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Optimum Seat Abreast Configuration for an Regional Jet

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Abstract

This work illustrates the importance of a multidisciplinary approach in the conceptual design of aircraft fuselage. The characteristic slender body of regional jets make the fuselage abreast layout a significant variable that drives overall aerodynamics and structural characteristic of these aircrafts. The optimum DOC for the Embraer EMB 170 was calculated varying the seat abreast layout and consequently the length and diameter of the fuselage while the original longitudinal stability is maintained. These calculation used Class II methods for drag and weight prediction. The actual configuration showed to be the optim.um design.

1. Introduction

The fuselage configuration of a commercial aircraft affects directly in the Direct Operating Cost (DOC). The number of decks of large passengers is the most dramatic layout choice but the number seat abreast is an important variable as well. It is not clear why similar aircrafts are designed using different seat abreast configuration as illustrated in Table 1.

The fuselage design is a multidisciplinary tradeoff where structural and aerodynamics objectives need to be balanced to achieve an optimum fuselage design. Fixing a number of passengers to a given seat space, the number of seats per row changes the fuselage length and diameter. It influences directly in the weight and drag of the aircraft. That can be simplified as a compromise between wider, shorter and lighter fuselage that has more parasite drag or a longer and narrower fuselage with less CD_0 but heavier, affecting the induced drag.

Table 1: Difference of seat abreast configuration of regional jets

Aircraft	MTOW(kg)	Cabin Width(m)	Passengers	Number of Seat Abreast
Mitsubishi MRJ70	36850	2.76	80	2 + 2
Mitsubishi MRJ90	39600	2.76	92	2 + 2
Bombardier CRJ-700 NG	38330	2.55	90	2 + 2
Bombardier CRJ-1000 NG	41640	2.55	104	2 + 2
Embraer E170	38600	2.74	78	2 + 2
Embraer E175-E2	44800	2.74	88	2 + 2
Comac ARJ21-700	40500	3.14	90	3 + 2
Comac ARJ21-900	43616	3.14	105	3 + 2
Antonov Na-148 100B	41950	3.15	98	3 + 2
Sukhoi SSJ100	45880	3.24	108	3 + 2

1.1 Passengers Aircraft Seats Layout

The seats layout of a passenger aircraft can define the majority aspects of the fuselage to a given payload. The maximum use of the available area directly influences the passengers comfort and the profitability of the aircraft.

Double-deck passengers are the most notorious fuselage layout alternative. Two decks for passengers and an additional deck for cargo characterize them. The most famous double-deck is the A380 but the early icon was the

Boing 747 with its partial double-deck. Boing has built as well one of the first double-decks icons, the flyboat Boing 314 Clipper.

Aircrafts that can accommodate twin-aisles are denominated wide-body and usually have seven or more seats per row. Typically the choice of the seats configuration is not only important for the conceptual design but for market position as well. Airbus chose the wide-body configuration to reposition its A 350 in the market of Boing 777 instead of to make it a player of the Boing 787 as first planned.

The choice of seats per row of regional passengers is more sensible. The characteristic narrow bodies of these aircrafts accommodate few seats abreast, usually in a 2 + 2 configuration. Changing one column of seats has effects that are more remarkable in the fuselage diameter and length than in bigger aircrafts.

2. Methodology

To explore the influence of the seat abreast configuration in the regional jet segment, the Embraer EMB 170 was chosen as base aircraft where the actual 2 + 2 seats layout was evaluated against 1 + 2, 2 + 3 and 3 + 3 configurations. The Direct Operational Cost (DOC) of these different fuselage configurations are calculated using Class II Methods of weight and drag prediction from Ref.[1].

These Class II Methods of drag and weight estimation were implemented in the software Matlab®.

2.1 EMB 170 Regional Jet

The regional jet EMB 170 is one of the greatest top selling of the Brazilian company Embraer. This twin-engine jet airliner was conceived using a narrow body "double-bubble" design that accommodates up to 78 passengers in a single economic class. This configuration uses four passengers per row. In the present work, the configuration with 74 passengers per seat in a single class was chosen owing to be the configuration of Ref.[3].

Geometry, performance, mission and weight data are taken from Ref.[3]. to [7]. . They have ready information about mission performance and weight but some reverse engineering was necessary to get all geometric data needed to use Class II methods. With the absence of airfoils information to calculate the form factor and wetted area of the aerodynamic surfaces, the airfoil thicknesses was guessed as 13% for wing root, 12% for break position and 10% for wing tip. The thickness for vertical and horizontal tail was considered as 12% in all positions. The summary of the geometry data of the EMB 170 is show below:

Table 2: Summary of the EMB 170 geometry data

Wing		**Horizontal Stabilizer**	
Reference area (m2)	81.62	Volume coefficient	0.94
Aspect Ratio	8.28	Taper	0.39
Taper	0.28	Aspect Ratio	3.94
Wing Span (m)	26.0	Area (m2)	24.24
Break span (m)	4.7	Sweep (deg)	34.80
Sweep (deg)	22.6	Vertical Stabilizer	
Chord center line (m)	5.5	Volume coefficient	0.086
Chord center break (m)	3.3	Taper	0.28
Chord tip (m)	1.55	Aspect Ratio	1.79
Airfoil thickness (root)	13%	Area (m2)	17.29
Airfoil thickness (break)	12%	Sweep (deg)	40.1
Airfoil thickness (tip)	10%		

Motor		**Fuselage**	
Thrust per motor (kg.f)	63164.7	Fuselage height (m)	3.36
Weight per motor (kg)	1192.0	Fuselage width (m)	3.07
Motor length (m)	4.13	Fuselage length (m)	30.0

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While mission and requirements are shown in Table 3:

Table 3: Mission and requirements

Mission		Requirements	
Range (km)	3333.6	Payload (kg)	9100.0
Alternative airport (km)	185.2	V_{loiter} (m/s)	141.5
Total range (km)	3518.8	V_{cruise} (m/s)	241.9
Ceiling (m)	12497.0	V_{dive} (m/s)	309.6
$Mach_{cruise}$	0.82	Static Margin	7.50%
Loiter	1h		

2.2 Class II Weight Prediction Method

The Class II Weight Estimation Method calculates the weight of the main parts of the aircraft separately using geometric and performance characteristics. This Class II methods are used in the conceptual design phase when is necessary a more mature calculation of components and aerodynamic surfaces.

The maximum take-off weight of an aircraft is computed as follow:

$$\boldsymbol{W_{T0} = W_{crew} + W_{payload} + W_e + W_{fuel} + W_{tfo}} \tag{1}$$

where W_{crew} represents the crew weight, $W_{payload}$ is the payload, W_e is the empty weight, W_{fuel} is the weight of fuel and W_{tfo} is the trapped fuel weight in the fuel lines.

The assumptions used to calculate W_{crew} are:

- average weight of the pilots is considered as 100 kg including luggage
- average weight of flight attendants is 75 kg
- two pilots and three attendants compound the crew

The value of W_e was calculated using the equations presented in Ref.[1]. for the aircraft components: fuselage, nacelle, engine, landing gear, pilone, systems and aerodynamic surfaces.

Some of these equations of Ref. [1]. use a W_{TO} guess meaning an implicit calculation and an iterative method is necessary to achieve the final value of W_{TO}.

$$\boldsymbol{W_{T0\_error} = W_{T0\_GUESS} - W_{T0\_CALC}} \tag{2}$$

The iteration stops when the difference between the W_{T0_GUESS} and the W_{T0_CALC} is less than a half kilogram.

The fuel weight (W_{fuel}) is calculated using a mission that counts with an alternative destination.

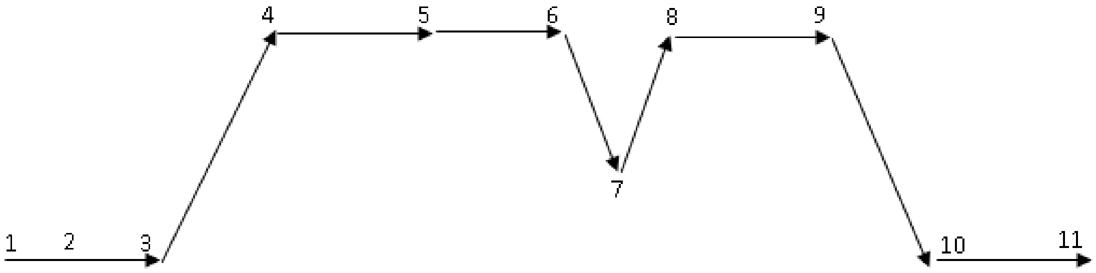

Figure 1: Mission used to calculate the fuel weight in a typical mission of the EMB 170

In each mission step, illustrated in Figure 1, there is weight loss due to fuel burning that is represented by ratio of the final step weight and the initial step weight.

The coefficient of the fuel fraction (M_{ff}) is defined as:

$$\boldsymbol{M_{ff} = \frac{W_1}{W_{T0}}\frac{W_2}{W_1}\frac{W_3}{W_2}\frac{W_4}{W_3}\frac{W_5}{W_4}\frac{W_6}{W_5}\frac{W_7}{W_6}\frac{W_8}{W_7}\frac{W_9}{W_8}} \tag{3}$$

The followed ratios were considered in according with Ref.[1]. :

Start-up and warm-up:

$$\frac{W_1}{W_{T0}} = 0.99 \tag{4}$$

Taxi:

$$\frac{W_2}{W_1} = 0.99 \tag{5}$$

Take-off:

$$\frac{W_3}{W_2} = 0.99 \tag{6}$$

Climb 1 and 2:

$$\frac{W_4}{W_3} = \frac{W_8}{W_7} = 0.985 \tag{7}$$

Cruise:

$$\frac{W_5}{W_4} = exp\left(\frac{-R\,C}{V\,(\mathrm{L}/\mathrm{D})_{\mathrm{cruise}}}\right) \tag{8}$$

where R is the cruise range, C is the engine specific consumption and V is the cruise velocity.

Descent 1 and 2:

$$\frac{W_7}{W_6} = \frac{W_{10}}{W_9} = 0.99 \tag{9}$$

Loiter:

$$\frac{\mathrm{W_6}}{\mathrm{W_5}} = \frac{\mathrm{W_9}}{\mathrm{W_8}} = \mathrm{exp}\left(\frac{-\mathrm{T}\times\mathrm{C}}{(\mathrm{L}/\mathrm{D})_{\mathrm{loiter}}}\right) \tag{10}$$

where T is the time spent in the step.

Landing and taxi:

$$\frac{W_{11}}{W_{10}} = 0.992 \tag{11}$$

Eq. (8) and (10) show that the weight estimation is dependent of the L/D of the aircraft. The $(\mathrm{L}/\mathrm{D})_{\mathrm{cruise}}$was calculated using Class II Method of drag prediction and the $(\mathrm{L}/\mathrm{D})_{\mathrm{loiter}}$ was inferred using the formulation of Raymer[1.] .

$$\left(\frac{L}{D}\right)_{loiter} = \frac{\sqrt{3}}{2} \times \left(\frac{L}{D}\right)_{Cruize} \tag{12}$$

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2.2.1 EMB 170 Weight validation

The Class II Method for weight was used in the actual EMB 170 design. The results are validated with the actual data and are shown below:

Table 4: Validation of Class II Method for weight estimation

Weights	**Actual (kg)**	**Calculated (kg)**	**Error**
W_{fuel}	6390	6458	1.06%
MTOW	35990	34698	-3.59%
MZFW	29600	28240	-4.60%

2.3 Class II Drag Prediction Method

The parasite drag is calculated for wing, horizontal tail, vertical tail, fuselage, nacelle and miscellaneous. This work uses the equations of Ref.[12]. . The estimation is calculated using the follow relationship:

$$\boldsymbol{C_{D0,i} = C_{f,i} F_i Q_i \left(\frac{S_{wet,i}}{S_{ref}}\right)} \qquad \textbf{(13)}$$

where $S_{wet,i}$ is the wetted area of the component i and S_{ref} the aircraft reference area.
The Table 5 presents the interference factors Q_i taken from Ref.[1]. and the laminar flow coverage ($k_{laminar}$) used to calculate the skin friction coefficients. The superficial roughness of all surfaces is assumed as 2.2 µm.
:

Table 5: Interference factor components

Component	$\boldsymbol{Q_i}$	**Laminar Flow**
Wing	1.0	25%
Horizontal Tail	1.0	25%
Vertical Tail	1.0	25%
Fuselage	1.0	15%
Nacelle	1.3	20%

$C_{f,i}$ is the friction coefficient and is given by:

$$\boldsymbol{C_{f,i} = \left(C_{f,i,laminar}\left(\mathrm{Re}_{\mathrm{i,transition}}\right) - C_{f,i,turbulente}\left(\mathrm{Re}_{\mathrm{i,transition}}\right)\right) . \mathrm{k}_{\mathrm{laminar}} + C_{f,i,turbulente}\left(\mathrm{Re}_{\mathrm{i,total}}\right)} \qquad \textbf{(14)}$$

where $\mathbf{k}_{\mathbf{laminar}}$ is the ratio of the component that is covered by laminar flow and was guessed as 25% for all components calculated.
F_i is the form factor fuselage, nacelles and aerodynamic and are calculated such as:

$$\mathbf{F_{fuselage} = 1 + \frac{60}{\lambda^3_{fuselage}} + \frac{\lambda_{fuselage}}{400}}\ , \quad \boldsymbol{\lambda}_{\mathbf{fuselage}} = \frac{\textbf{fuselage length}}{\textbf{fuselage diameter}} \qquad \textbf{(15)}$$

$$\boldsymbol{F_{nacelles}} = \mathbf{1 + \frac{0.35}{\lambda_{nacelle}}}\ , \quad \boldsymbol{\lambda}_{\mathbf{nacelle}} = \frac{\textbf{nacelle length}}{\textbf{nacelle diameter}} \qquad \textbf{(16)}$$

$$F_{aero\_surf} = 1.34\ \mathrm{M}^{0.18}(\cos\Lambda_{\mathrm{max\_th}})^{0.28}\ \left(1 + \frac{0.6}{x_{max_{th}} \cdot \bar{c}}(t/c) + 100(t/c)^4\right) \tag{17}$$

where $\cos\Lambda_{\mathrm{max\_th}}$ is the sweep at maximum airfoil thickness, $x_{max_{th}}$is the chord fraction of the maximum thickness and $\bar{c}$ is mean aerodynamic chord.

The excrescences were count in the parasite drag as an increment of the 5% of the final value.

The wave drag coefficient (C_{DW}) was calculate only for the wing using the formulation of Ref.[10]. and the constant K of the induced drag coefficient is calculated as Ref.[1]. . The total drag became:

$$C_D = C_{D0} + KC_L{}^2 + C_{DW} \tag{18}$$

2.4 Direct Operating Cost

The usual measure of the profitability of an aircraft is the Direct Operating Cost (DOC) of it.. The annual salary of the captain and first office are guessed as 85000 USD and 50000 USD respectively. The fuel price of 2.37 USD per gallon was picked up in December of 2014 in Ref. [14]. The Direct Operating Cost was calculated as Ref.[11]. :

$$\mathrm{DOC} = (\mathrm{C_{crew}} + \mathrm{C_{pol}} + \mathrm{DOC_{maint}} + \mathrm{DOC_{depr}} + \mathrm{C_{lf}} + \mathrm{C_{nf}})/(1 - (0.02 + \mathrm{frt} + 0.07)) \tag{19}$$

where:
C_{crew} – Crew cost
C_{pool} – Fuel and oil cost
DOC_{maint} – Total maintenance cost
DOC_{depr} – Total depreciation cost
C_{lf} – Landing fee cost
Cnf – Navigation fees cost
frt – Registration fees cost factor

3. Results

Using the model validated of the actual configuration, other three configuration where calculated.

These configurations differ from the actual one by the number of seats per row and the aircraft length that fits it. Each fuselage section is calculated using a Matlab script given by Prof. Bento[13.] .

The static margin and tail volume coefficients are maintained constant as the original EMB 170. It is necessary an iterative approach to achieve these targets. The iterative process is described below:

1) The origin is in the leading edge of the centerline as Figure 2
2) The static margin and tail volume are constants
3) The fuselage is moved forward and backward to correct CG in according to the static margin
4) The fuselage placement changes the volume coefficients and then the empenagens sizes are corrected
5) These corrections change the tail weight and consequently the CG position
6) The fuselage is moved iteratively until the CG convergence

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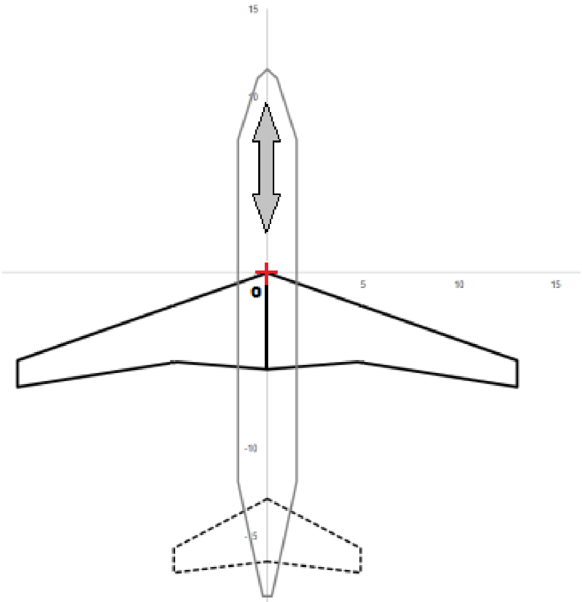

Figure 2: Origin fixed at leading edge of the wing centerline. The grey arrow indicates the fuselage movement

When the iterative approach of CG position and tail coefficients converge, an inner iteration of W_{TO} is started to correct the W_{TO_error} as shown in Equation (2).
The inner iteration related to W_{TO_guess} and the outer iteration related with CG position are sequentially perform until the global convergence is completed. The results for the three new configurations and the actual one can be seen in Figure 3. The longer configuration was named EMB 170 SB where SB means slender body. Analogously the 5 and 6 seats per row were named EMB 170 WB and EMB 170 UWB those are respectively wide body and ultra wide body. The configurations are not "wide body" in a strict meaning. They indicate that the new configurations are wider than the original one.

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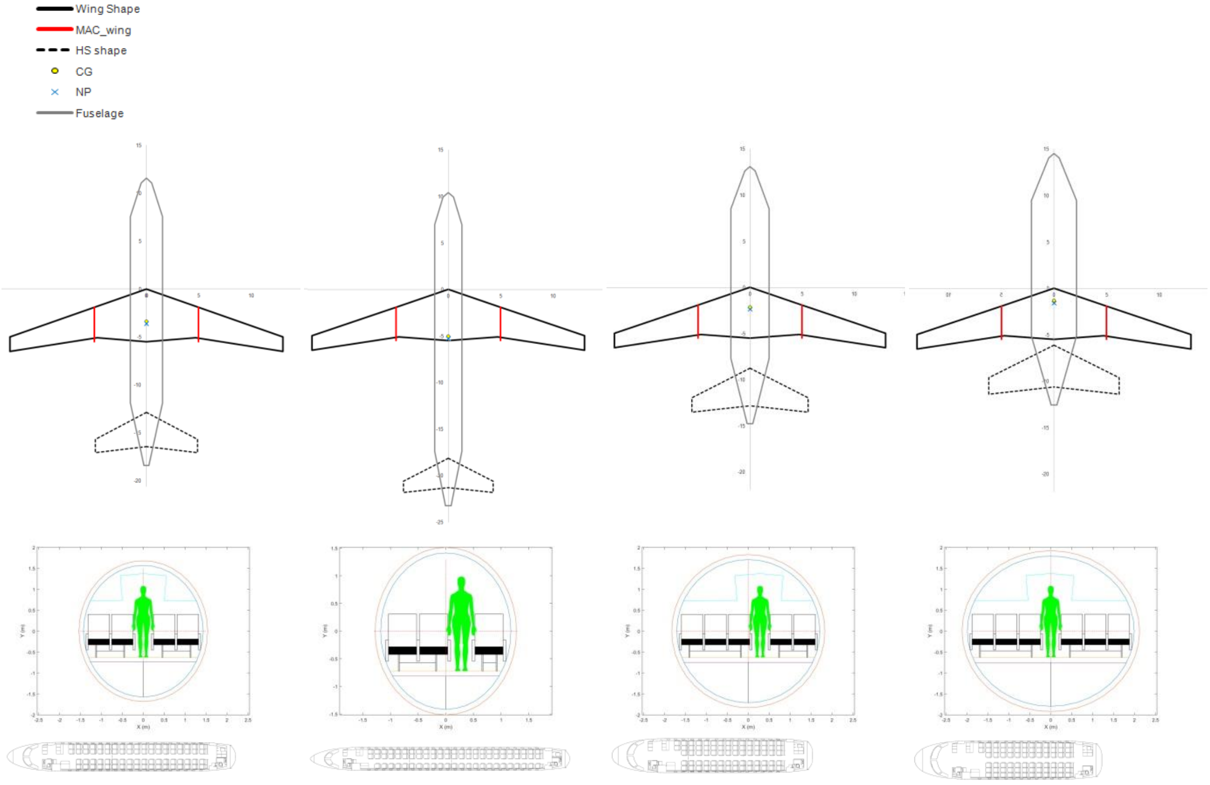


a) b) c) d)

Figure 3: EMB 170 schematic illustration of configurations with different number of seats per row: a) Actual design, b) SB, c)WB, d)UWB

The characteristic of each configuration and the results are shown below in Table 6. The DOC of the original configuration is the lowest one. It can drive to the conclusion that the actual EMB 170 configuration is the optimum configuration this type of aircraft and mission.

Table 6: Characteristic and results of the calculated configurations

	EMB 170	**EMB 170-SB**	**EMB 170-WB**	**EMB 170-UWB**
Passengers	74	74	74	74
Seats per row	4	3	5	6
Fuselage height (m)	3.36	3.03	3.66	3.84
Fuselage width (m)	3.07	2.56	3.66	4.24
Fus. height/width	1.10	1.20	1.00	0.90
$C_{D,0}$ (counts)	135	131	149	163
$C_{D,\mathrm{i}}$ (counts)	126	138	124	128
$C_{D,\mathrm{wave}}$ (counts)	22	28	21	23
$C_{D,cruise}$ (counts)	276	288	282	298
L/D_{cruise}	17.5	17.5	16.7	15.9
MTOW (kg)	34698	36303	34382	34878
MZFW (kg)	28240	29541	27790	27986
DOC (US$/nm)	4.83	5.02	4.86	5.01

The Table 7 shows main values of Table 6 as percentage of the actual values of the EMB 170. This table gives a better understanding of the sensibility of seat abreast layout.

Table 7: Comparative results between the new configurations and the original one

	EMB 170-SB	**EMB 170-WB**	**EMB 170-UWB**
Fuselage height (m)	-9.9%	8.8%	14.3%
Fuselage width (m)	-16.9%	18.9%	37.9%
$C_{D,0}$ (counts)	-3.0%	10.4%	20.7%
$C_{D,cruise}$ (counts)	4.3%	2.2%	8.0%
L/D_{cruise}	0.0%	-4.6%	-9.1%
MTOW (kg)	4.6%	-0.9%	0.5%
MZFW (kg)	4.6%	-1.6%	-0.9%
DOC (US$/nm)	3.9%	0.6%	3.7%

The comparison between Figure 4 with Figure 5 shows that the DOC result is a compromise between aerodynamics and structural influences. While the Figure 5a) illustrate that the L/D decrement with the increment of seats per row, the Figure 5b) shoes an inflection of the results tendency. The UWB configuration does not present the lowest W_{TO} as expected because in this particular configuration the additional tail size is more relevant in the final weight than the decrement of fuselage weigh.

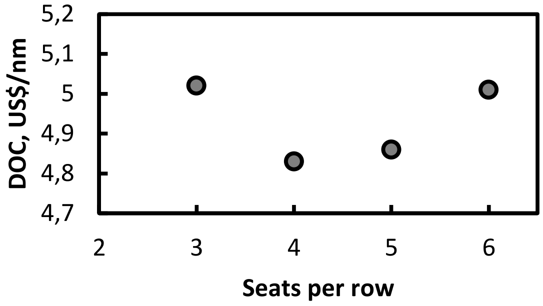
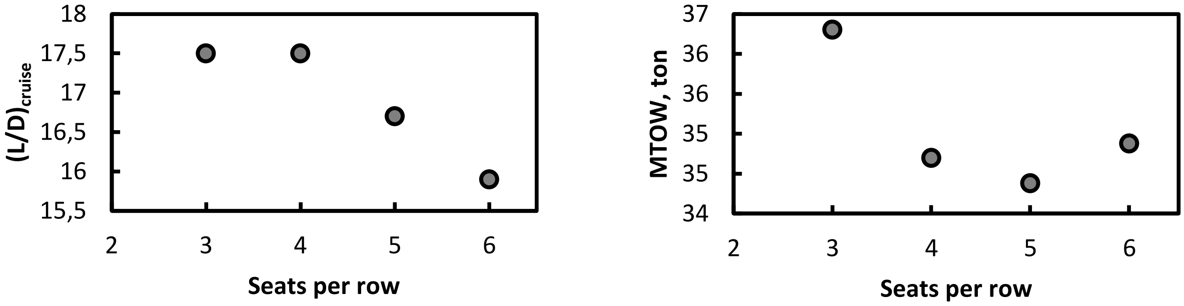


Figure 4: Direct Operating Cost of the different configurations

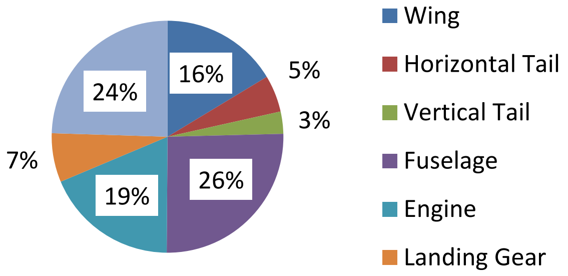


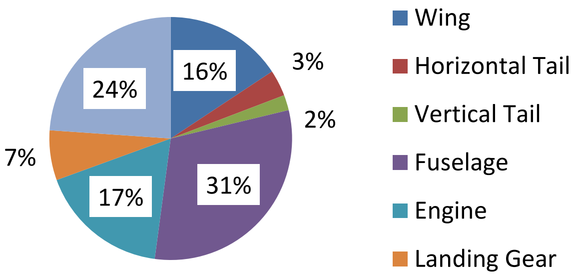
a)

b)

Figure 5: Aerodynamics vs structural characteristic of the different configurations: a) glide ratio, b) MTOW.

Figure 6 illustrate this tendency: the fuselage is lighter in UWB configuration than in WB but the increment in tail weight is enough to increase the W_{TO}.





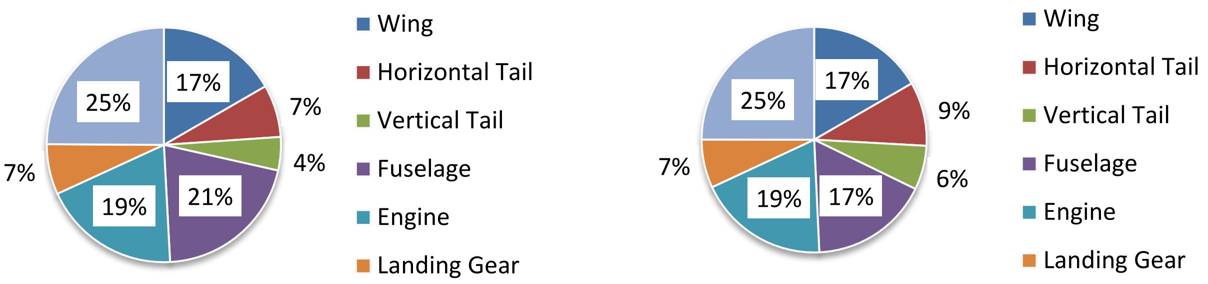
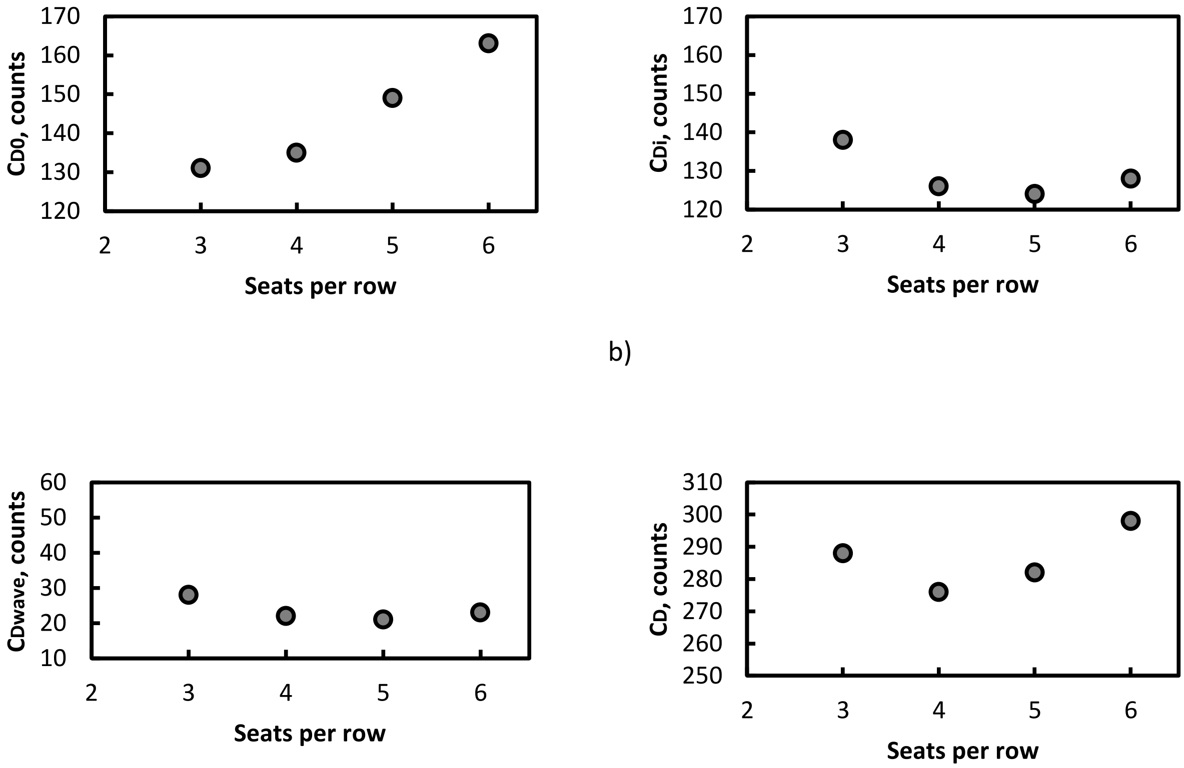


Figure 6: Influence of the static margin in the relative weight of the tail compared with the total empty weight

The parasite drag decrease while the fuselage is narrowed as shown in Figure 7 a). As expected the induced drag shown in Figure 7 b) follow the tendency of the MTOW because it is correlated with $C_L{}^2$. The same tendency, but soft, is shown in Figure 7 c) owing the wave drag is influenced by the wing load.



a)

b)

c)

d)

Figure 7: Different contributions of the total drag: a) parasite drag, b) induced drag, c) wave drag and d) total cruise drag

4. Conclusion

This work has shown how the tradeoff of a streamlined aircraft or a more structural efficiency can drive the aircraft conceptual design. As an example, the EMB 170 regional jet had the DOC calculated using Class II Method of drag and weight prediction. The results are compared with a narrower version and two wider versions that maintain the same volume coefficients of the tail and static margin. The original version showed to be the optimum design. The widest body has shown to be heavier than the second most widest owing to the increment of tail size to maintain the same static margin.

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