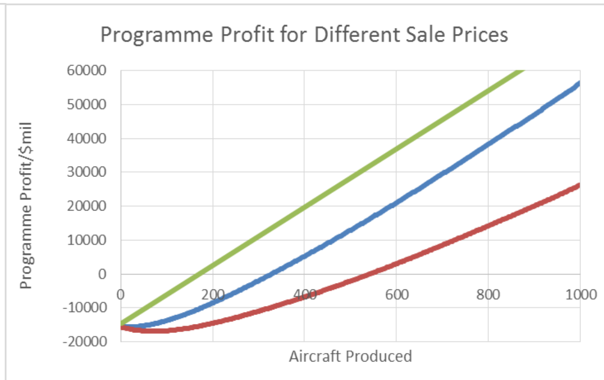


Figure 17: Programme Profit vs Sale Price

Figure 16 shows how as more aircraft are produced, more is 'learnt' by the manufacturer and so the cost of manufacture falls. ***Figure 17*** uses this data to show the profit and loss of the aircraft programme as the number of aircraft produces increased. As the recurring costs fall, assuming a fixed sale price, the profit per aircraft rises increasing the manufacturer's overall profit. The graph in blue shows the profit if the aircraft are sold at the manufacturer's study price of $170m.

However, in reality the vast majority of aircraft sold are done so at a discounted price. The red graph takes a more realistic view, taking the sale price as $140m or a 22% discount, in reality this trend is often even greater than shown here, with discounts of up to 45% [15]. For comparison, a simplistic model is shown in green, where the aircraft is sold at the MSP and the RCs are set to a nominal $84million (the same as when 700 aircraft are sold).

Due to the high starting point of the learning curve, the first aircraft produced are sold at a loss, for the red graph, this is the first 64. This means that the cost of the programme to the manufacturer continues to increase, up to a maximum of $17.0b, an additional cost of $2.3b on top of the NRCs. After this point, the aircraft are sold for an increasing profit, with the programme breaking even at 540 sold. In terms of time and delivery dates, assuming the average rate of production of the aircraft will be similar to the B787 and enough are ordered to warrant a maximum production rate, the breakeven point of 540 aircraft would be expected after 3.5 years of production. If production commences at the start of 2025, the 540th aircraft can be expected midway through 2028.

10.3. Family Variants and Market Position

The oVal's design allows alternative variants of the airframe to be designed and manufactured with far less investment than the original programme for the nominal version. This is achieved by having a common wing across the aircraft family, and through adding or removing fuselage frames to stretch or shrink the aircraft (see ***Figure 18***). From stretching, the capacity can be increased up to the region of 250 passengers and decreased to 200 for the shrink aircraft (both in 2-Class configuration).

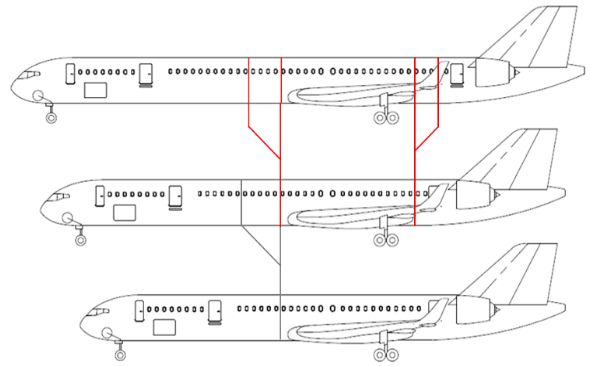


Figure 18: oVal concept family variants.

Figure 19 shows the market position of the oVal variants, with other in production aircraft shown in blue, future aircraft in orange and out of production aircraft in white. The oVal family is well placed to operate in a very similar way to the B767, with similar passenger numbers and a range of up to 5000nm without extra fuel tanks and possibly up to 6000nm and beyond in the extended range variants.

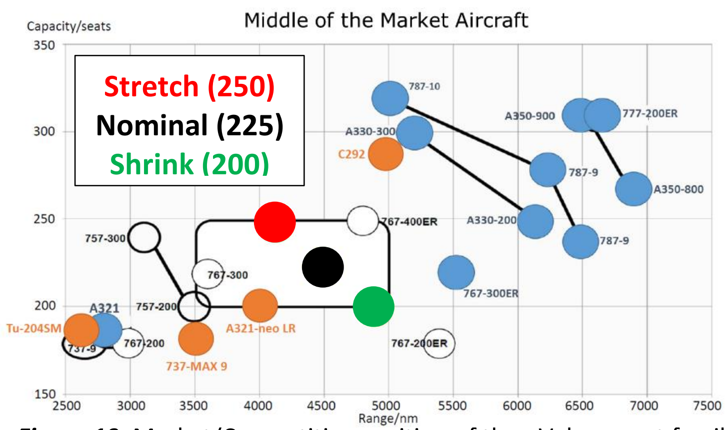


Figure 19: Market/Competitive position of the oVal concept family.

It is expected that the oVal will be primarily sold in emerging markets, with the established US and European markets leaning towards higher capacity wide body aircraft such as the Boeing 787 and Airbus A350 [16]. However, in the emerging markets in Asia, it can be expected that in the coming years that there will be significant demand for more wide body airliners with smaller passengers capacities. If predictions are accurate, the rapid growth expected in Asia will be similar in nature to that seen in the USA in 1982 when the first B767 entered service [17]. With the oVal's potential for stretch, shrink and extended range variants, it could become a work-horse of Asian fleets as the B767 did in the USA.

11. CRITICAL ANALYSIS OF THE oVal CONCEPT DESIGN

From taking a high-level view of the oVal concept, an aircraft achieving a DOC reduction of 11% over the 2010 'state of the art' has been developed with clear steps identified to ensure that the concept will be technologically viable for an EIS of 2025. In order to critically analyse the design, the concept must be reviewed considering the impact on aircraft performance of the 'novel' aircraft configuration.

Firstly, the V-tail of the oVal concept was initially selected based upon the configuration's potential mass and drag reductions due to the reduced number of lifting and control surfaces required (i.e. 2 rather than

3 for a T-tail). However, it was found that the V-tail had a surface area 10m^2 larger than an equivalent T-tail which had been developed in parallel. Hence, the use of the V-tail increased the overall aircraft drag. On the other hand, the use of V-tail provided a 178kg mass saving over the T-tail. Therefore, when comparing the V-tail to the T-tail using the current DOC calculation methods, a $40 per 1000nm trip saving is achieved by implementing the V-tail configuration. As the V-tail only provides a marginal improvement over the T-tail when designed with the current analysis methods, it can be considered to be ‘performance neutral’. Due to this, the V-tail does not provide a significant contribution to the 11% DOC reduction and therefore, the V-tail may not currently offset the engineering effort and cost required.

The elliptical fuselage cross section was also selected due to the potential for drag reduction. Following aerodynamic analysis of the fuselage, it was found that the elliptical fuselage reduced the drag originating from the fuselage by 8% when compared to a cylindrical fuselage section. However, a significant structural mass penalty of 5 tonnes resulted from supporting the pressurised elliptical fuselage section. Therefore, this offsets the reduction achieved in fuselage drag and results in the further development of the elliptical fuselage element of the concept being unfeasible due to its detrimental effect on the concept performance. Future design schemes should not include the elliptical fuselage within the configuration.

The final ‘novel’ element selected was the rear-engine aircraft concept and this was primarily chosen for the potential of increasing the utilisation of the aircraft through reduced turn-around times by using fuselage-integrated airstairs. Upon reflection, this element of the configuration isn’t beneficial for the design mission of 4500nm due to such routes having longer turn-around times compared to the 30 minutes turn-around times of domestic operations. However, the selection of a rear-engine configuration has been justified due to the markets that the oVal concept is targeted at. The oVal concept family is aimed at operating in emerging markets with developing airports and infrastructure. Therefore, the integrated airstairs enabled through the rear-engine configuration, will permit the aircraft to operate at airports that currently don’t have jetways capable of supporting an aircraft of this size. Essentially, the additional development costs associated with realising a rear engine aircraft are offset by the ability of the operator to capitalise quickly on new routes in emerging markets regardless of the maturity of the airport.

Returning to a top level view of the oVal concept, the aircraft as a whole is currently heavier than anticipated. The design team were expecting a final MTOW of approximately 150,000kg (similar to a B767-200). However, the current MTOW of the aircraft is 175,000kg. This 25 tonne increase is as a result of the heavy structural mass estimates for the wing and fuselage due to treating the composite materials as ‘black metal’. This significantly restricted the mechanical properties and design freedom available to the structural designers, resulting in a heavy structure. With improved analysis methods, the aircraft structure could be refined further, reducing the MTOW of the aircraft. This would translate into fuel savings and therefore increase the DOC savings offered by the oVal concept. Limited analysis methods and design data also hindered the design of the V-tail and elliptical fuselage. Therefore, further refined analysis is required before the performance impact of these novel configuration elements can be conclusively stated.

To summarise, the oVal concept represents a disruptive aircraft to the traditional derivative approach to aircraft design. The use of a novel configuration, whilst presenting certification and development challenges for the future, has provided an aircraft which can forge new paths in emerging markets allowing airlines to capitalise on blossoming routes at a potentially faster rate than if using a conventional aircraft. In addition, the marketing appeal of a novel configuration to airline passengers should not be underestimated, especially considering the public anticipation which existed for the conventionally configured Boeing 787 ‘Dreamliner’.

12. CRITICAL ANALYSIS OF WAY OF WORKING

Due to the iterative and multi-disciplinary nature of aircraft design, the oVal concept was sized after the initial PDR concept selection using 3 design loops (iterations). To enable the team to work collectively towards a common goal, each design loop had a specific objective (***Figure 20***):

- **1st Loop**: Establish a post-PDR baseline using improved empirical methods.
- **2nd Loop**: A performance driven loop focused on using DOC metrics to inform design decisions.
- **3rd Loop**: Detailed design and system integration checks.

As the maturity and complexity of the design and analysis increased throughout each design loop, sub-loops were often formed between a group of specialists to solve a specific design challenge. An example of this was during the integration of the landing gear which required an intensive sub-loop within the 2nd Loop between the Landing Gear, Wing Structural Design and Weight & Balance team specialists.

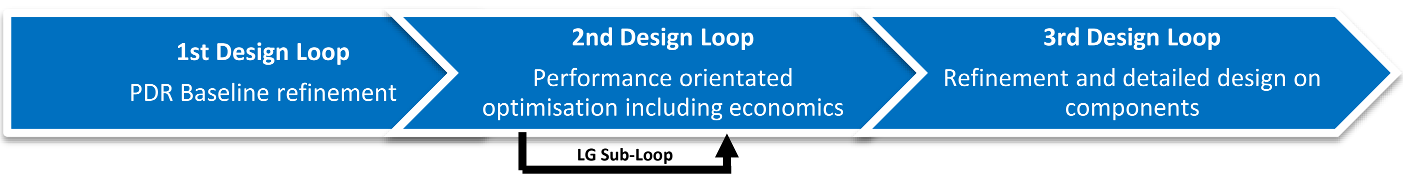


Figure 20: Design iteration/loop progression and aims. Note the Landing Gear (LG) Sub-Loop during the second design loop.

In order to conduct the group-wide design loops a robust workflow was required. An N^2 diagram identified the inputs and outputs and relationships between each technical specialism was developed. The order of the workflow was firstly developed through identifying the values that each team specialist believed they would need. Specialisms that altered the 'global' design of the aircraft (e.g. Aerodynamics and Structures) were placed at the start of the workflow and specialisms which generated 'performance' metrics of the aircraft (i.e. propulsion and economics) were at the end of the workflow.

However, it was identified that the N^2 diagram alone was insufficient to ensure that each team specialist was working to the same 'baseline' of design values. For this reason, the sizing procedure depended on an effective data sharing and update system, as well as regular meetings, to make critical decisions. Individual calculation sheets were not shared whereas their critical N^2 values were. Meetings were held twice a week for everyone to discuss changes and updates; however the Sub-loop teams were set to meet at their own discretion to enable the design to be pushed forward. A Group workflow conversation was set up online to ensure everyone was aware of the updates. Naturally, a transparent data management mechanism was required to give everyone the data they needed at the right time. Cloud Based storage such as Google Drive allowed a) a universally accessible medium to view and retrieve files and b) an editing platform that could be updated on-line (Google Docs/Sheets), meaning only one copy of any document was ever needed. This eliminated any information duplication.

The update procedure was a sign-off centred approach to ensure the right parties were informed of critical changes. The split between GA updates and Datasheet updates was made distinct: The impact on the different calculations was recorded using the live datasheet update system which occurred on a daily basis. The impact these changes had on drawings would often become prevalent once ALL the stakeholders in the change had processed it in their calculations, so to reduce the time inefficient process of updating drawings at every change, an ECN (Engineering Change Note) register was created to log the changes required to the GA/Drawing. This log was signed off and implemented every week This meant a new baseline of a GA/Cabin Layout/Drawings/Datasheet could be created every week, and previous versions logged to monitor improvement and mitigate the chance of data loss due to accidental deletion.

An anonymous group survey was conducted to quantitatively review the group's experience of the management process. All the contributions of the Project Management Input were ranked 1-6, with 6 being most satisfied, with every answer scoring 5 and above (***Figure 21***). Points of improvement were identified as using a defined system for group communications rather than a 'pseudo' system on the Facebook page to increase transparency.

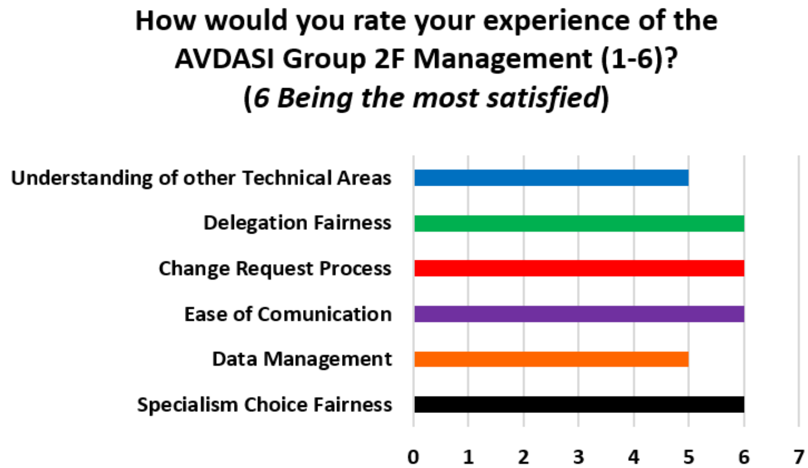


Figure 21: Results from the team survey regarding the management experience during the project.

13. CONCLUSIONS AND FUTURE WORK

This report has detailed the design of the oVal concept aircraft, from concept selection through to maturity at the FDR level. The oVal concept aircraft represents a disruptive 'middle of the market' aircraft focused at 'opening up' new routes in emerging markets. The rear-engine, V-tail aircraft configuration with an elliptical fuselage cross section presented numerous design challenges throughout the design iterations. Following economic analysis, the current FDR-level oVal aircraft achieves a DOC saving of 11% compared to the 2010 state of the art. However, this saving is not achieved through the use of the novel configuration elements and is achieved due to the reduced development costs for a predominately composite aircraft for EIS of 2025. Therefore, it is anticipated that a conventional aircraft configuration could have achieved a similar DOC saving. Nevertheless, the rear-engine configuration of the concept shows strong potential for operations within emerging markets through the use of integrated airstairs, removing the need to rely on jetways or ground airstairs which may not be available for an aircraft of this size at developing airports.

The V-tail configuration was identified to be 'performance neutral' whilst the elliptical fuselage was found to have a detrimental effect on the concept's performance. Therefore, the elliptical fuselage should be omitted from future design iterations. The V-tail shall be retained and further analysis is required to conclusively identify the performance and certification impact of adopting such a configuration.

Due to the novel concept and configuration selected, numerous design and analysis hurdles were confronted by the team through effective project management and engineering judgement. By combining an un-conventional configuration with currently accepted technologies, such as composites, a promising, innovative and versatile aircraft concept to satisfy the 'middle of the market' has been devised.

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