PRELIMINARY DESIGN OF A LONG RANGE WINDOWLESS AIRCRAFT CONCEPT

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Abstract

The objective of this paper is to describe the preliminary design of a windowless configuration of a long-range aircraft and to analytically assess the achieved weight reduction. As a matter of fact, the reduction of weight is directly linked with reduction of fuel consumption; consequently there are advantages in terms of aircraft operative costs and emissions of carbon dioxide. A feasibility study will bring to the assessment of weight and cost reduction in consideration to the introduction of innovative screens, to give passengers the possibility to see through the fuselage itself.
The proposed methodology consists in the preliminary design of a long-range aircraft, considering some defined design parameters and constraints. The activity will finally lead to weight reduction evaluation, in case the same aircraft will be designed windowless.
In the end the methodology is applied to two existing aircrafts to estimate potential benefits of the windowless configuration if compared to the traditional one: the Airbus 340-500 and the Being 777-300.

1 Introduction

Based on market forecasts, air traffic is expected to double by next 20 years and the whole airliners fleets will be increased with about 35000 new aircrafts. According to this perspective, production and management costs will play a key role, as well as green design perspective.
In this perspective the windowless configuration aims to reduce the aircraft's weight and so emissions of carbon dioxide and operative costs.
In literature the windowless concept has been studied through three different configurations:

- windowless cockpit as described in [1, 2];
- windowless fuselage used on blended wing body aircraft in [3, 4];
- windowless fuselage in traditional passenger aircrafts.

The first configuration consists in a windowless cockpit so without the windscreens, which are replaced with monitors and cameras to guarantee a 360° view.
Secondly, a few windowless configurations have been analyzed considering blended wing body aircrafts that can not have a sufficient number of windows to ensure passenger comfort, so it is necessary to use monitors instead of real windows.
The third configuration is applied on a traditional fuselage, whose windows are removed, except those of emergency exits, and replaced with a visual system.
The strength of this configuration is that it does not require a complete redesign of the fuselage itself and of the manufacturing process, since it could be considered as a development of existing cabins. The internal cabin layout would be very similar to the traditional one, helping passengers to accept the new concept. Finally, a windowless fuselage has lower manufacturing costs and it is more resistant to fatigue damage, if compared to a traditional one.

In the proposed concept, to overcome problems related passengers' comfort, as claustrophobia, windows are replaced with monitors connected to external cameras. Monitors could have bigger size than windows, to enable a wider field of view.
The monitors should be light and efficient. The choice has fallen upon OLED (Organic Light Emitting Diode) screens, in fact in consideration of both performances and weight saved, they outclass the traditional screens as LCD (Liquid Crystal Display). These monitors are connected to external cameras to show the outside view and they are partially covered by an internal cabin-lining layer to recreate the elliptical shape of windows and to provide a sense of perspective as it was described in [5] and shown in Figure 1. This configuration could provide

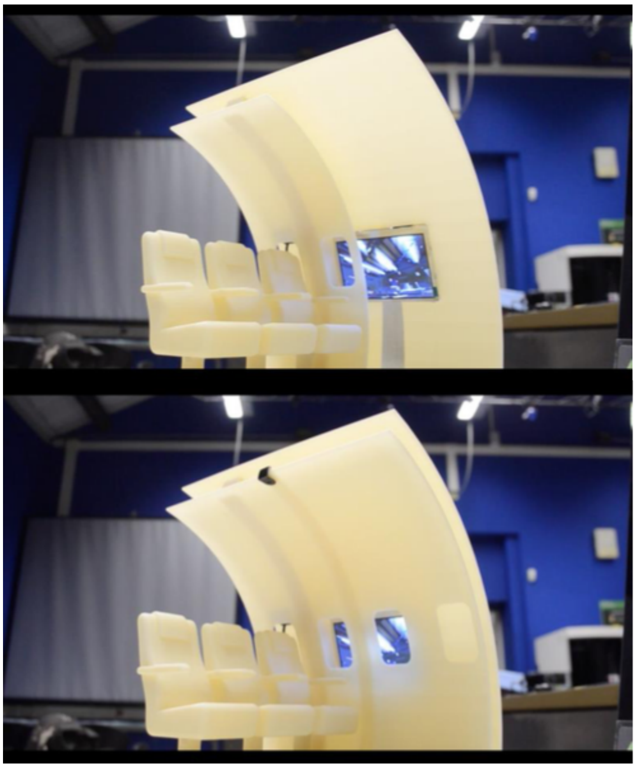

Figure 1 Small scale model of false windows manufactured using Additive Manufacturing.

additional future developments of usage, such as:

- the possibility to check the ground to be clear of FOD (foreign object debris);
- the possibility to evaluate engine damages or to other external parts of the aircraft;
- passengers can be provided with additional information about weather and the position of the aircraft;
- the crew can quickly communicate with passengers and vice versa.

In the following sections the advantages of this concept will be analyzed describing the preliminary design methods and tools used to conduct the study (section 2) and discussing the results obtained considering two long-range aircraft, namely Airbus 340-500 and Boeing 777-300 (section 3).

2 Method and tools

The windowless configuration is compared to a traditional one in terms of weight using the neutral hole theory. The weight can be linked to the number of removed windows, for each system affected by the weight reduction.
To a first approximation, the aerodynamic performances of the airplane are considered as constants.

2.1 Background

From a survey on existing long-range aircrafts a few quantitative relationships between the number of windows and the main aircrafts sizing parameters have been obtained. The following linear equations are derived interpolating data from eight different long range aircraft with a single deck:

- the fuselage length L (m) as a function of the number of windows on one side of the aircraft $N_{w/2}$:

$$L = 0.7361 \cdot N_{w/2} + 18.816 \tag{1}$$

- the cabin length L_c (m) as a function of the number of windows on one side of the aircraft $N_{w/2}$:

$$L_c = 0.528 \cdot N_{w/2} + 20.745 \tag{2}$$

- aircraft the take-off weight W_{TO} (kg) as a function of the number of windows on one side of the aircraft $N_{w/2}$:

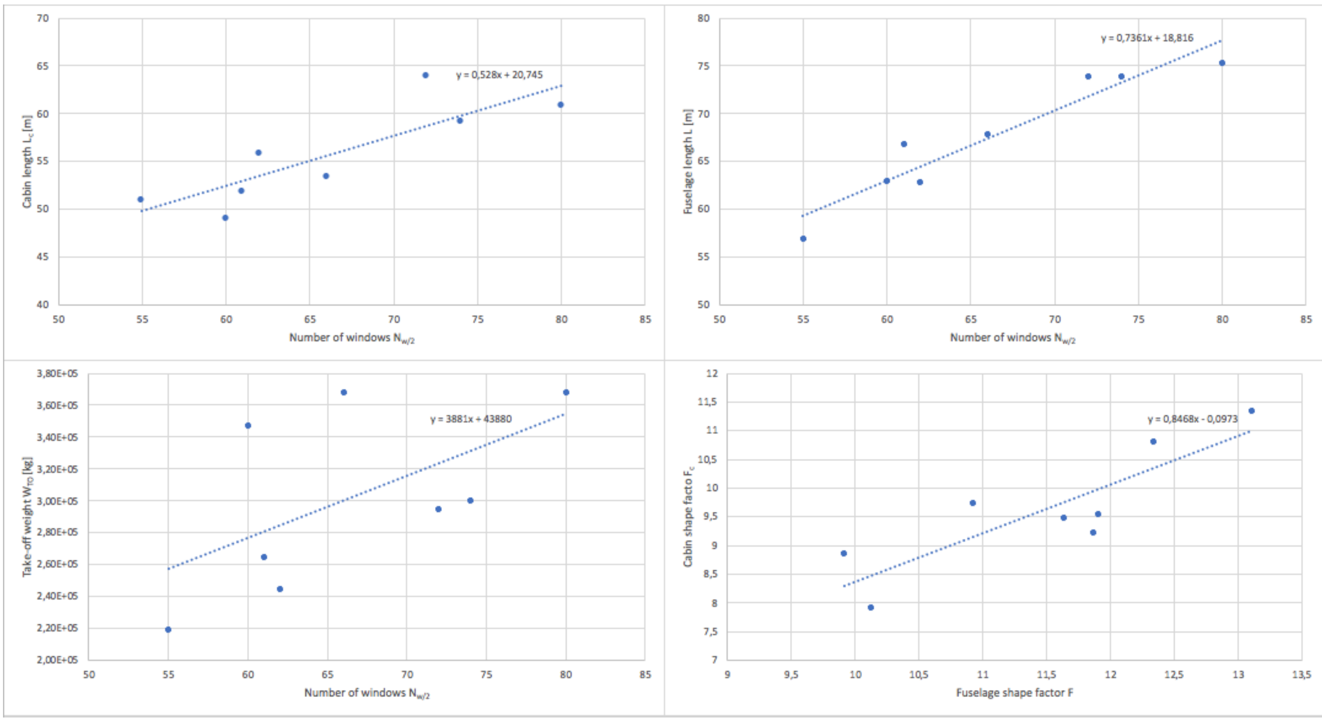

Figure 2 The linear equations of: i) cabin length vs number of windows (top left), ii) fuselage length vs number of windows (top right), iii) take-off weight vs number of windows (bottom left), and iv) cabin shape factor vs fuselage shape factor (bottom right) are derived interpolating data from eight different long range aircraft with a single deck.

$$W_{TO} = 3881 \cdot N_{w/2} + 43880 \qquad (3)$$

Besides, interpolating the same data, it has been obtained the linear relationship between the shape factor of the fuselage $F=L_f/d$ and the shape factor of the cabin $F_c=L_c/d$:

$$F_c = 0{,}8468 \cdot F - 0.0973 \qquad (4)$$

The plots of these four relations are represented in Figure 2.

2.2 Weight reduction

The weight reduction can be estimated considering the removal of the following elements:

- panes;
- metal frames;
- longitudinal reinforcements;

and the addition of the following elements:

- alloy necessary to "refill" the holes due to the absence of the windows;
- the parts of stringers that were absent due to the presence of the windows in the traditional cabin;
- visual systems (cameras, monitors and cables).

Considering an aircraft with N_w windows of elliptical shape with a and b the major and the minor semi-axis respectively, L_c the length of the passengers cabin, d the fuselage width, t its thickness and ρ_a the material density, it is possible to write the equations for each component.

The weight of the panes W_p is the sum of the weights of the three panes of a window (pressure pane, safety pane and dust cover):

$$W_p = N_w \cdot A \cdot [\rho_{lex} \cdot (t_1 + t_2) + \rho_{plex} \cdot t_3] \qquad (5)$$

in which $A = a \cdot b \cdot \pi$ is the area of a window, t_1, t_2 and t_3 the thickness of the three panes, ρ_{lex} and ρ_{plex} the densities of the materials of the panes (lexan and plexiglass).

The weight of the structural elements is derived using the neutral hole theory [6] in absence of real data. In fact windows are holes in the fuselage, so there is a concentration of stresses around them and it is necessary to reinforce them with external elements. Therefore the weight of the longitudinal reinforcements W_r is given as:

$$W_r = 2 \cdot L_c \cdot (t_r - t) \cdot w \cdot \rho_a \qquad (6)$$

with t_r the thickness of the longitudinal reinforcements and w their height. Then the weight of metal frames W_f, which are around every window, could be expressed with the following equation:

$$W_f = \sqrt{2} \cdot k \cdot A_0 \cdot b \cdot \rho_a \cdot N_w \qquad (7)$$

with k the ratio between the two semi-axis of the window and A_0 the area of the compacted reinforcement in which the loads are maximum. The weight of the material to "refill" the holes is the product of the windows volume and alloy density:

$$W_a = A \cdot t \cdot \rho_a \cdot N_w \qquad (8)$$

The weight of the "added" parts of the stringers W_S is given by the product of the stringers part volume ($V_s = b_s \cdot a_s \cdot t_S$) and alloy density:

$$W_s = V_s \cdot \rho_a \cdot N_w \qquad (9)$$

Finally the weight of monitors, cameras and cables, necessary for connection, W_{mc} :

$$W_{mc} = (W_m \cdot N_m + W_c \cdot N_c) \cdot X \qquad (10)$$

in which the coefficient X represents the weight of the cables associated with the installation of each monitor and camera. This factor strongly depends on the type of connection (in series or single) and if there is an external elaborating system. It can vary from 10% to 40% of the weight of the monitors and cameras. The weight of one monitors W_m and one camera W_c depends on the chosen model. The number of the monitors N_m could be expressed as a function of the cabin length:

$$N_m = \frac{L_{ce}}{L_m} = \frac{L_c - L_e}{L_m} \qquad (11)$$

in which L_{ce} is the effective cabin length coverable with monitors and so L_e represents the cabin length occupied by the doors, the emergency exits, the galleys and the toilets. L_m is the length of one monitor. The number of cameras N_c is supposed to be the double of the number of windows to cover the whole outside view.
Therefore, the total saved weight is:

$$\Delta W = W_p + W_r + W_f - W_a - W_s - W_{mc} \qquad (12)$$

It strongly depends on the number of windows N_w, the cabin length $L_c$and the cabin width d. In Figure 2 the reduced weight is represented for different fuselage widths, in function of the number windows.
Finally a further 25% has been added to the total saved weight to consider the indirectly weight reduction of each aircraft systems ("snowball effect"). It also possible to evaluate the reduction of weight of each system using equation in [7].

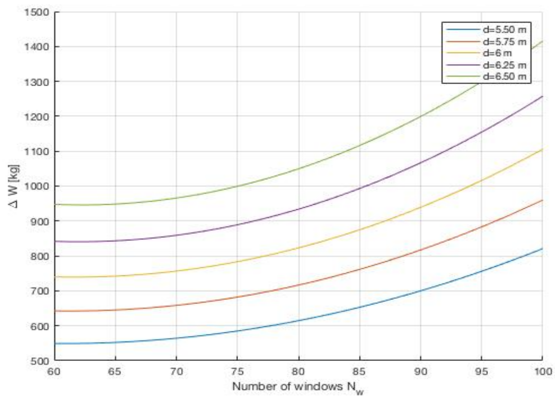

Figure 3 Weight reduction in relation of the removed

2.3 Fuel consumption due to monitors and cameras

The visual system absorbs electrical power. To evaluate the fuel consumption associated to electrical energy consumption, the method proposed by Scholtz at al. [8] is applied. The flow of the fuel $\dot{m}_p$ depends on the shaft power factor k_p, the thrust specific fuel consumption *SFC* and the power *P* that the device needs:

$$\dot{m}_p = k_P \cdot SFC \cdot P \qquad (13)$$

The k_p depends on the altitude and the Mach

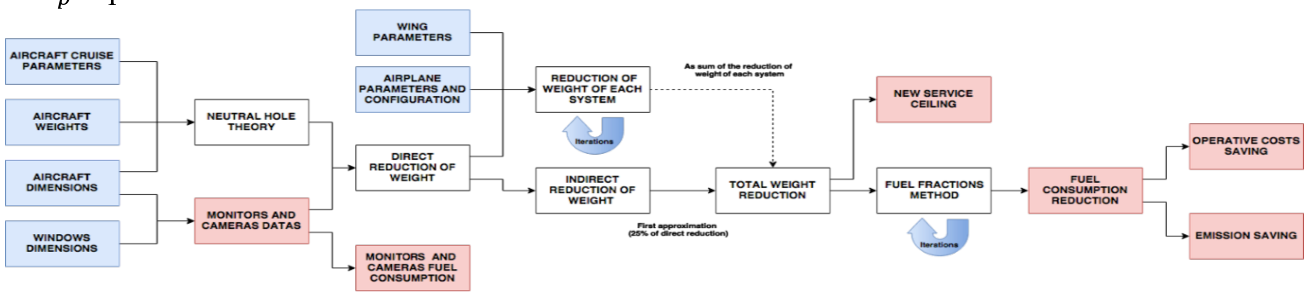

Figure 4 Block diagram.

number. The *SFC* is a specific characteristic of the engine.
Therefore, considering the number and the consumption of monitors and cameras, the fuel consumption is given by:

$$\dot{m}_p = k_P \cdot SFC \cdot (N_m \cdot P_m + N_c \cdot P_c) \qquad (14)$$

For this case, the value is very low and consequently negligible.

2.4 Implementation

The fuel fraction method [9] is applied to evaluate the saved fuel in relation to the reduced aircraft weight, calculating, through an iterative process, the required fuel for each segment of the flight mission.
Figure 4 represents a block diagram of the code used to implement the equations. Aircraft parameters are inputs (blue blocks), while the outputs (red blocks) are calculated to prove the advantages introduced by a windowless configuration in terms of emissions and operational costs.
The code starts sizing the reinforcements, through the neutral hole theory and the visual system. Then it is possible to estimate the direct reduction of the weight due to the removal of windows. The indirect reduction can be calculated in two different ways as explained in section 2.2. Through the fuel fractions method, the reduction of fuel consumption is obtained (considering a fuel density of 0.804 kg/m^3), as well as saved emissions (supposing that one liter of fuel burnt produces 2.531 kilograms of carbon dioxide) and operational costs with a global medium price of jet fuel of 0.401 \$/l.
Moreover, exploiting a chosen atmosphere model (as ISA 76) it is possible to estimate how much the service ceiling is increased. It is also possible to estimate the consumption due to monitors and cameras.

3 Results

3.1 Study cases

The weight savings are calculated for the two reference long-range aircraft: Airbus 340-500 and Boeing 777-300. Table 1 reports the parameters that most influence the weight/fuel consumption reduction. All windows are removed, except for those of the emergency exits, and replaced with 77" OLED screens (1.431 kg) connected with small external cameras (37 g). The weight of the cables is supposed the 30% of the weight of the visual system.
The direct reduced weight is 914 kg for A340 and 1180 kg for B777. It has to be considered that for each kilogram saved in the preliminary design, approximately 1.25 kilograms are saved in the final project. The total reduced weight is 1140 kg for A340 and 1470 for B777. The results, for the three systems affected, are shown in Table 1.

3.2 Costs and emissions

Exploiting the fuel fractions method, we obtain the reduction of fuel consumption. The A340 saves 0.05 liters for kilometer and the B777 0.06 liters per kilometer. Furthermore, assuming that for one liter of fuel 2.5281 kilograms of

CO_2 are emitted, a windowless A340 saves 0.12 kilograms of CO_2 and the B777 0.16 kilograms per kilometer. In terms of operative costs flying with a windowless A340 and B777 is cheaper respectively 0.02 and 0.03 dollars per kilometer. A long-haul aircraft, exploiting a windowless aircraft, as average of A340 and B777, produces the 0.72% less pollutant emissions than a traditional one and it is the 0.85% cheaper. The annual savings are represented in Table 1.

		A340	B777
Parameters	W_{TO} [t]	368	300
	N_w	154	150
	L_c [m]	53.5	59.2
	d [m]	5.64	6.2
Reduced weight [kg]	$\Delta W_{add.}$	1198	1480
	ΔW_{remove}	285	300
	ΔW_{direct}	914	1180
	ΔW_{total}	1140	1470
Annual savings	Operative costs [$]	64000	82000
	Emission [kg]	390000	500000

Table 1 Parameters and results

Conclusions

Based on the analysis performed, the proposed windowless concept allows a reduction of the fuel consumption and the associated emissions, limiting the passenger discomfort due to the removal of windows. Deeper analysis, such as structural, aerodynamics and interiors design, could find more advantages and eventually disadvantages for this configuration. From a structural perspective, the dynamic effect on the windows reinforcements and interactions between windows and other cut-outs, as doors, could be further considered referring to the analysis in [10, 11]. Further studies could deeply analyze the fatigue effects. Deeper aerodynamical analysis could be performed: in fact, aside from the drag reduction due to the removal of windows, the wing surface could be decreased, choosing to embark less fuel, with a lower aerodynamic drag. Finally, new interiors design could introduce passengers in a better way to this new concept, with wider and interactive screens. Furthermore, the visual system of the first class could be different than the one of the second class. In the mid-term future the visual system could be improved with eye tracker devices or using augmented reality glasses and eliminating the weight of the monitors. From a manufacturing point of view a fuselage without holes is cheaper than one with a hole, further studies could quantify this saving. Finally, thanks to the elimination of the windows holes, there will be less diffusion of the external noise in the passenger cabin.

Beyond these technological and economic considerations, the proposed concept could provide a contribution to the global strategies of reducing air pollution through the restraint of the emissions of the aviation industry.

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