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FROM PRELIMINARY AIRCRAFT CABIN DESIGN TO CABIN OPTIMIZATION

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Abstract

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.

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 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.

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.

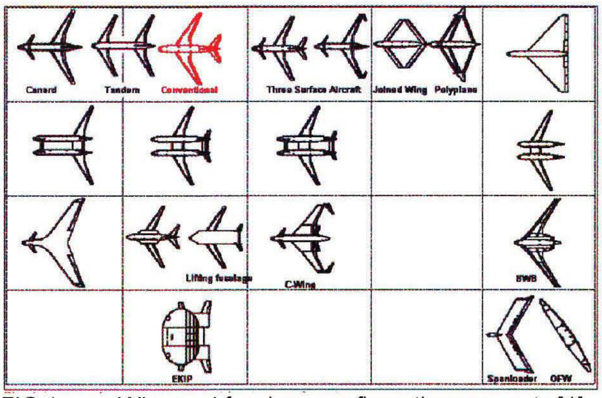

FIG.1 Wing and fuselage configuration concepts [1]

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:

(1) $n_{SA} = 0.45\sqrt{n_{PAX}}$.

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

(2) $n_{PAX} = n_{SA} \cdot n_r = n_{SA}^2 \cdot \frac{n_r}{n_{SA}} \Rightarrow n_{SA} = \sqrt{\frac{n_{SA}}{n_r}} \cdot \sqrt{n_{PAX}}$.

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].

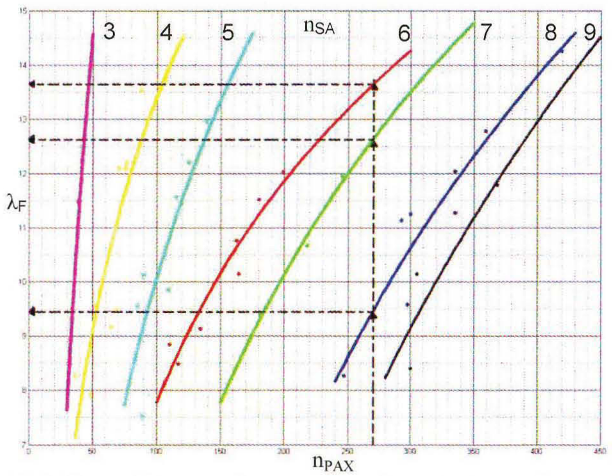

FIG. 2 Diagram showing the relation between the slenderness, number of passengers and number of seats abreast for 23 selected aircraft (magenta – n_{SA}=3; yellow – n_{SA}=4; light blue – n_{SA}=5; red – n_{SA} =6; green – n_{SA} =7; blue – n_{SA} =8; black – n_{SA} =9)

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

(3) $\begin{array}{ll} n_{SA} \le 6 & \Rightarrow 1\ Aisle \\ 6 < n_{SA} \le 12 & \Rightarrow 2\ Aisles \end{array}$

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.

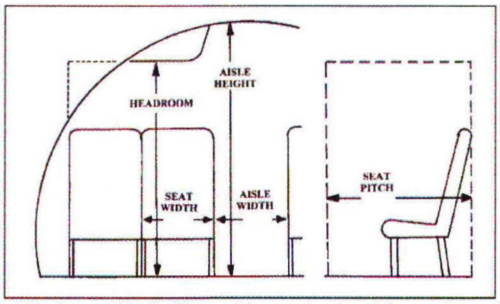

FIG. 3 Definition of important cabin and seat parameters [5]

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

TAB 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.

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]).

TAB 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	

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.

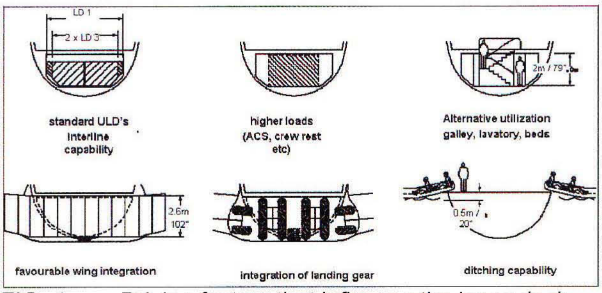

FIG. 4 Driving factors that influence the lower deck shape of the fuselage [1]

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

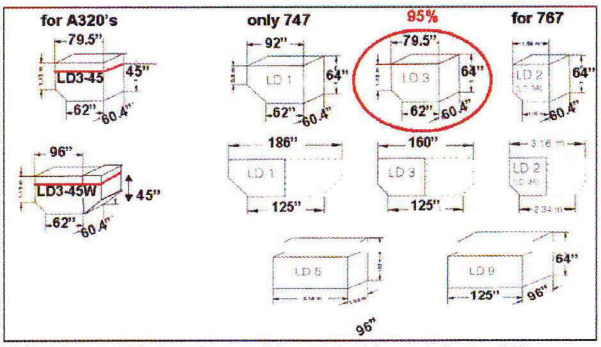

FIG. 5 Dimensions of lower hold containers [1]

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

$$\begin{aligned} d_{F,o} &= d_{F,i} + w_t \\ d_{F,o} &= d_{F,i} + t_{skin} + h_{frame} + h_{stringer} + t_{isolation} + t_{liningpanel} \end{aligned} \quad , \tag{5}$$

where w_t represents the wall thickness. However, in practice it might be difficult to obtain these values. As a 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

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

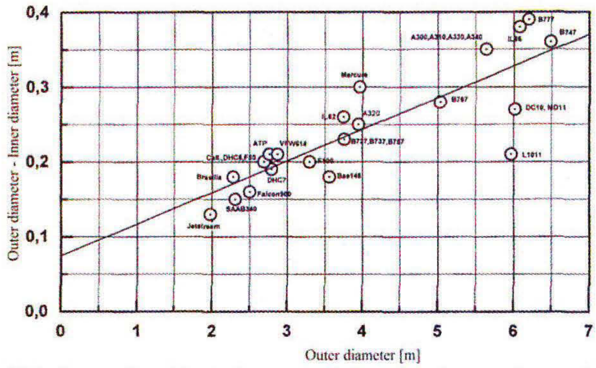

FIG. 6 Empirical diagram relating fuselage outer and inner diameter [7]

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

(8) $l_F = l_{cabin} + l_{cockpit} + l_{tail} = l_{cabin} + 4\,\mathrm{m} + 1.6 \cdot d_F$.

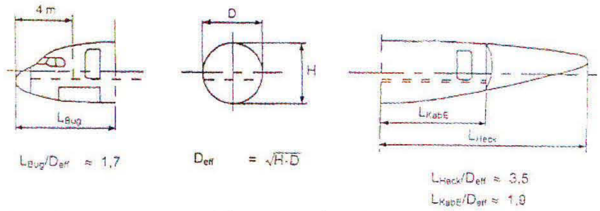

FIG. 7 Length of fuselage front and rear part [8]

TAB.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

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

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

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

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:

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

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.

Table 4 lists values for the $S_{OS,lat}$, $S_{OS,ce}$ and k_{OS} for selected aircraft with 1 or 2 aisles [10], [11].

	n_{OS}		Selected Aircraft	k_{OS}	$S_{OS,lat}$	$S_{OS,ce}$	ρ_B
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

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

(12) $\rho_B < 180$ kg/m³ for single aisle aircraft,
$\rho_B < 185$ kg/m³ 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/m³,
- Cargo: 160 kg/m³.

2.7 The Slenderness Parameter

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

(13) $\lambda_F = l_F / d_F$.

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

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

The following sections detail this optimization based approach.

3 CABIN OPTIMIZATION

This Section aims to determine the objective function and find its minimum. Based on these results, a broader examination, extending on a larger number of parameters is foreseen for future work.

The objective function relates cabin parameters to fuselage parameters, with the purpose to minimize the fuselage drag and mass. This reduces fuel consumption and allows for an increase in payload.

For sure, the fuselage shape follows cabin parameters. But at a second glance it can be seen that the empennage size also depends on cabin geometry, because the cabin length determines the lever arm of the empennage and hence the area of the horizontal and vertical tail.

The drag expressed in (14) represents the *drag being in the responsibility of the cabin*, consisting of zero-lift drag (surface of *fuselage and tail*) and induced drag (mass of *fuselage and tail*). Hence it is necessary to:

- estimate fuselage drag and mass,
- perform a preliminary sizing of the empennage,
- estimate empennage drag and mass,
- calculate total drag from zero lift drag and induced drag as a function of the fuselage slenderness parameter, $\lambda_F = l_F / d_F$, which represents the objective function.

The fuselage *drag being in the responsibility of the cabin* is

(15)
$$D_F = q S \cdot \left(C_{D,0,F} + k\, C_{L,F}^{\;2}\right)$$
$$q = \frac{1}{2}\rho V^2; \quad k = \frac{1}{\pi \cdot A \cdot e} ,$$

where $C_{L,F} = \dfrac{2 \cdot m_F g}{\rho \cdot V^2 \cdot S_w}$.

Typical values for the aspect ratio, *A*, range between 3 and 8. The Oswald efficiency factor, *e*, ranges from 0.7 to 0.85 [5].

3.1 Fuselage Drag and Mass

For the aircraft, as well as for aircraft components, such as the fuselage, the drag calculated as the sum of zero-lift drag and induced drag is expressed through the drag coefficients

(16) $C_D = C_{D,0} + k \cdot C_L^{\;2}$.

The zero-lift drag (also called parasite drag) consists primarily of skin friction drag and is directly proportional to the total surface area of the aircraft or aircraft components exposed ('wetted') to the air [5].

There are two ways of calculating the zero-lift drag [5]: *First*, by considering an equivalent skin friction coefficient, C_{fe} which accounts for skin friction and separation drag:

(17) $C_{D,0,F} = C_{fe} \cdot \dfrac{S_{wet,F}}{S_W}$.

Second, by considering a calculated flat-plate skin friction coefficient, C_f, and a form factor, *F*, that estimates the pressure drag due to viscous separation. This estimation is done for each aircraft component, therefore an interference factor, *Q*, is also considered. The fuselage drag coefficient is then:

(18) $C_{D,0,F} = C_{f,F} \cdot F_F \cdot Q_F \cdot \dfrac{S_{wet,F}}{S_W}$.

The first approach considers in general the aircraft as a whole. The second approach allows a component-based examination and is potentially more accurate. Further on, each factor of the zero-lift drag will be calculated.

For the fuselage wetted area there are several calculation possibilities. Chosen was (19), from [12], which has a slenderness ratio dependency for

(19) $S_{wet,F} = \pi \cdot d_F \cdot l_F \cdot \left(1 - \dfrac{2}{\lambda_F}\right)^{2/3} \left(1 + \dfrac{1}{\lambda_F^{\;2}}\right)$.

The form factor is given in [5] as

(20) $F_F = 1 + \dfrac{60}{\lambda_F^{\;3}} + \dfrac{\lambda_F}{400}$.

The fuselage has an interference factor of $Q_F=1$, because (by definition) all other components are assumed to be related in their interference to the fuselage [5].

The friction coefficient depends on the Reynolds number, Mach number and skin roughness. The contribution to the skin friction drag is mainly depending on the extent to which the aircraft has a laminar flow on its surface. A typical fuselage has practically no laminar flow. Laminar flow normally can be found only over 10 % to 20 % of wing and tail [5]. For turbulent flow, the friction coefficient can be calculated with (21)

$$(21)\quad C_{f,turbulent} = \frac{0.455}{(\log_{10} Re)^{2.58}(1+0.144M^2)^{0.65}} \quad , \qquad Re = V\, l_F / \upsilon$$

where υ represents the kinematic viscosity of the air, which depends on the air temperature and thus flight altitude.

The *drag-due-to-lift* (also called induced drag) which falls in the responsibility of the cabin can be estimated first based on the fuselage-tail group weight. The lift produced by the wing in order to keep the fuselage respectively cabin in the air (noted with m_F) equals the weight of the fuselage-tail group (represented by the sum $m_f+m_h+m_v$)

$$(22)\quad L_F = m_F \cdot g \Rightarrow qS \cdot C_{L,F} = (m_f + m_h + m_v)\cdot g \quad .$$

Thus the induced drag

$$(23)\quad D_{i,F} = k \cdot \frac{(m_f + m_h + m_v)^2 \cdot g^2}{qS} \quad , \qquad \begin{array}{l} where\ f - fuselage \\ h - horizontal\ tail \\ v - vertical\ tail \end{array}$$

The mass of the fuselage can be calculated from [12]:

$$(24)\quad \begin{aligned} m_F &= 0.23 \cdot \sqrt{V_D \frac{l_H}{2d_F}} \cdot S_{wet,F}^{\ 1.2} \\ V_D &= M_D \cdot a \\ M_D &= M_{CR} + \Delta M \\ \Delta M &\approx 0.05 \ldots 0.09 \quad . \end{aligned}$$

l_H is the lever arm of the horizontal tail. The value is in many cases close to 50 % of the fuselage length (see Table 4). In this case, (24) can be written as a function of the slenderness parameter:

$$(25)\quad m_F = 0.115 \cdot \sqrt{V_D \cdot \lambda_F} \cdot S_{wet,F}^{\ 1.2} \quad .$$

3.2 Empennage Preliminary Sizing

The empennage provides trim, stability and control for the aircraft. The empennage generates a tail moment around the aircraft center of gravity which balances other moments produced by the aircraft wing – in the case of the horizontal tail, or by an engine failure – in the case of the vertical tail. Figure 6 shows possible tail arrangements. More information with respect to the characteristics of each configuration can be found in the literature, such as [5].

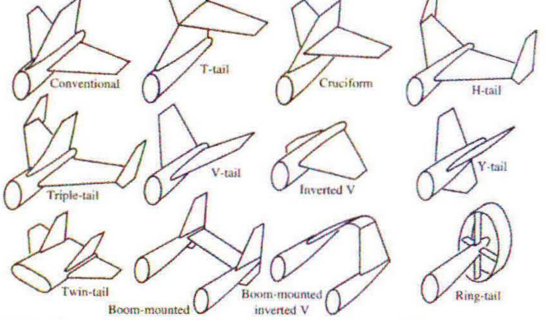

FIG. 6 Empennage configurations [5]

Once the configuration is chosen, other parameters can and must be preliminarily estimated:

- Aspect ratio
- Taper ratio
- Sweep
- Span
- Thickness to chord ratio at tip and root

Typical values for aspect and taper ratios for the vertical and horizontal tail are indicated in Table 3. The leading-edge sweep of the horizontal tail is usually 5° larger than the wing sweep. The vertical tail sweep ranges from 35° to 55°. The thickness ratio is usually similar to the thickness ratio of the wing [5].

TAB. 3 Typical values for aspect and taper ratios of the empennage [5]

	Horizontal tail		Vertical tail	
	A	λ	A	λ
Fighter	3…4	0.2…0.4	0.6…1.4	0.2…0.4
Sailplane	6…0	0.3…0.5	1.5…2.0	0.4…0.6
T-Tail	–	–	0.7…1.2	0.6…1.0
Others	3…5	0.3…0.6	1.3…2.0	0.3…0.6

Further on, preliminary values of the parameters defining the empennage are required. For the initial estimation of the tail area the 'tail volume method' can be used. The tail volume coefficients C_H and C_V are defined as

$$(26)\quad C_H = \frac{S_H \cdot l_H}{S_W \cdot c_{MAC}}; \quad C_V = \frac{S_V \cdot l_V}{S_W \cdot b} \quad .$$

One of the most important considerations, especially for this paper, is that the moment arm of the empennage should be as large as possible in order to have smaller empennage surfaces, and thus reduced mass and drag. The moment arm is reflected in the slenderness parameter: a longer moment arm gives a larger value for the fuselage slenderness.

Tail volume coefficients can be extracted from historical data, as showed in Table 4.

TAB. 4 Typical values for the tail volume coefficient [5]

	Horizontal C_H	Vertical C_V
Sailplane	0.50	0.02
Homebuilt	0.50	0.04
General aviation – single engine	0.70	0.04
General aviation – twin engine	0.80	0.07
Agricultural	0.50	0.04
Twin turboprop	0.90	0.08
Flying boat	0.70	0.06
Jet trainer	0.70	0.06
Jet fighter	0.40	0.07
Military cargo / bomber	1.00	0.08
Jet transport	1.00	0.09

The moment arms can be estimated using statistics (see Table 5).

TAB. 5 Statistical values for the empennage moment arms [5]

Aircraft configuration	Moment arms, l_H and l_V
Front-mounted propeller engine	60 % of the fuselage length
Engines on the wing	50-55 % of the fuselage length
Aft-mounted engines	45-50 % of the fuselage length
Sailplane	65 % of the fuselage length
Canard aircraft	30-50 % of the fuselage length

Based on the data from Table 5, (26) can be rewritten as a function of the fuselage length. The tail surface areas in question are

(27) $S_H = \dfrac{C_H \cdot S_W \cdot c_{MAC}}{l_H}; \quad S_V = \dfrac{C_H \cdot S_W \cdot b}{l_V}$.

3.3 Empennage Drag and Mass

The drag of the empennage can be calculated with the same procedure as for the fuselage. Equation 18 remains valid. The wetted area depends on the geometrical characteristics of the empennage 'wing' (horizontal and vertical) (Table 3):

(28) $S_{wet,H} = 2 \cdot S_{\exp,H}\left(1 + 0.25 \cdot (t/c)_r \cdot \dfrac{1+\tau_H \cdot \lambda_H}{1+\lambda_H}\right)$.

$\tau_H = (t/c)_t / (t/c)_r$

(29) $S_{wet,V} = 2 \cdot S_{\exp,V}\left(1 + 0.25 \cdot (t/c)_r \cdot \dfrac{1+\tau_V \cdot \lambda_V}{1+\lambda_V}\right)$.

$\tau_V = (t/c)_t / (t/c)_r$

The tail thickness ratio is usually similar to the wing thickness ratio; for high speed aircraft the thickness is up to 10 % smaller [5]. According to [5] the root of the wing is about 20 % to 60 % thicker than the tip chord (which means τ is about 0.7).

The form factor of the empennage is the same as the form factor for the wing

(30) $F = \left[1 + \dfrac{0.6}{x_t}\left(\dfrac{t}{c}\right) + 100\left(\dfrac{t}{c}\right)^4\right] \cdot \left[1.34 \cdot M^{0.18} \cdot \cos(\varphi_m)^{0.28}\right]$,

where φ_m represents the sweep of the maximum-thickness line and x_t is the chordwise location of the airfoil maximum thickness point.

The position of maximum thickness, x_t, is given by the second digit of the NACA four digit airfoils, which are frequently chosen for the empennage.

The interference factor for the conventional empennage configurations has the value Q=1.04. An H-Tail has Q=1.08 and a T-Tail has Q=1.03 [5].

The empennage may have laminar flow over 10% to 20 % of its surface. The friction coefficient for the laminar flow is

(31) $C_{f,laminar} = 1.328/\sqrt{Re} = 1.328\sqrt{(V \cdot c_{MAC,H,V})/\upsilon}$.

The mean aerodynamic chord of the horizontal, respectively vertical tail becomes the characteristic length for the Reynolds number.

The final value of the friction coefficient accounts for the portions of turbulent and laminar flow:

(32) $C_f = k_{laminar} \cdot C_{f,laminar} + (1 - k_{turbulent}) \cdot C_{f,turbulent}$.

The empennage mass (horizontal and vertical tail) is given by [12]

(33) $m_H = k_H \cdot S_H \cdot \left(62 \cdot \dfrac{S_H^{\;0.2} \cdot V_D}{1000 \cdot \sqrt{\cos \varphi_{H,50}}} - 2.5\right)$,

(34) $m_V = k_V \cdot S_V \cdot \left(62 \cdot \dfrac{S_V^{\;0.2} \cdot V_D}{1000 \cdot \sqrt{\cos \varphi_{V,50}}} - 2.5\right)$,

$k_H = 1$ *for fixed stabilizers*

1.1 *for variable incidence tails*

$k_V = 1$ *for fuselage mounted horizontal tails*

$k_V = 1 + 0.15 \cdot \dfrac{S_H \cdot z_H}{S_V \cdot b_V}$ *for fin mounted stabilizers*

z_H – *height of the horizontal tail above the fin root*

φ_{50} – *sweep angle at 50 % of the chord* .

When putting together the equations listed above, the function of the "total drag being in the responsibility of the cabin" is obtained.

3.4 Objective Function

The basic objective function of the fuselage-tail group has the form

(35) $D_F = D_F(l_F, d_F)$.

Optimizing this function means finding that combination of fuselage length and diameter which produces the lowest drag. The hypothesizes taken into account are:

1) The aircraft has a conventional configuration.
2) The results from preliminary aircraft sizing are known.

Preliminary sizing of the aircraft has the primary purpose to obtain optimum values for wing loading and thrust to weight ratio. It delivers the main input parameters required for the cabin optimization process: the wing area, the aircraft cruise speed and the cruise altitude. For obtaining the results in this paper the wing area and Mach number of the ATR 72 were used.

3.5 Optimization Results

3.5.1 Total Drag of the Fuselage-Tail Group

This Subchapter calculates the zero-lift drag of the fuselage-tail group and the induced drag of the fuselage-tail group, which takes into account lift to carry the fuselage-tail mass.

The variation of the total drag of the fuselage-tail group with the fuselage length and diameter is shown in Figure 7.

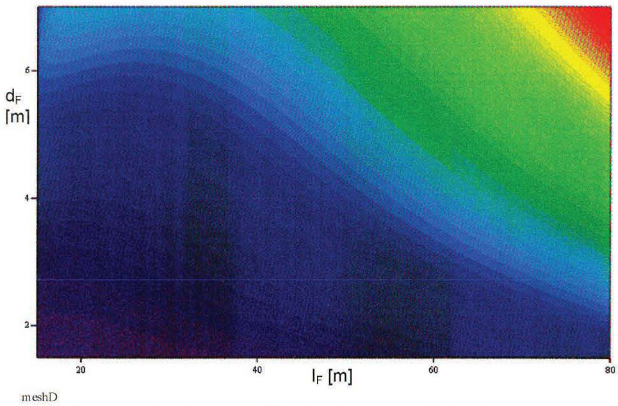

FIG. 7 Total drag of the fuselage-tail group as function of fuselage length and diameter

In order to have a better visualization of the results, it makes sense to illustrate the relative drag. For passenger transport aircraft meaningful conclusions can be drawn based on the representation of the drag relative to the *cabin surface* – drag divided by the product ($l_F \cdot d_F$) – as a function of the fuselage length and diameter (see Figure 8). The cabin surface depends directly on the number of passengers; therefore drag relative to cabin surface plays an important role for this paper.

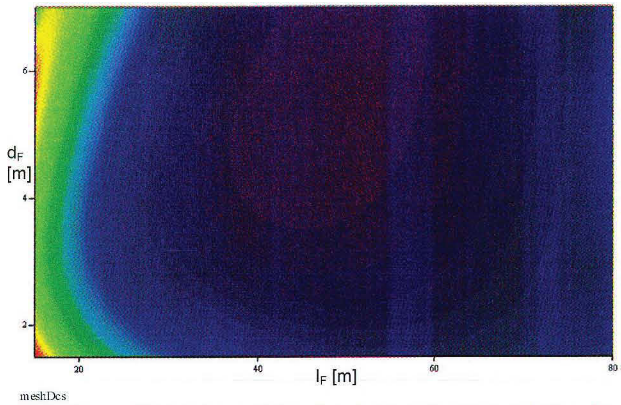

FIG. 8 Total drag of the fuselage-tail group relative to the cabin surface ($l_F \cdot d_F$) as a function of fuselage length and diameter

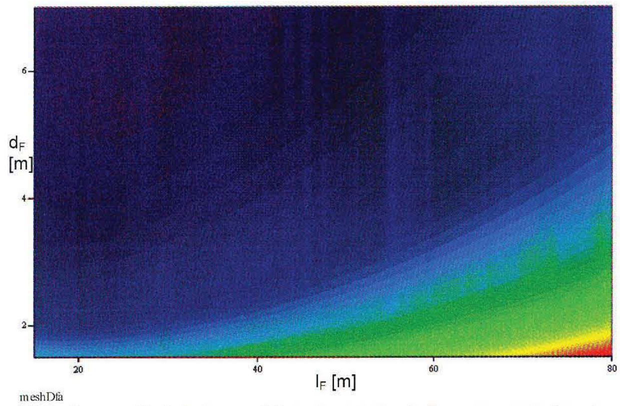

FIG. 9 Total drag of the fuselage-tail group relative to the frontal area ($d_F^2 \cdot \pi/4$) as a function of fuselage length and diameter

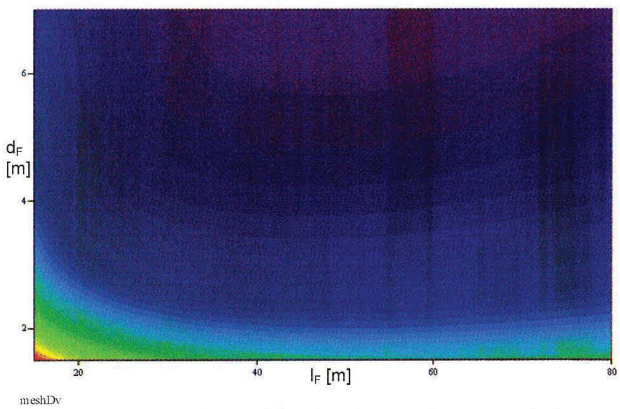

FIG. 10 Total drag of the fuselage-tail group relative to the volume ($d_F^2 \cdot l_F \cdot \pi/4$) as a function of fuselage length and diameter

For freighter aircraft, a better visualization of the dependency can be obtained when the "drag in the responsibility of the cabin" is represented relative to the *frontal area*, respectively *volume* (see Figures 9 and 10).

It is to be noticed that the friction coefficient and form factor used to calculate the zero-lift drag of the empennage highly depend on the geometry, which in turn depend on the geometry of the aircraft wing (as shown in Paragraph 3.3). The influence of the empennage on the total drag is first of all contained in the wetted area estimation, while the type of surface and profile where considered for a selected aircraft (i.e. the ATR 72).

The following conclusions can be drawn:

– Figure 7 presents an expected drag variation: the smaller the fuselage the smaller the drag; the variation shows also that it's better to keep the fuselage longer rather than stubbier.
– Figure 8 indicates a zone of minimum relative drag for fuselages with lengths between 30 (e.g. A 318) and 70 meters (e.g. A 340, A380). Extremities (very small length, very high diameters) produce significant relative drag.
– Figures 9 and 10 reflect the cargo transportation requirements: for transporting large items it is important to have a large fuselage diameter; if volume transport is of importance, a large diameter at a length of about 50 m would be best.

It is interesting to note that (maybe with exception of Beluga) no civil freighter exists that was designed specifically for this purpose. All civil freighters have been derived from passenger aircraft, while military freighters play only a minor role for civil freight transport. If the aircraft manufacturer would like to keep the advantages of this practice, the passenger transport aircraft – or the future freighter – should be designed according to the range of dimensions *common to both graphs* shown in Figures 8 and 10. This range is approximately $l_F \in [40,60]; d_F \in [3.8,7]$, which means that B747 or A380 type of aircraft are better suitable for freighter conversions than single aisle aircraft.

3.5.2 Total Drag of the Fuselage

This Subchapter calculates the zero-lift drag of the fuselage and the induced drag of the fuselage, which takes into account lift to carry the fuselage mass.

In order to be able to relate the drag to the slenderness and draw other meaningful conclusions, the empennage contribution will be neglected in this Section (see (36) and Figures 11 to 14):

(36) $D_F = f(\lambda_f, l_F \cdot d_F)$.

According to Figure 11 it seems that for larger fuselage length-diameter products the slenderness should lie between 5 and 10 for an optimal drag. For smaller aircraft it seems the designer has the flexibility to choose a convenient slenderness, according also to other criteria than drag.

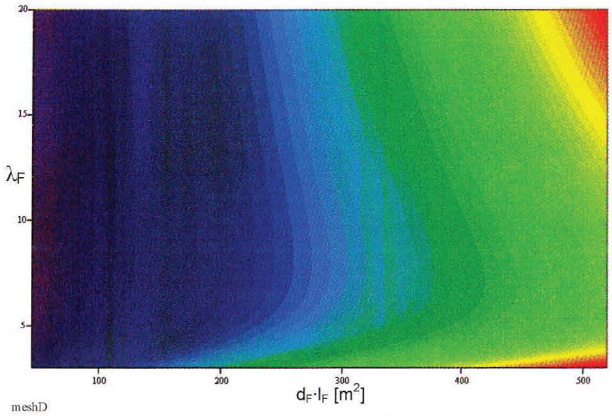

FIG. 11 Total fuselage drag as a function of the slenderness and ($l_F \cdot d_F$)

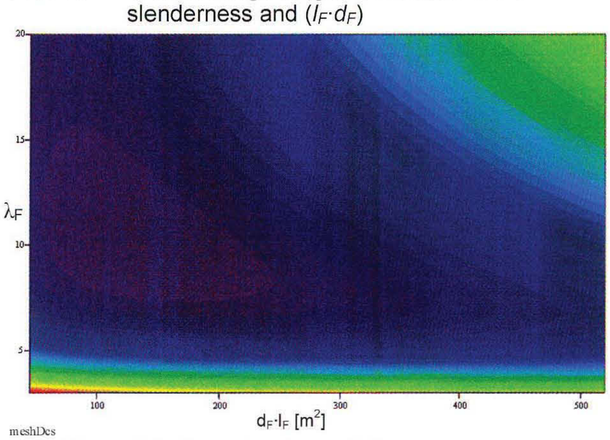

FIG. 12 Total fuselage drag relative to cabin surface ($l_F \cdot d_F$) as a function of the slenderness and ($l_F \cdot d_F$)

When looking at the fuselage drag relative to cabin surface a zone of optimal slenderness can be delimited. Previously Figure 7 allowed us to favor longer fuselages instead of stubbier ones. In the same way Figure 11 delimits a range between 5 and 10 for the value of slenderness for the larger aircraft. Figure 12 shows now, that for passenger transportation, smaller aircraft can have an increased slenderness up to 16.

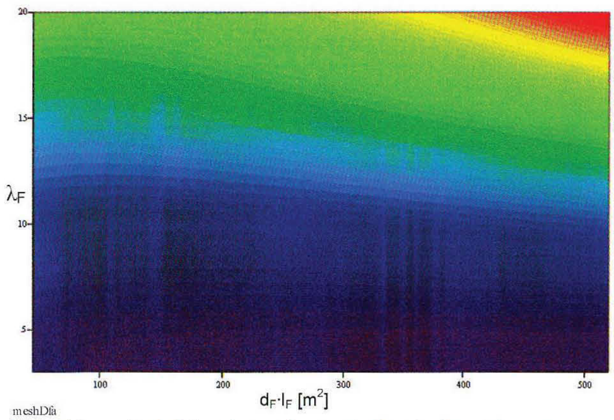

FIG. 13 Total fuselage drag relative to frontal area ($d_F^2 \cdot \pi/4$) as a function of the slenderness and ($l_F \cdot d_F$)

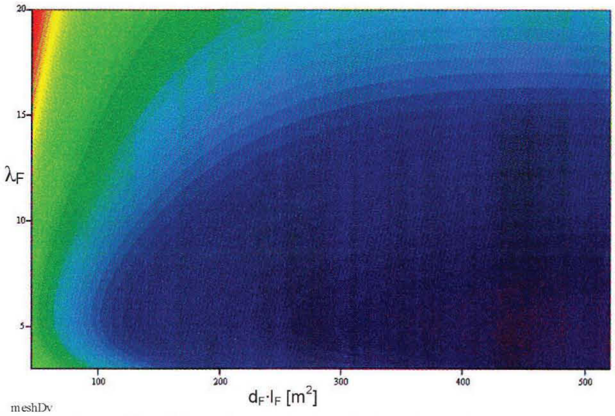

FIG. 14 Total fuselage drag relative to volume ($l_F \cdot d_F^2 \cdot \pi/4$) as a function of the slenderness and ($l_F \cdot d_F$)

Drag relative to frontal area and volume reflect the characteristics of cargo transport aircraft. Figures 13 and 14 show that the design of a freighter, in comparison to a passenger transport aircraft, could look quite different: a much smaller slenderness would be required (up to 7).

3.5.3 Considerations with Respect to the Fuselage Wetted Area Calculation

In order to understand how the fuselage shape affects the drag, the zero lift drag was expressed as a function of the slenderness parameter and the influence of the empennage was removed (see Section 3.5.4). The estimation method used for the wetted area - as a component of the drag, depending on the slenderness – has a great impact on the results. Three different ways of calculating $S_{wet,F}$ were chosen:

- Torenbeek approach [12], as given in (19);
- Three-parts-fuselage approach, as indicated in Figure 15 and (37);
- Simple approach (aircraft as a cylinder) as indicated in (38).

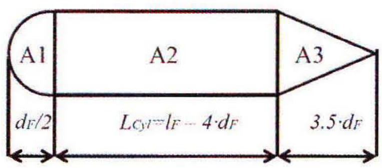

FIG. 15 Three parts approximation for the calculation of the wetted area

$$(37)\quad \begin{cases} A_1 = \pi \cdot d_F^{\ 2};\ A_2 = L_{Cyl} \cdot \pi \cdot d_F;\ A_3 = (d_F/2) \cdot s\pi \\ s = \sqrt{(3.5 \cdot d_F)^2 + (d_F/2)^2} \\ S_{wet,F} = A_1 + A_2 + A_3 \end{cases}$$

$$(38)\quad S_{wet,F} = \pi \cdot d_F \cdot l_F$$

The visualization of the three wetted areas in a single graph, relative to $d_F^{\ 2}$, shows the different validity domains for each case.

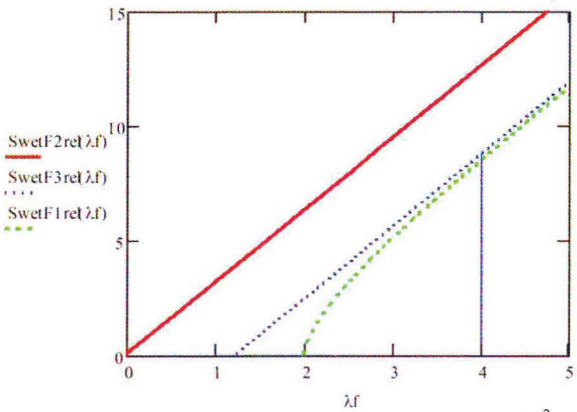

FIG. 16 Wetted area of the fuselage relative to $d_F^{\ 2}$ as a function of the slenderness parameter: 1. Torenbeek (green), 2. Fuselage as a cylinder (red), 3. Fuselage as a sum of cockpit, tail and cabin (blue)

The following observations can be extracted from Figure 16:

- The simple approach (red) is valid also for small slenderness λ_F.
- The Torenbeek approach and the 3-parts aircraft approach are valid for the rest of the aircraft, but not for aircraft with a small diameter.
- The Torenbeek approach (green) is valid for aircraft having a slenderness $\lambda_F > 2$.
- The 3-parts approach (blue) is valid for aircraft having a slenderness[1] $\lambda_F > 4$.

3.5.4 Fuselage Zero Lift Drag

For each type of wetted area, the zero lift drag of the fuselage was then represented relative to[2]:

- Cabin surface: $d_F \cdot l_F$
- Cabin frontal area: $\pi \cdot d_F^{\ 2} / 4$

A summary of the studied cases is presented in Table 6.

TAB. 6 Cases studied for the illustration of the zero lift drag as a function of the slenderness

ID	Case	Variable Name	Figure
1	Torenbeek approach		
1.a	Relative to cabin surface	$D_{0,Tcs}$	FIG. 17
1.b	Relative to frontal area	$D_{0,Tfa}$	
2	Three-parts aircraft approach		
2.a	Relative to cabin surface	$D_{0,Pcs}$	FIG. 18
2.b	Relative to frontal area	$D_{0,Pfa}$	
3	Simple approach		
3.a	Relative to cabin surface	$D_{0,Scs}$	FIG. 19
3.b	Relative to frontal area	$D_{0,Sfa}$	

The optimal values of the slenderness parameter, calculated with the wetted area from Torenbeek, are as follows (see Figure 17):

- $\lambda_F = 9.8$ when the cabin surface is constant (red)
- $\lambda_F = 3.5$ when the frontal area is constant (blue)

[1] The cylindrical part of the fuselage becomes too small and the equation is no longer valid (see Figure 15).
[2] The zero lift drag relative to volume cannot be expressed as a function of the slenderness.

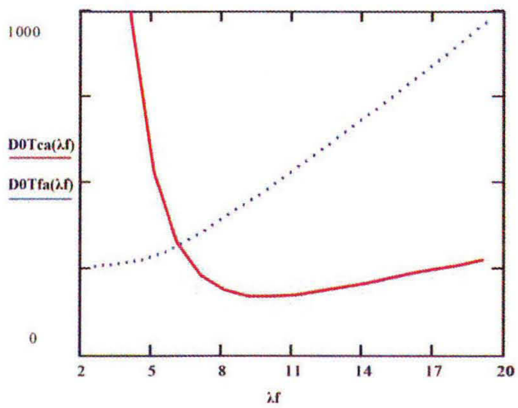

FIG. 17 Fuselage Zero Lift Drag as a function of slenderness: Cases 1.a, 1.b

The optimal values of the slenderness parameter, calculated with the wetted area from (37), are as follows (see Figure 18):

- $\lambda_F = 10.7$ when the cabin surface is constant (red)
- $\lambda_F = 4$ when the frontal area is constant (blue)

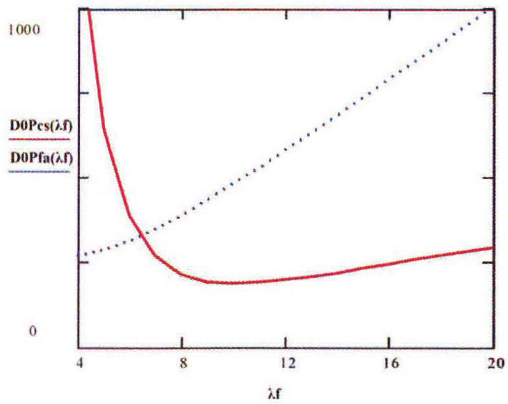

FIG. 18 Fuselage Zero Lift Drag as a function of slenderness: Cases 2.a, 2.b

The optimal values of the slenderness parameter, calculated with the wetted area from (38), are as follows (see Figure 19):

- $\lambda_F = 16.4$ when the cabin surface is constant (red)
- $\lambda_F = 5$ when the frontal area is constant (blue)

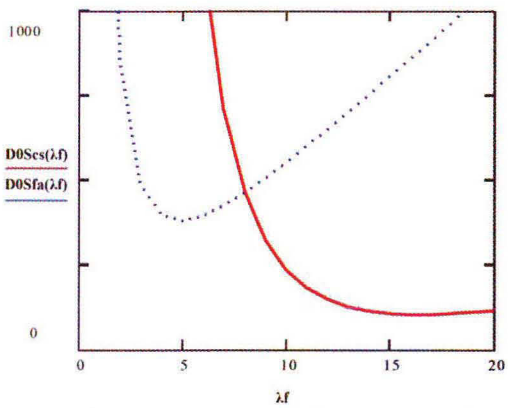

FIG. 19 Fuselage Zero Lift Drag as a function of fuselage slenderness: Cases 3.a, 3.b

However, this simple consideration (38) leads to larger, unrealistic values for the slenderness parameter in comparison to the values in the first two cases.

3.5.5 Considerations with Respect to the Fuselage Mass Calculation

The same type of evaluation that was made for the wetted areas can be conducted for the mass estimations, by looking at different authors. So far the Torenbeek approach was used to calculate the fuselage mass (see (25)). Another approach is indicated in [7] as shown in (39), called "Markwardt's approximation".

(39) $m_F = 13.9 \cdot S_{wet,F} \cdot \log(0.0676\, S_{wet,F})$.

Equation 39 represents the analytical interpretation of the statistical data gathered in Figure 20.

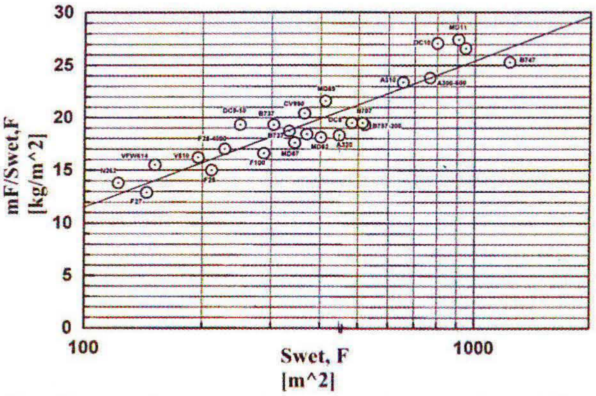

FIG. 20 $m_F/S_{wet,F}$ as a function of the wetted area [7]

When representing the two possibilities of expressing the mass relative either to $d_F{}^2$ or to $d_F \cdot l_F$ (see Figure 21), the following observations can be extracted[3]:

- The mass is zero for $\lambda_F = 2$; this results from the wetted area equation.
- Markwardt's approximation climbs faster than Torenbeek's approximation, which means the mass penalty with Markwardt's approximation is greater for slenderness values of conventional fuselages.
- Torenbeek's approximation becomes unrealistic for large slenderness values.

Reference [13] presents the results of an investigation towards different mass estimations for aircraft components. For aircraft investigated, Markwardt's approach (39) returned a deviation of approximately $\pm 4\,\%$ from the original aircraft mass data, while Torenbeek's approach deviated from $-9\,\%$ up to $-20.6\,\%$. The wetted area calculated from Torenbeek (19) showed a deviation from $-4.7\,\%$ up to $-8.6\,\%$.

[3] In both cases the wetted area was calculated with Equation 19 [12].

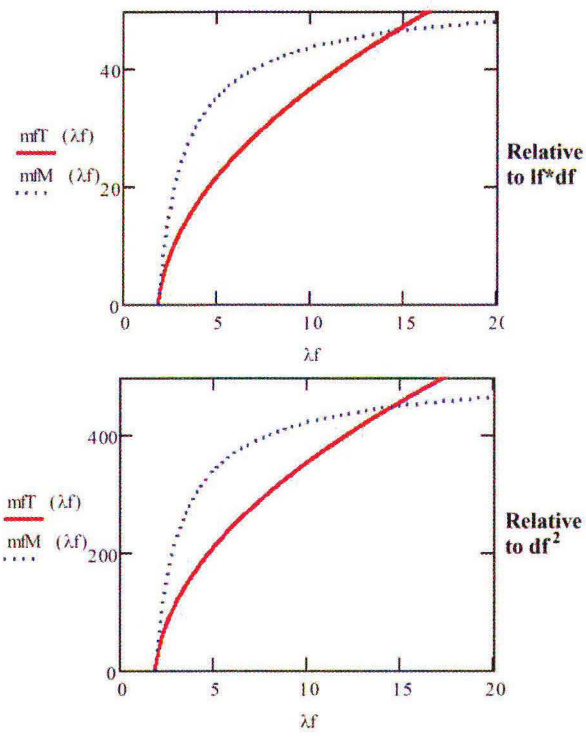

FIG. 21 Relative fuselage mass after Torenbeek (red) and Markwardt (blue) as a function of the slenderness parameter

3.5.6 Considerations with Respect to the Cabin Parameters

The basic requirement when designing the fuselage is the number of passengers (or the payload) that need to be transported. For a given (i.e. constant) number of passengers, it makes sense to optimize the number of seats abreast in connection to the fuselage drag and fuselage slenderness.

An easy way of calculating the number of seats abreast n_{SA} for a given number of passengers is given by [5] (see (1), Section 2.2). A practical question arises: if the so calculated n_{SA} has the value of 5.76 (as it is the case for the A 320 aircraft, which has 164 passengers in a two class configuration – see Table 7) which is the optimal value between the value of 5 and the value of 6? Table 7 gathers some examples in order to compare the calculated value with the real value of the n_{SA} parameter.

TAB. 7 n_{SA} parameter for selected commercial transport aircraft

Aircraft type	Number of passengers	n_{SA} calculated from Reference [5]	n_{SA} real
ATR 72	74	3.87	4
A 318	117	4.87	6
A 319	134	5.21	6
A 320	**164**	**5.76**	**6**
A321	199	6.35	6
A330-300	335	8.24	8
A 340-600	419	9.21	8

In order to find the optimum and to answer the above question, the following procedure was followed:

- A reference value of the parameter n_{SA} was calculated from (1).

- The resulting value was varied under and above the reference value.
- For the obtained values the corresponding fuselage length and diameter were calculated with (4) and (8).
- For each length-diameter pair the drag and the drag relative to the cabin surface was calculated with (35) and graphically represented.

The results are indicated in Figures 22 to 25.

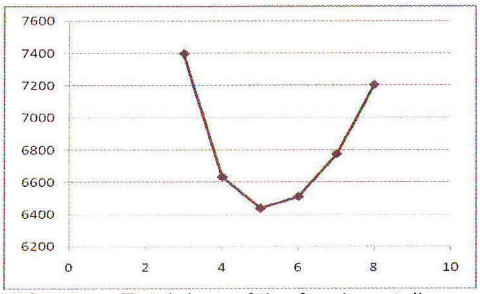

FIG. 22 Total drag of the fuselage-tail group as a function of number of seats abreast for a constant number of passengers

For the reference aircraft (A320), with 164 passengers in a standard configuration, Figure 22 indicates that the value of 5 provides a slightly smaller drag than the real value of 6 seats abreast. On the other hand, when looking at the relative drag (Figure 23), the value of 6 is favored.

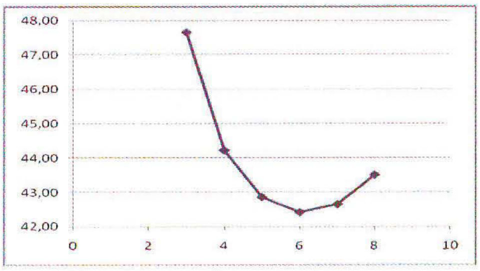

FIG. 23 Total drag of the fuselage-tail group relative to cabin surface ($l_F \cdot d_F$) as a function of number of seats abreast for a constant number of passengers

With this approach, the effect of the empennage can now also be expressed in connection with the slenderness. The total drag and the drag relative to cabin surface of the fuselage-empennage group are shown in Figures 24 and 25. The first chart indicates an optimal value of 12.5 while the second chart indicates an optimal value of 10.2.

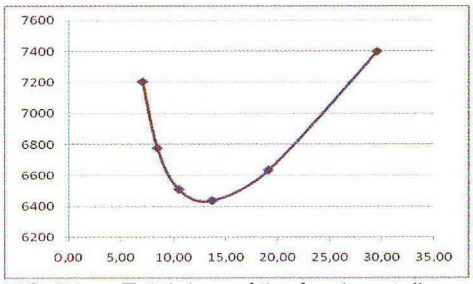

FIG. 24 Total drag of the fuselage-tail group as a function of slenderness for a constant number of passengers for the selected values of the parameter n_{SA}

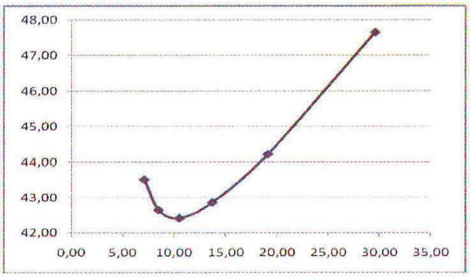

FIG. 25 Total drag of the fuselage-tail group relative to cabin surface ($l_F \cdot d_F$) as a function of the slenderness parameter for the selected values of the parameter n_{SA}

4 UTILIZATION OF CHROMOSOME-BASED ALGORITHMS FOR OPTIMIZING THE CABIN

4.1 Evolutionary and Genetic Algorithms

This section presents the results after coding and running a genetic algorithm with the purpose to find the optimal fuselage shape that minimizes the "drag in the responsibility of the cabin". Although this approach is especially valid for complex objective functions, depending on a large number of variables, the purpose here is to apply the algorithms in a simple case and to compare the results with the ones obtained in Chapter 3. Therefore the same two variables are intended to be optimized here: the fuselage length and diameter.

All the variations made to find an optimum start from a baseline aircraft model described by corresponding input values for the variables. The baseline model used for this research is the ATR 72 – a propeller driven commercial regional transport aircraft.

The values of each parameter are coded such as the genes are coded in the chromosomal structure. Each variable is associated with a bit-string with the length of 6. This length is argued by [3]. Two variables, each represented by 6 bits give $(2\cdot 6)^4=20736$ possible fuselage - empennage shape variations that minimize drag.

Starting from the aircraft baseline, an initial population of chromosomes, representing random values within an interval for each parameter, is defined. In all the chromosome-based routines, the initial population is created by using a digital random number generator to create each bit in the chromosome string. Then, this string is used to change the input variables of the baseline design, creating a unique "individual" for each chromosome string defined. Where the optimizers differ is how they proceed after this initial population is created. Selection of the "best" individual or individuals is based primarily on the calculated value of the objective function [3].

The next essential step is the concept of crossover, equivalent to mating in the real world of biology. Crossover is the method of taking the chromosome/gene strings of two parents and creating a child from them. Many options exist, allowing a nearly limitless range of variations on GA methods [3]:

1) *Single-Point Crossover* – The first part of one

parent's chromosome is united with the second part of the other's. The point where the chromosome bit-strings are broken can be either the midpoint or a randomly selected point.

2) *Uniform Crossover* – Combines genetic information from two parents by considering every bit separately. For each bit, the values of the two parents are inspected. If they match (both are zero or both are one), then that value is recorded for the child. If the parents' values differ, then a random value is selected.
3) *Parameter-Wise Crossover* – Combines parent information using entire genes (each 6 bits) defining the design parameters. For each gene, one parent is randomly selected to provide the entire gene for the child.

For the selection of the parents there are as well several possibilities [3]:

1) *Roulette Selection* – The sizes of the "slots" into which the random "ball" can fall are determined by the calculated values of the objective function based on actual data.
2) *Tournament Selection* – Selects four random individuals who "fight" one-vs.-one; the superior of each pairing is allowed to reproduce with the other "winner".
3) *Breeder Pool Selection* – A user-specified percentage (default 25%) of the total population is then placed into a "breeder pool"; then, two individuals are randomly drawn from the breeder pool and a crossover operation is used to create a member of the next generation.

Best Self-Clones with Mutation. A type of evolutionary algorithm, different than genetic algorithms through the lack of crossover, uses the concept of 'queen' of the population. The queen is the variant which gives best values for the objective functions. She is the only one allowed to further reproduce. The next generation is created by making copies (clones) of the queen's chromosome bit-string and applying a high mutation rate to generate a diverse next generation.

Monte Carlo Random Search. Using the same chromosome/gene string definition different versions are randomly created and analyzed, without considering any evolutionary component. Due to the binary definition of the design variables, a number of $2^{(2\cdot 6)}$ variants can be analyzed. However, in practice, the analysis is reduced to a smaller number (Reference [3] generated 20 population packages of 500 individuals each, which yields a number of 20000 aircraft variants to be analyzed out of the total design space).

4.2 Results

The aim of the genetic algorithm is to find the fuselage length and diameter which minimize the two variable objective function plotted in Figure 8. It is to be remembered that Figure 8 shows the variation of the total drag of the fuselage-tail group relative to cabin surface. The values read from the plot are than easily compared with the results generated by the genetic algorithm. The advantages of the Genetic Algorithms are, however, decisive when the objective functions have more than two variables and plotting is no longer possible.

The procedure used to program the genetic algorithm that finds the best values for the two variables is shown in Figure 19. The detailed steps followed for programming the algorithm are described in Table 8, while the results are listed in Table 9.

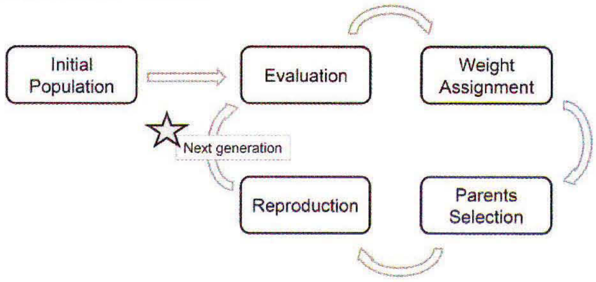

FIG. 19 The procedure used for programming the genetic algorithm (Based on [14])

TAB. 8 The steps of the genetic algorithm

Input data	- Number of bits for each chromosome[1] - Number of generations - Number of members for each generation - Definition domain for each variable of the objective function
Algorithm steps	- Creation of the initial population of members (first generation): ○ The crossover is made by concatenating randomly selected numbers[2,3] between 0 and 2^n-1. - Evaluation of the objective function[4]: ○ The numbers are scaled to the definition domain. - Creation of the next generations[5] (chosen was the Roulette method for the parents selection): ○ Calculation of a total weight[6] representing the total 'surface' of the roulette, where each member has a partial surface proportional to its weight[7]. ○ Random generation of a number between 0 and the total weight[8] for choosing the first parent. ○ The same procedure for the second parent. - Crossover of the chromosomes of the two parents[9] - Evaluation of the objective function[10]
Output data	- After the creation of the last generation, display of the best values of the objective functions, and the values of the corresponding variables

[1] A chromosome is associated with each variable of the objective function.
[2] n represents the number of bits contained by each chromosome (6 bits were chosen in this case)
[3] For the concatenation to be possible, the numbers are first transformed in base 2 numbers.
[4] For the evaluation the numbers are transformed back in base 10.
[5] Every generation represents the result of the crossover of the members from the previous generations.
[6] If it is intended to find the maximal value of the objective function, then the total weight represents the sum of the values of the objective function for each member of the population; if the purpose is to find the minimal value (our case) then the total weight represents the sum of the inverse of these values.
[7] In other words, proportional to how 'good' the value of the objective function is for the respective member.
8 The better a member is, the greater the surface is, so the chances to be selected become greater as well.
[9] One chromosome from one parent and one from the other (for a two variable function).
[10] In the same way as for the first generation.

The following important observations can be extracted:

- The Roulette selection is made for 90% of the members, while for the rest 10%, the best parents are directly chosen.
- If the percent of the very good members going directly to the next generation is to high, then the diversity of the members drops considerably and the risk of a convergence towards local (instead of global) minimums grows.
- There is no convergence criteria – after a relatively

small number of generations (imposed from the beginning), no significant improvement in the values of the objective function is registered.

– The optimal number of generations, the optimal number of members for each generation and the percent of the very good members going directly to the next generation must be found based on experience.

The shape of the objective function plays a decisive role in choosing the right optimization algorithm. If the shape is rather linear, then there is no risk in finding just a local minimum. However, if the function is very complicated then the stochastic algorithms, such as GA, are better, as the risk of finding just a local minimum decreases.

TAB. 9 Results of the genetic algorithm

Input Parameters	- Number of bits for each chromosome: 6 - Number of generations: 6 - Number of members for each generation: 100 - Definition domain for each variable of the objective function: [,] for l_F, [,] for d_F		
Variables	l_F	d_F	Drag/(l_F*d_F)
Generation 1	41.4286	**5.7286**	41.8312
Generation 2	50.5211	4.7190	41.7160
Generation 3	51.4286	5.3079	41.5289
Generation 4	47.8571	5.4762	41.2689
Generation 5	**50.7143**	**5.7286**	**41.2655**
Generation 6	**50.7143**	**5.7286**	**41.2655**
Observations	The last two generations provide identical results, up to the 4th digit behind the decimal point, showing the desired convergence. Only six generations are required to obtain an optimum, due to the small number of variables of the objective function. For such a simple function, with no local minimums, the genetic algorithm approach does not represent the optimal choice. However, this exercise sets the basis for the future work.		

In Figure 8 a zone of minimum relative drag can be identified. In practice it is difficult to 'read' the optimum values for fuselage length and diameter. The use of genetic algorithms brings its contribution in detecting the most likely minimum value of the drag and the corresponding fuselage dimensions with enough (predefined) accuracy. The results listed in Table 9, corresponding to a slenderness of $\lambda_F = 8.85$ match with the minimum zone indicated In Figure 8.

5 SUMMARY AND CONCLUSION

This paper dealt with two major aspects related to the aircraft cabin:

1) the cabin preliminary design, with the aim to describe the basic methodology, as part of aircraft design.
2) the cabin optimization, with the aim to find the optimum of relevant parameters.

With respect to cabin optimization, this paper sought the answer to the following questions:

1) What length minimizes the drag given a certain maximum diameter?
2) What slenderness minimizes the drag and the relative drag given a certain number of passengers?
3) What number of seats abreast is optimal given a certain number of passengers?
4) Which is the influence of the wetted area calculation method upon the results?
5) Which is the influence of the mass calculation method upon the results?

In order to find the answers, the fuselage "drag being in the responsibility of the cabin" was calculated.

Two approaches were selected to conduct the cabin optimization:

1) An in depth analytical approach, based on the available handbook methods, was used as *basic method*.
2) An exemplarily stochastic approach, based on chromosomal algorithms, was used as *reference method*, for the case of further extension of the research.

A two variable objective function was used in both cases. The use of two variables – either the fuselage length and fuselage diameter, or the fuselage slenderness and fuselage length multiplied by diameter – allowed plotting and therefore the visualization of each variation, and, as a consequence, no difficulty was encountered in reading the minimum from the plot.

In order to find an exact number of the minimum, an optimization method had to be applied. A Genetic Algorithm was chosen which confirmed the minimum of the plot and yielded an accurate number for the minimum depending on the number of iterations.

The results are summarized in Table 10. The main observation is that the slenderness parameter for freighter aircraft should be considerable smaller than for civil transport aircraft, especially if large items are to be transported and hence frontal area is of importance.

TAB. 10 Summary of results

Aircraft	Drag relative to...	Model	Drag calculated with... zero-lift drag	induced drag	Plot	d_F	l_F	λ_F	Remark
Pax	cabin surface area	Fuselage-Tail	x	x	Fig. 8	5.7286	47.8571	8.85	Genetic Algorithm
Freighter	frontal area	Fuselage-Tail	x	x	Fig. 9	7	25	3.6	
Freighter	volume	Fuselage-Tail	x	x	Fig. 10	7	50	7.1	
Pax	cabin surface area	Fuselage	x	x	Fig. 12			10.0	
Freighter	frontal area	Fuselage	x	x	Fig. 13			3.0	
Freighter	volume	Fuselage	x	x	Fig. 14			5.0	
Pax	cabin surface area	Fuselage	x		Fig. 17			9.8	Torenbeek
Freighter	frontal area	Fuselage	x		Fig. 17			3.5	Torenbeek
Pax	cabin surface area	Fuselage	x		Fig. 18			10.7	Three-parts
Freighter	frontal area	Fuselage	x		Fig. 18			4.0	Three-parts
Pax	cabin surface area	Fuselage	x		Fig. 19			16,4	Simple
Freighter	frontal area	Fuselage	x		Fig. 19			5.0	Simple
Pax	cabin surface area	Fuselage-Tail	x	x	Fig. 25			10.2	n_{SA} variation

For a passenger aircraft, the results show that a slenderness of about 10 minimizes the “drag in the responsibility of the cabin” relative to cabin surface. For a freighter aircraft, a slenderness of about 4 minimizes the "drag in the responsibility of the cabin" relative to frontal area. A slenderness of about 8 minimizes the "drag in the responsibility of the cabin" relative to cabin volume.

In order to obtain more accurate results, a multidisciplinary approach would be required. Cabin and fuselage design should be considered as part of the whole aircraft design sequence. In this way all "snow ball" effects could be accounted for. The use of stochastic optimization algorithms seems to be a good solution for multidisciplinary design optimization. This approach should be broadened and is foreseen for the future work.

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