U.P.B. Sci. Bull., Series D, Vol. 75, Iss. 3, 2013 ISSN 1454-2358

FROM PRELIMINARY AIRCRAFT CABIN DESIGN TO CABIN OPTIMIZATION - PART I -

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This paper conducts an investigation towards main aircraft cabin parameters. The aim is two-fold: First, a handbook method is used to preliminary design the aircraft cabin. Second, an objective function representing the "drag in the responsibility of the cabin" is created and optimized using both an analytical approach and a stochastic approach. Several methods for estimating wetted area and mass are investigated. The results provide optimum values for the fuselage slenderness parameter (fuselage length divided by fuselage diameter) for civil transport aircraft. For passenger aircraft, cabin surface area is of importance. The related optimum slenderness parameter should be about 10. Optimum slenderness parameters for freighters are lower: about 8 if transport volume is of importance and about 4 if frontal area for large items to be carried is of importance.

These results are published in two parts. Part I includes the handbook method for preliminary designing the aircraft cabin. Part II includes the results of the optimization and the investigations of the wetted areas, masses and "drag in the responsibility of the cabin".

Keywords: preliminary cabin design, optimization, evolutionary algorithms

1. Introduction

1.1 Motivation

Today overall aircraft design strongly depends on cabin design. Modern aircraft designs like the B787 or the A350 XWB apply a design approach called "from inside out" when it comes to setting fuselage parameters i.e. the fuselage width. If in the past the cabin width was kept constant for all the aircraft family variations, today other factors, like the tendency towards extreme wide bodies, made the aircraft manufacturers change their approach and allow more design flexibility with this respect. This modern approach follows a passenger comfort based optimization. This paper combines this approach with the more traditional view of a performance based optimization. Today both views are important at the same time: Passenger comfort challenges environmental requirements for CO_2

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reduction and energy savings. The purpose of a performance based cabin optimization is to achieve the fuselage shape delivering the lowest fuel consumption. In other words: the proposed objective function relates the "aircraft drag being in the responsibility of the cabin" to the fuselage slenderness parameter, l_F / d_F, (fuselage length divided by fuselage diameter) which in turn is a function of cabin layout parameters like n_{SA}, (number of seats abreast).

1.2 Definitions

Preliminary aircraft design The preliminary aircraft design is performed during the definition phase of aircraft development and is based on preliminary sizing and conceptual design that take place during the project phase. These two activities represent the basics of the aircraft design as a discipline. Aircraft design tries to supply the best possible specifications for the specialized disciplines and predefines the best possible framework for the detailed work [1].

Optimization In a wide sense, optimization refers to choosing the best values out of a wide set of available alternatives. There are a lot of optimization methods available, which need to be chosen according to the optimization problem (a short overview is given in Reference [2]). The most common optimization problem is finding the minimum or maximum of an objective function.

Evolutionary Algorithms An Evolutionary Algorithm works by applying a heuristic process of survival of the fittest to a defined population of potential solutions (i.e. aircraft designs). The design variables are coded into (usually) binary strings. The algorithm starts with a number of binary strings defining an initial population of designs. Then the parameters are evaluated for each of these designs. The optimum design is improved through a process involving selection and successive generations of alternative aircraft individuals as defined by the designs' bit-strings [3]. The evolutionary algorithms and their derivations can generally be classified as chromosome-based algorithms.

Genetic Algorithms A Genetic Algorithm is a stochastic global optimization method derived from the Evolutionary Algorithms; it is especially useful for complicated objective functions. Members of a randomly generated starting population are analyzed and evaluated. The best members are most likely to be permitted to reproduce. Each individual is parametrically described by the values of a chromosome-like genetic bit-string. Reproduction occurs by "crossing" their genes with those from another selected "parent". The next generation is evaluated and the process continues until the population all resemble each other or the values of the objective function are no longer improving. This is presumed to represent an optimum [3].

Monte Carlo Represents a stochastic method which uses a random probability function to generate a very large number of potential designs. All these designs are defined, analyzed, and compared in order to find the "best" one, defined as the design that meets all the performance constraints and has the best value of the selected optimization parameters [3].

1.3 Objectives and Structure of the Paper

Four major objectives were defined for this paper. *First*, its aim is to describe and utilize a basic cabin design methodology as part of preliminary aircraft design. *Second*, the goal is to define an objective function representing the "aircraft drag being in the responsibility of the cabin". Based on the objective function, it is then the aim, as part of the *third* objective, to conduct several investigations with respect to the fuselage slenderness ratio l_F / d_F as a function of cabin layout parameters such as n_R or n_{SA}. Further parameters to be investigated at this stage are: wetted areas, masses as well as empennage parameters influencing the drag. Important variations are plotted and optimal values are found using basic calculations. The *fourth* objective is to extend the optimization considerations towards the utilization of chromosome-based algorithms. Such algorithms are better suitable when the objective function depends on a larger number of variables. The aim for this paper is, however, to shortly present and exemplarily use a genetic algorithm as an outlook for further research extension.

The structure of the paper covers the four objectives as follows:

Section 2 *Preliminary Aircraft Cabin Design* – delivers all the basic cabin parameters, necessary in the preliminary fuselage design phase.

Section 3 *Cabin Optimization* – determines the drag being in the responsibility of the cabin and delivers the optimal slenderness ratio. Several analyses with respect to other cabin parameters are included in this Section.

Section 4 *Utilization of Chromosome-Based Algorithms for Optimizing the Cabin* – shortly presents a genetic algorithm and uses it for minimizing the objective function.

Section 5 *Summary and Conclusions* – concludes upon the results and compares them with the current literature.

This first part of the research includes only Section 2, while Sections 3, 4 and 5 will be presented in **Part II** of this paper.

2. Preliminary Aircraft Cabin Design

2.1 Design Requirements

The conceptual design of the fuselage is bounded by a wide set of requirements coming either from the manufacturer, from the operator, from the airport or from the regulator (EASA for Europe or FAA for USA). An airline is interested to carry as much payload as possible, while ensuring enough passenger comfort. Other requirements are reduced maintenance costs or enough operational flexibility. An airport would require an aircraft with feasible ground operation. In this context, the manufacturer aims to build a flexible, cost efficient, performance based design, while accounting for all the rest of requirements.

Conventional fuselage configurations incorporate the payload entirely, while allowing good access to cabin and cargo. In the same time the fuselage delivers a lightweight structure while forming a pressure vessel. Unconventional configurations eliminate or minimize the role of the fuselage, by ceasing the feature of carrying the payload for instance to the wing. Figure 1 shows different fuselage configurations.

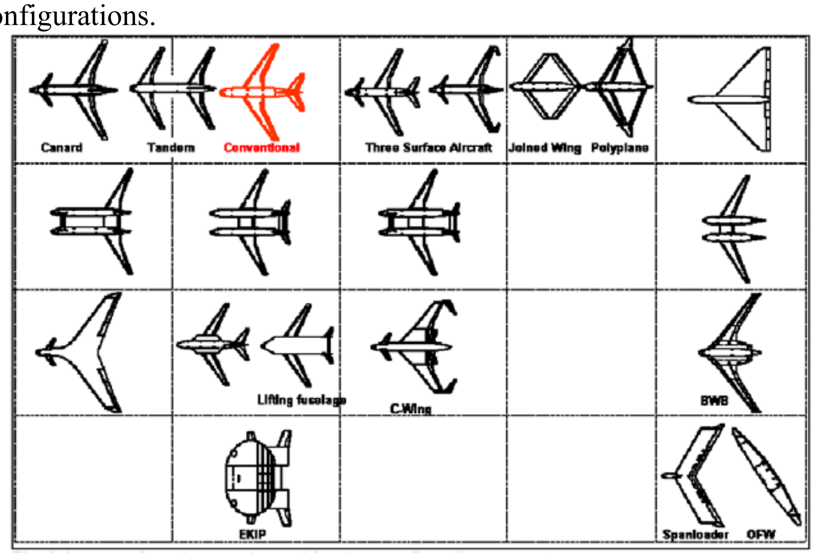

Fig.1. Wing and fuselage configuration concepts [1]

Once a configuration is chosen, the main parameters describing the cabin can be obtained. Based on the design requirements (e.g. number of passengers that need to be transported), several other estimations can be launched:

– Estimation of an optimum number of seats abreast as a function of the number of passengers.
– Calculation of the cabin width (based on seat width, number of aisles and aisle width).
– Estimation of the cabin length (by considering the average seat pitch, the required cabin floor area, or by considering a preliminary cabin layout).
– Calculation of the fuselage length (by using a value for the slenderness parameter or by summing the cockpit length, the tail length and the cabin length).
– Check of the preliminary fuselage geometry ensuring sufficient cargo volume to accommodate check-in baggage and cargo.

The preliminary fuselage/cabin design method presented in the following sections uses the design logic "from requirements to solution" [1]. The methodology is given for conventional commercial transport aircraft.

2.2 Fuselage Upper Cross Section

Parameters of the upper cross section which need to be defined are:

- Number of seats abreast
- Sidewall clearance
- Wall slope
- Wall thickness
- Aisle width
- Cabin height
- Bin volume
- Floor (beam) height
- Floor thickness
- Seat width
- Seat rail height (depending on the floor architecture)

The number of seats abreast, n_{SA} is a parameter that greatly reflects on the degree of passenger comfort. The n_{SA} parameter can be determined statistically. Later it will be shown that this parameter can be related to the fuselage slenderness and optimized (see Section 3.5.6). According to [5] the following equation is valid:

$$n_{SA} = 0.45\sqrt{n_{PAX}} \quad . \tag{1}$$

The number of passengers is the product of the number of seats abreast and the number of seat rows. The significance of the value 0.45 follows from the derivation

$$n_{PAX} = n_{SA} \cdot n_r = n_{SA}^{\;2} \cdot \frac{n_r}{n_{SA}} \Rightarrow n_{SA} = \sqrt{\frac{n_{SA}}{n_r}} \cdot \sqrt{n_{PAX}} \quad . \tag{2}$$

A statistic made on 23 types of single aisle and wide body commercial transportation aircraft delivered the value 0.469 for the coefficient $\sqrt{n_{SA}/n_r}$. Indeed this value confirms the value of 0.45 from [5].

Figure 2 presents a statistical diagram showing the relation between the number of passengers and the slenderness ratio, for different number of seats abreast ranging from 3 to 9. For a given number of passengers, the number of seats abreast is chosen from the diagram so that a suitable slenderness ratio results.

It's important to keep in mind that for a number of seats abreast larger than 6 the certification regulations require an additional aisle. CS 25.815 [4] states

$$\begin{array}{ll} n_{SA} \leq 6 & \Rightarrow\ 1\ Aisle \\ 6 < n_{SA} \leq 12 & \Rightarrow\ 2\ Aisles \end{array} \quad . \tag{3}$$

Today cabin design reflects the strategy 'from inside out'. This strategy is also driven by the policy of the airlines following passenger requirements for comfort. The design of the cabin should consider this strategy already during early phases of aircraft development. At the same time, aircraft performance may not be compromised.

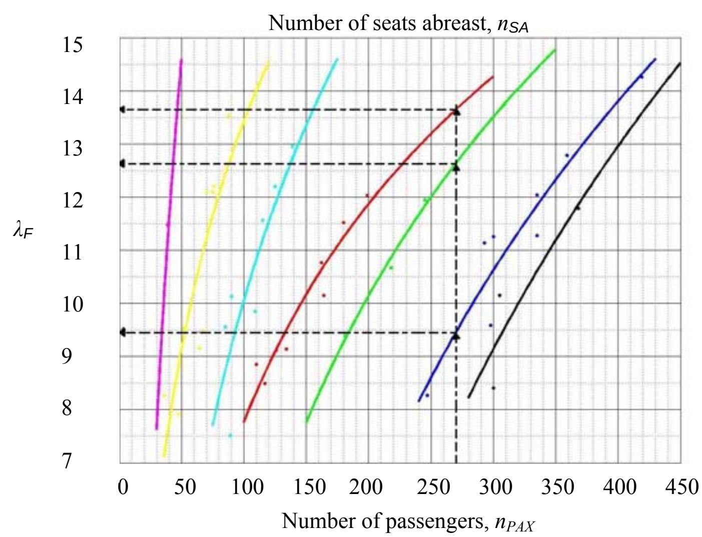

Fig. 2. Diagram showing the relation between the slenderness, number of passengers and number of seats abreast for 23 selected aircraft (magenta – n_{SA} = 3; yellow – n_{SA} = 4; light blue – n_{SA} = 5; red – n_{SA} = 6; green – n_{SA} = 7; blue – n_{SA} = 8; black – n_{SA} = 9)

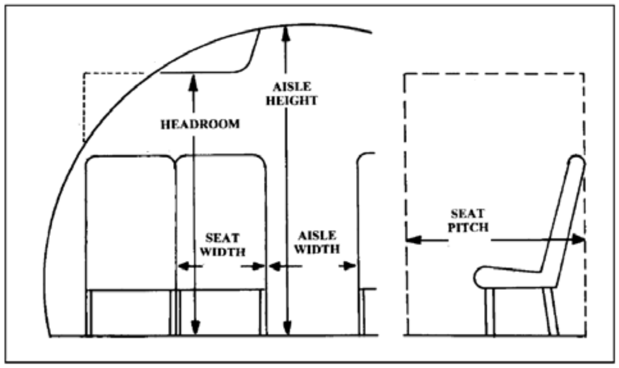

Fig. 3. Definition of important cabin and seat parameters [5]

Important cabin parameters are indicated in Figure 3. Values of these and other cabin parameters are given in Table 1.

Table 1

Cabin parameters according to Airbus [1]

Parameter	Value
Sidewall clearance	0.02 m (At shoulder)
Floor beam height**	80-250 mm
Floor panel**	10 mm
Seat rail height**	5-65 mm*
Cargo hold ceiling**	10 mm
Floor thickness	**100-300 mm**
Skin thickness***	2-4 mm
Stringer height***	30-40 mm
Frame height***	50-100 mm
Isolation***	25-35 mm
Lining panel***	5-10 mm
Outer contour to cabin lining	**100-200 mm**
Seat width (double)	44 in – Economy 54 in – Business 58 in – First
Seat width (cushion)	19 in
Armrest width	2 in

* depending on the floor architecture
** the sum these parameters gives the floor thickness
*** the sum these parameters gives distance from the outer contour to the cabin lining

The aisles have to be wide enough to allow safe evacuation. Minimum aisle width is given in Table 2.

Table 2

The minimum width of the aisles according to CS 25.815

CS 25.815 **Width of Aisle** The passenger aisle width at any point between seats must equal or exceed the values in the following table:		
Passenger seating capacity	Minimum passenger aisle width (inches)	
	Less than 25” from floor	25” and more from floor
10 or less	12*	15
11 to 19	12	20
20 or more	15	20
	* A narrower width not les than 9” may be approved when substantiated by tests found necessary by the authority	

Presented cabin parameters finally determine cabin dimensions and hence the fuselage size. Therefore they have a major influence on aircraft mass and drag and consequently fuel burn and costs. In addition cabin parameters can also influence boarding time, de-boarding time and even passenger health (Deep Vein Thrombosis [6]).

2.3 Fuselage Lower Cross Section

The fuselage lower cross section needs to take account of several design drivers (see [1]):

- Wing integration
- Landing gear integration
- Ditching capability
- Alternative cargo hold utilization (galleys, lavatories, beds)
- Type and dimensions of lower hold containers (ULD – Unit Load Device)

These design drivers are depicted in Figure 4.

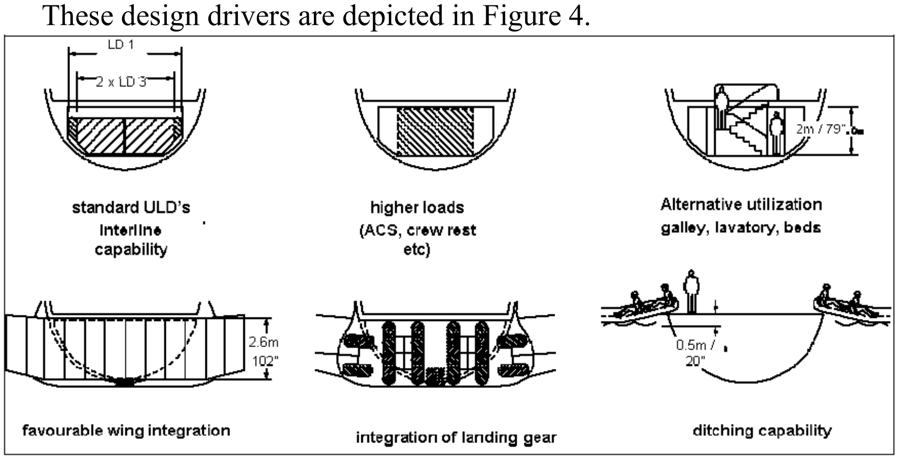

Fig. 4 Driving factors that influence the lower deck shape of the fuselage [1]

Parameters that describe the fuselage lower cross section are (see Table 1):

- 'Belly' depth
- Cargo hold ceiling
- Floor (beam) height
- Floor thickness
- Floor panel thickness

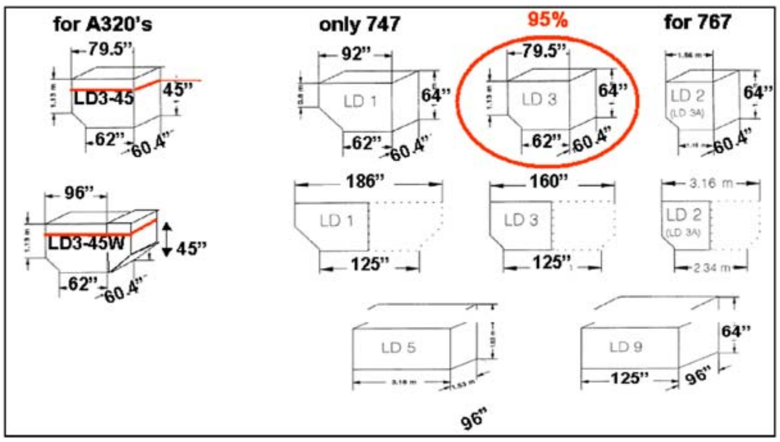

Fig. 5 Dimensions of lower hold containers [1]

There are several types of ULD's (Figure 5) which can be chosen according to the necessities. 95% of the ULD's are LD3 type [1].

2.4 Inner and Outer Fuselage Diameter

The inner fuselage diameter can be obtained as the sum of major parameters describing the upper fuselage cross section: seat width, armrest width, aisle width, sidewall clearance

$$d_{F,i} = n_{SA} \cdot w_{seat} + (n_{SA} + n_{aisle} + 1) \cdot w_{armrest} + \\ + n_{aisle} w_{aisle} + 2 s_{clearence} \quad . \tag{4}$$

The outer diameter can be calculated from the inner diameter and the values of skin thickness, stringer height, frame height, insulation and lining panel thickness. It is

$$d_{F,o} = d_{F,i} + w_t \\ d_{F,o} = d_{F,i} + t_{skin} + h_{frame} + h_{stringer} + t_{isolation} + t_{lining\ panel} \quad . \tag{5}$$

where w_t represents the wall thickness. However, in practice it might be difficult to obtain these values. As first information, Table 1 provides data from Airbus.

Another approach used by [7] is to calculate the difference between the inner and outer diameter from a diagram shown in Figure 6. Based on this diagram an empirical equation is

$$d_{F,o} = 1.045 d_{F,i} + 0.084\text{m} \quad . \tag{6}$$

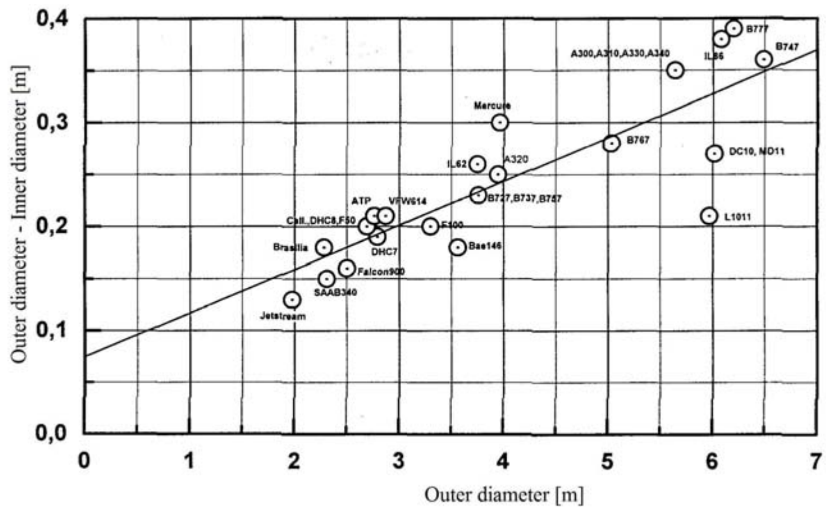

Fig. 6 Empirical diagram relating fuselage outer and inner diameter [7]

2.5 Cabin and Fuselage Length

A first and simple approximation of the cabin length is

$$l_{cabin} = n_r \cdot k_{cabin} = \frac{n_{pax}}{n_{SA}} \cdot k_{cabin} \quad , \tag{7}$$

where k_{cabin} has the significance of an average seat pitch taking account of the surface of the additional cabin items mentioned above. The value of k_{cabin} lies between 1.0 m and 1.1 m [9]. A statistic performed on the same 23 selected aircraft shows that wide bodies have an average k_{cabin} of 1.17 m while single aisle aircraft have an average k_{cabin} of 1.08 m.

At a later stage of the cabin definition, the cabin length is determined from all items in the cabin: seats, lavatories, galleys, crew rest and stowage compartments. The required cabin area of all these items is summed up to yield the total cabin area. The cabin length follows simply from dividing the cabin area by the cabin width as determined from (4). The required number of the cabin items and their floor area depends on cabin comfort standards (Table 3 and [9]).

The length of the fuselage can be determined based on the cabin length. [8] states

$$l_F = l_{cabin} + l_{cockpit} + l_{tail} = l_{cabin} + 4\text{ m} + 1.6 \cdot d_F \quad . \tag{8}$$

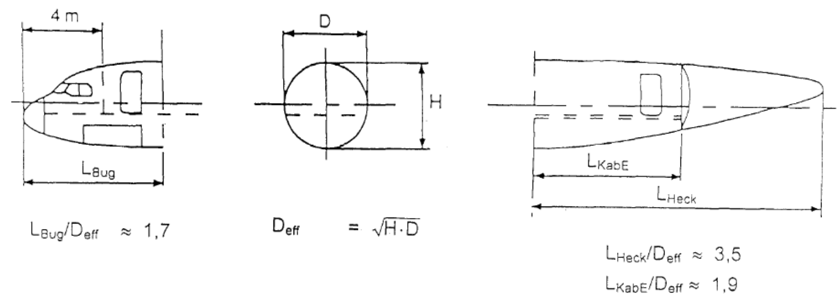

Fig. 7 Length of fuselage front and rear part [8]

Table 3

Cabin comfort standards for short, medium and long range aircraft [8]

	SR*	MR**		LR***		
	YC	FC	YC	FC	BC	YC
Seats in %	100	8-10	90-92	5-7	18-20	73-77
Seat pitch [in]	32	40	32	60	38	32
Seat width (double) [in]	40	48	40	53	50	40
Recline capability [in]	5	7.5	5	15	7	5
Crew per Pax	1/45	1/8	1/35	1/8	1/20	1/35
Lavatories per Pax	1/60	1/14	1/45	1/14	1/25	1/45
Galleys/Trolleys per Pax	1.7	9	2.3	9	7	2.7
Wardrobe stowage	No	1.5	No	1.5	1.5	No

* SR – Short Range; SR ≤ 3000 NM
** MR – Medium Range; 3000< MR < 5500 NM
*** LR – Long Range; LR ≥ 5500 NM

2.6 Cargo Volume

The aircraft cabin design method uses simple approximations to generate preliminary results. However these results need to be checked. For the fuselage it is required that the volume of the cargo compartment is able to accommodate all the cargo plus all the baggage that does not fit in the cabin. [9] provides an inequality for this statement

$$V_{CC} \geq V_C + (V_B - V_{OS}) \ , \tag{9}$$

where:

V_{CC} volume of the cargo compartment,
V_C volume of cargo,
V_B volume of baggage,
V_{OS} volume of overhead stowage.

$$V_{CC} = l_F \cdot k_{CC} \cdot S_{CC} \ , \tag{10}$$

where:

k_{CC} proportion of the fuselage length used for cargo ranging from 0.35 to 0.55,
S_{CC} cross section of the cargo compartment.

Each term can be determined as follows:

$$
\begin{aligned}
&V_B = m_B / \rho_B \\
&V_C = m_C / \rho_C \\
&V_{OS} = S_{OS,tot} \cdot l_{OS} \\
&S_{OS,tot} = n_{OS,lat} \cdot S_{OS,lat} + n_{OS,ce} \cdot S_{OS,ce} \\
&l_{OS} = k_{OS} \cdot l_{cabin}
\end{aligned}
\quad , \qquad (11)
$$

where:

m_B mass of baggage,
m_C mass of cargo,
ρ_B density of baggage,
ρ_C density of cargo,
$S_{OS,tot}$ total cross section of the overhead stowages calculated as a sum of the cross sections of lateral stowages, $S_{OS,lat}$, and central stowages, $S_{OS,ce}$,
$n_{OS,lat}$ number of lateral rows of overhead stowages,
$n_{OS,ce}$ number of central rows of overhead stowages: $n_{OS,ce} = n_{aisles}$ - 1,
l_{OS} total length of the overhead stowages (lateral and central),
k_{OS} proportion of the cabin length occupied by the overhead stowages.

The baggage must not exceed the maximum load of the overhead stowage, thus density

$\rho_B < 180\ kg / m^3$ for single aisle aircraft, (12)
$\rho_B < 185\ kg / m^3$ for twin aisle aircraft.

Assuming that the overhead stowage is not completely loaded (baggage of different types and sizes) the density values supplied by [12] can be used for preliminary cabin design:

– Baggage: 170 kg / m^3,
– Cargo: 160 kg / m^3.

Table 4

Lists values for the SOS,lat, SOS,ce and kOS for selected aircraft with 1 or 2 aisles [10], [11].

	n_{OS}		Selected Aircraft	k_{OS}	$S_{OS,lat}$	$S_{OS,ce}$	ρB
Number of aisles :1	$n_{OS,lat}=2$ $n_{OS,ce}=0$	Single Aisle	A 318	0.738	0.208	-	175.95
			A 319	0.760	0.208		176.32
			A 320	0.771	0.208		175.92
			A 321	0.786	0.208		176,54
			B 737-600	0.687	0.187		192.23
			B 737-600 BB[1]	0.687	0.209		172.32
			B 737-700	0.744	0.187		192.00
			B 737-700 BB	0.744	0.209		171.83
			B 737-800	0.697	0.187		192.51
			B 737-800 BB	0.697	0.209		172.24
			B 737-900	-	0.187		192.04
			B 737-900 BB	-	0.209		171.85
			Average	**0.723**	**0.201**	**-**	**180.13**

Number of aisles :2	$n_{OS,lat}$=2 $n_{OS,ce}$=1	Wide Body	A 330-200	0.789	0.153	0.230	226.02
			A 330-300	0.808	0.153	0.230	226.11
			A 340-300	0.808	0.153	0.230	226.11
			A 340-500	0.811	0.147	0.230	229.44
			A 340-600	0.804	0.147	0.230	229.56
			A350-800-F[2]	-	0.195	0.320	159.93
			A350-800-P[3]	-	0.195	0.269	182.03
			A350-900-F	-	0.196	0.320	159.40
			A350-900-P	-	0.196	0.269	181.77
			A 380 UD-F[4]	0.744	0.144	0.253	201.15
			A 380 UD-P	0.709	0.108	0.247	233.91
			A 380 MD-F	0.705	0.255	0.253	159.51
			A 380 MD-P	0.672	0.251	0.247	170.43
			B 777-200 ER	0.736	0.227	0.199	161.69
			B 777-300 ER	0.753	0.227	0.199	161.68
			B 787-8	0.749	0.324	0.252	148.60
			B 787-9	0.77	0.324	0.252	148.46
			B 747-400 MD	-	0.262	0.168	174.32
			B 747-8	0.673	0.274	0.210	158.38
			Average	**0.751**	**0.208**	**0.241**	**185.01**
		Overall average		**0.737**	**0.213**	**-**	**182.57**

[1] Additionally the BB (i.e. Big Bins) versions of the four B 737 aircraft were considered for the statistic
[2] F stands for Fixed stowages
[3] P stands for Pivoting stowages
[4] Both main deck (MD) and upper deck (UD) were considered

2.6 The Slenderness Parameter

The slenderness parameter (also called fineness ratio) is given by the length of the fuselage divided by the fuselage diameter

$$\lambda_F = l_F / d_F \quad . \tag{13}$$

According to own statistics, the value of the slenderness for today's aircraft is about 10.3. This parameter is a key parameter in aircraft design, respectively aircraft cabin design. If the aircraft is too short (with a small slenderness), then the empennage surface increases, due to the short lever arm. On the contrary, a long fuselage means a high wetted area and, accordingly, high drag. This interdependency represents for this paper the core of the optimization problem.

The equations of the fuselage drag D_F, consisting of zero lift drag $D_{0,F}$ and induced drag $D_{i,F}$, can be analytically derived so that the relation can be reduced to a function of the fuselage length and diameter

$$D_F = D_{0,F} + D_{i,F} = f\left(l_F(n_r), d_F(n_{SA}), \lambda_F\right) \quad . \tag{14}$$

Part II of this paper details this optimization based approach.

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