



Preliminary design of a short-medium range windowless aircraft

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Abstract

This paper describes a new aircraft concept, where all windows, except those for emergency exits, are replaced with simulated windows, which consist of monitors connected to external cameras to overcome the discomfort for the passenger due to the absence of real windows. This concept is developed through an analytical method to estimate the potential advantages for the environment and for airline companies deriving from a windowless configuration for a short-medium range aircraft, within the boundaries of the preliminary design. Actually, the reduction in weight is directly linked to the reduction in fuel consumption, providing advantages in terms of operating costs and emissions of carbon dioxide. The method is applied to four models of short and medium range aircraft, namely Boeing 737–800, Airbus 320, ATR72 and Embraer 190. The results show the benefits of a windowless configuration that become very positive for the operating life of an aircraft and the total fleet, potentially leading to the saving of millions of tons of carbon dioxide every year when applied to the whole fleet of the analyzed aircraft.

Keywords Aircraft preliminary design · Windowless configuration · Regional aircraft · Fuel consumption reduction · Fuselage design

1 Introduction

The increase in air traffic is expected to grow with an annual trend of 4.3%, in the next 20 years, in accordance with the Airbus Global Market Forecast 2019–2038;¹ thus, there is a greater focus on the environmental impact generated by the transport sector. In this perspective, much research is aimed at defining and developing new designs and technologies to reduce fuel consumption and, consequently, of polluting emissions. This trend is well explained in the work of Frota [1], in particular the authors believe the “classical” aircraft configurations inhibit innovative practices and to ensure a growth in the aviation sector radical changes in the way we design and operate aircraft are required. A similar thesis can be found in the work of Jupp [2].

In this paper, we consider the short-medium range aircraft category (single-aisle), whose sales are expected to account for 76% of the new aircraft deliveries in the next 20 years

(Airbus Global Market Forecast 2019–2038). For example, Kaparos et al. [3] analyzed a design methodology for a box wing aircraft, applying the method to the Airbus A320. Welstead et al. [4] explore the design space of the single-aisle commercial transport concept with a turboelectric propulsion system architecture to evaluate the reduction in fuel consumption.

In the windowless configuration, the reduction in aircraft weight, and consequently, the decrease in fuel consumption, is caused by the removal of windows and their reinforcements and, indirectly, by the possibility of lightening the whole aircraft systems.

In literature, the windowless concept has been occasionally studied through three different configurations:

- windowless cockpit in the works of Zaneboni et al. [5] and of Berth et al. [6];
- windowless fuselage used on blended wing body aircraft by Liebeck [7] and Van Der Voet et al. [8];
- windowless fuselage in traditional passenger aircraft by Bagassi et al. [9–11].

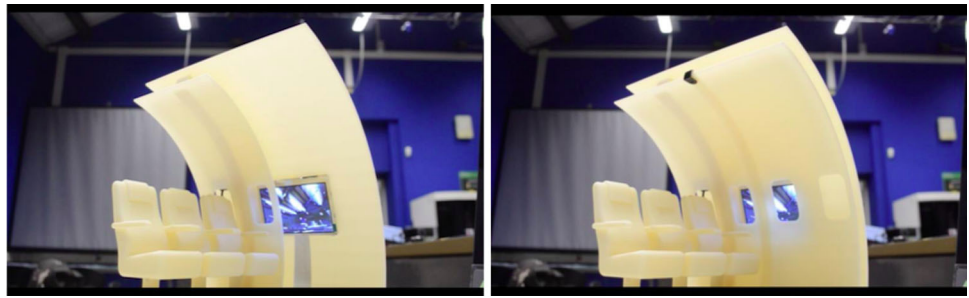
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¹ Boeing Commercial Market Outlook 2019–2038 or Embraer Market Outlook 2019–2038 have similar forecasts.

In the first configuration, the windscreen is removed and replaced by monitors connected with external cameras and

Fig. 1 Physical prototype model for concept assessment



sensors to guarantee a 360° view. These technologies are studied as a further development of ECVFIS (Enhanced Cockpit Visual and Flight Information System). The second configuration consists in the replacement of windows with monitors on blended wing body aircraft, where it is impossible to have openings due to the particular shape of the wing-fuselage structure. The last concept includes passenger aircraft exploiting a traditional configuration, where the windows along the fuselage are removed. This third category results more feasible than the previous configurations, in fact:

- it does not require a complete redesign of the fuselage and of the manufacturing process;
- it could be studied on the existing cabin design;
- from a passenger point of view, aircraft internal layout is apparently the same, if compared to a traditional cabin.

Beyond the structural advantages and benefits in terms of consumption, passenger comfort is a key issue. Therefore, to overcome the sense of claustrophobia, passengers should stay in a totally closed space without the possibility to look outside, windows are replaced by monitors connected with external cameras. It is considered to implement OLED (Organic Light Emitting Diode) screens, as this technology is very efficient in terms of electrical consumption, weight, and realism, compared to the projected image. Monitors, connected with external cameras, show the aircraft outside view and they are partially covered by an internal frame to recreate the elliptical shape of windows and to provide a sense of perspective as it is described by Bagassi et al. in [9] and shown in the model in Fig. 1. Thanks to this concept, it will be possible to provide many additional features, such as:

- check the ground around the aircraft to be clear of FOD (Foreign Object Debris);
- evaluate damage to engine or to other external parts of the aircraft;
- provide passengers with additional information about weather conditions, route and aircraft position;

- provide the crew with a quickly way of communicating with passengers and vice versa directly through the monitors.

In the following sections, the advantages of this concept will be analyzed by describing the preliminary design methods and tools used and discussing the results obtained considering four short and medium range aircraft models (Airbus 320, Boeing 737–800, ATR72 and the Embraer 190). In fact, the aim of this paper is to create an analytical method, in the preliminary design field, to estimate the weight reduction and, consequently, the emissions and operating costs saving, of an existing passenger aircraft exploiting a windowless configuration.

2 Method and tools

In the windowless configuration, aircraft weight reduction is considered compared to a traditional aircraft, removing windows reinforcements. In the proposed approach, the reduction of weight is considered as a function of the number of windows. The preliminary design is conceived considering a medium range aircraft.

As an initial approximation, the aerodynamics performance of the aircraft is considered as a constant.

2.1 Background equations

To define an analytical method it is necessary to identify some statistical relations between the number of windows and the aircraft length, both of the fuselage and of the cabin. These equations serve to relate the number of windows statically with some important parameters in the following method. This, so that we obtain a final curve that gives a preliminary trend of the weight reduction as a function of the number of windows.

The following equations are derived by interpolating a sample of ten different aircraft models with a single aisle deck:

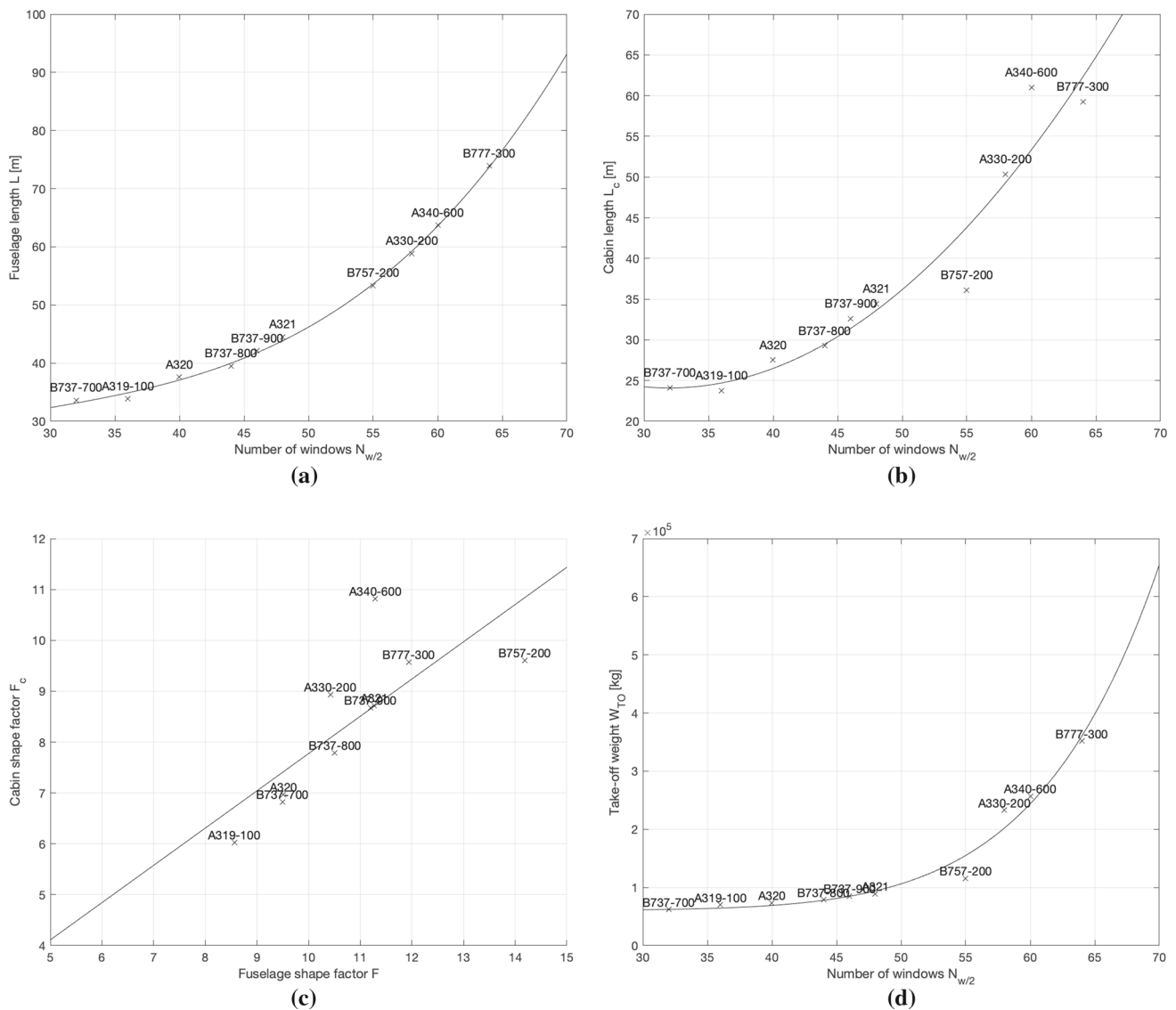


Fig. 2 Background equations obtained from a sample of ten single-aisle aircraft. **a** Fuselage length as a function of the number of windows. **b** Cabin length as a function of the number of windows. **c** Cabin shape

factor as a function of the fuselage shape factor. **d** Max Take-Off Weight as a function of the number of windows

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

$$L = 0.0006518 \cdot N_{w/2}^3 - 0.05641 \cdot N_{w/2}^2 + 2.012 \cdot N_{w/2} + 5.151; \tag{1}$$

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

$$L = 1.035 \cdot 10^{-5} \cdot N_{w/2}^3 + 0.03588 \cdot N_{w/2}^2 - 2.324 \cdot N_{w/2} + 61.38. \tag{2}$$

The linear relationship between the shape factor of the fuselage $F = L/d$ and the shape factor of the cabin $F_c = L_c/d$, is obtained by interpolating the same sample of aircraft models, Fig. 2c:

$$F = 1.3 \cdot F_c + 0.2. \tag{3}$$

In this case we choose a linear interpolations in accordance with the work of Torenbeek [12] and update it.

Finally a qualitative relationship between take-off weight W_{TO} [kg] and the number of windows on one side of the aircraft $N_{w/2}$ is derived, Fig. 2d:

$$W_{TO} = 4.839 \cdot 10^{-9} \cdot N_w^{7.636} + 6.081 \cdot 10^4. \quad (4)$$

These previous equations have only statistical value, they do not want to define a physical correlation between the number of windows and the various parameters. In fact the number of windows in the passenger cabin is not a continuous function of aircraft general parameters but the result of the frame interval along the longitudinal axis and this interval is well known (it depends on the aircraft model). The number of windows is a design data and not a parameter and it is, about, one per half meter independently from the number of the side by side seats and the number of aisles.

2.2 Weight reduction

Weight reduction is the algebraic sum of the weight of the removed elements as panes, metal frames and longitudinal reinforcements, and of added elements, as the visual system and the alloy necessary to “refill” the holes and the part of stringer that were absent due to the presence of the windows in the traditional cabin.

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

The weight of panes W_p can be expressed as:

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

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 of a window (pressure pane, safety pane and dust cover), ρ_{lex} and ρ_{plex} the densities of the materials of the panes (Lexan and Plexiglas).

Windows are openings on the fuselage surface and they weaken the structure. For this reason, the fuselage must be reinforced with external reinforcements. The size of the reinforcements are not easy to find for every aircraft model, so a preliminary method is necessary to estimate it. The lack of data makes it difficult (if not impossible) to create a FEM model, inside a reverse engineering process. Moreover, we prefer to use an analytical equation to simplify the process. However, to the authors' knowledge, there are not more recent publications than that of Mansfield [13] to estimate the reinforcements size. In this paper, the author describes a case study on an aircraft of the same category of those analyzed in this work.

The neutral hole theory [13] is used to size all the elements in absence of actual data. Therefore, it is possible to estimate the weight of:

- the two longitudinal reinforcements W_r with a thickness t_r and a height w :

$$W_r = 2 \cdot L_c \cdot (t_r - t) \cdot w \cdot \rho; \quad (6)$$

- the metal frames W_f , around each window:

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

where $k = a/b$ and A_0 is the area of the compacted reinforcement in which the loads are maximum.

Then the weight of the material necessary to “refill” the holes, W_a , is the product of the window volume and alloy density:

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

The weight of the “added” parts of the stringers W_s is given by the product of the stringers part volume V_s and alloy density:

$$W_s = V_s \cdot \rho_a \cdot N_w. \quad (9)$$

Finally, the weight of monitors, cameras and connective cables, W_{mc} :

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

in which X is the coefficient that represents the weight of the cables to connect each monitor and cameras as fraction of the weight of the visual system (generally from 10% to 40%). This factor strongly depends on the type of connection, in series or single, and whether there is an external elaborating system or not. The weight of one monitor W_m and one camera W_c depends on the chosen technology. The number of monitors N_m was calculated considering they cover the whole space along the passenger cabin, except those occupied by doors, emergency exits, galleys and toilets. The following equation was used:

$$N_m = 2 \cdot \frac{L_{ec}}{L_m} = 2 \cdot \frac{L_c - L_e}{L_m} \quad (11)$$

in which L_{ec} is the effective cabin length, expressed as the difference of the cabin length L_c and length not coverable with monitors L_e . L_m is the length of one monitor.

The number of cameras N_c is considered twice the number of windows in order to obtain a wide view of the outside in any flight phase and for any attitude angle. The cameras are arranged as in Fig. 3c to exploit the greater horizontal FOV (Field of View) in the cameras (all commercial cameras have a greater horizontal FOV than vertical FOV). There are blind spots in the outside scene near the aircraft surface, but we

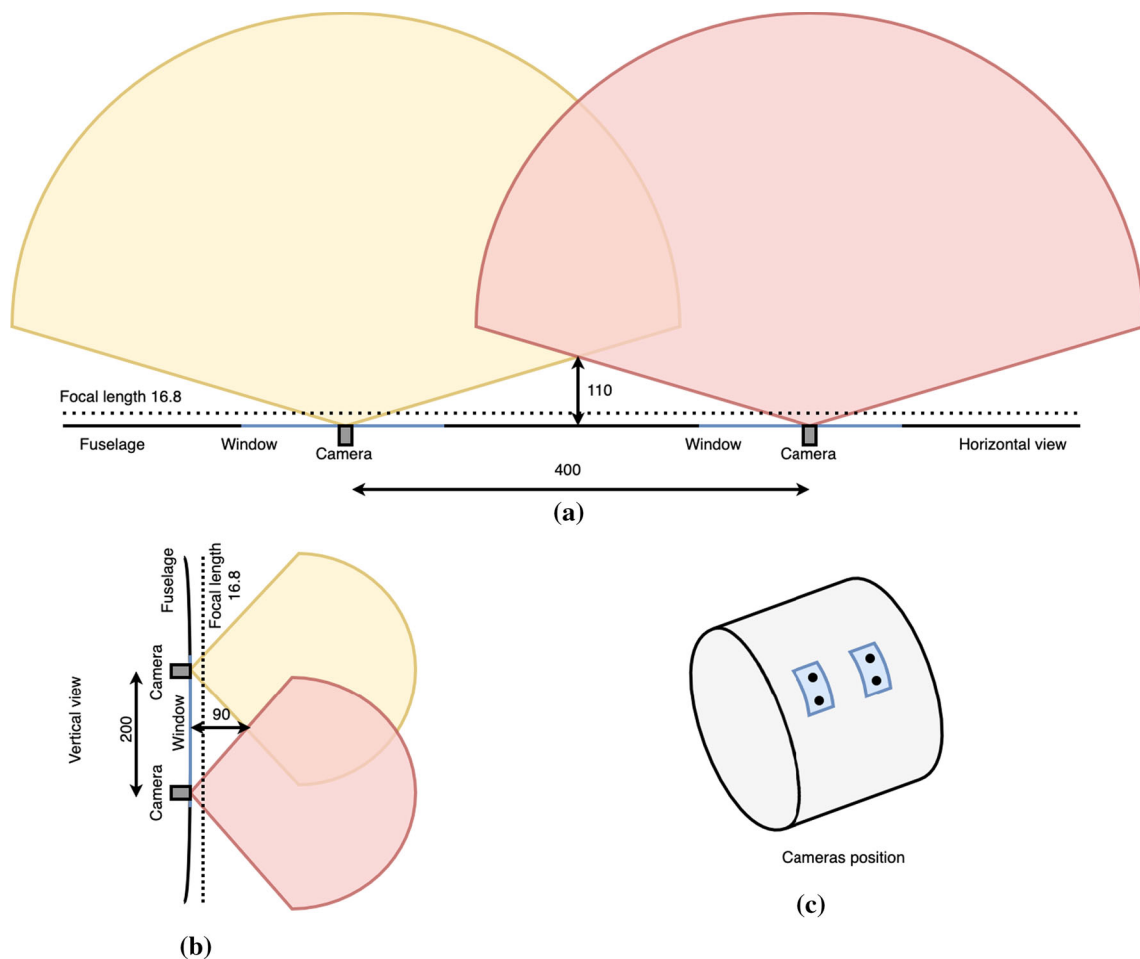


Fig. 3 Camera position and FOV (Field Of View) [mm]. **a** Camera horizontal FOV. **b** Camera vertical FOV. **c** Camera position on the fuselage

must consider that there are no objects to focus or to see in the immediate surroundings. A preliminary estimation of the field of view and blind spots is reported in Fig. 3a, b. Images must be re-elaborated by a software to have a single outside scene, coherent for each virtual window. Moreover the visual system is developed using existing technologies. In a following phase new technologies for aeronautical use must be developed and certified, both from a physical and electronic point of view. Finally the monitors and cameras design, as size and position, could be changed following the airlines evaluation.

Therefore the total reduction in weight is the algebraic sum of added and removed components:

$$\Delta W = W_p + W_r + W_f - W_a - W_s - W_{mc}. \tag{12}$$

The variation in weight ΔW is mostly affected by the following design parameters:

- number of windows N_w , which affects the W_p , W_f , W_a , W_s and N_c and N_m so W_{mc} ;

- cabin length L_c , which affects W_r and W_{mc} ;
- fuselage width d which affects W_r .

Figure 4 represents the reduced weight is represented for different fuselage widths, according to the number of windows and using equation (2) to define the cabin length as a function of the number of windows.

Because of the so-called “snowball effect,” it is supposed, as an initial approximation, that the total weight reduction is increased by 25% compared to that saved in the preliminary design phase. A deeper analysis could be made using the relations in [12] for the three systems most affected by the empty weight reduction:

- wing group;
- landing gear group;
- control surfaces group.

The weight of the wing group is a function of the zero-fuel weight, the wing geometry and the ultimate load factor. We consider the wing geometry to be constant and, as a result,

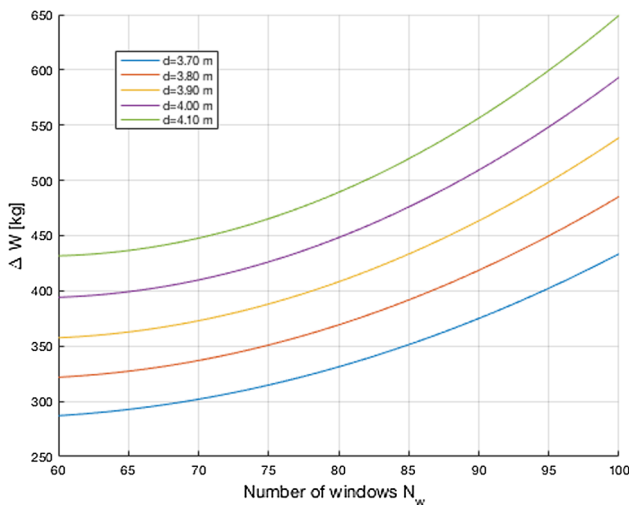


Fig. 4 Weight reduction in relation of the removed windows for different fuselage diameters

the wing aerodynamics remains as is, also because changing wing surface or thickness would change the volume of the wing tanks. The ultimate load factor is constant for the range of analyzed aircraft. The zero-fuel weight W_{zf} varies with the empty weight W_e (the payload and crew weight does not change):

$$W_{wg} \propto W_{zf}^{0.7} \propto W_e^{0.7} \quad (13)$$

The weight of the landing gear group (both the main gear and the nose gear) and of the control surfaces group are non-linear functions of the take-off weight and consequently of the empty one.

2.3 Fuel consumption due to monitors and cameras

The visual system consumes electrical power and consequently fuel. To estimate the fuel consumption linked to electrical power consumption, the method proposed by Scholtz et al. in [14] is used. 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 needed by the device:

$$\dot{m}_P = k_P \cdot SFC \cdot P. \quad (14)$$

The first two parameters of the second term in the equation are specific characteristics of the aircraft, SFC is constant for a given engine at cruise speed, a typical value of today's jet engines in cruise flight is $1.6 \cdot 10^{-5} \text{ kg}/(\text{N} \cdot \text{s})$. The variable k_P is calculated considering statistical equation by [14], as a function of the altitude h and the Mach's number M :

$$k_P = 0.0057 + 4.68 \cdot 10^{-8} \cdot \frac{1}{m} \cdot h - 0.0106 \cdot M$$

$$-4.44 \cdot 10^{-13} \cdot \frac{1}{m^2} \cdot h^2 + 1.85 \cdot 10^{-7} \cdot \frac{1}{m} \cdot h \cdot M + 0.0049 \cdot M^2. \quad (15)$$

Therefore, because of monitors and cameras, the fuel consumption is given by the following equation:

$$\dot{m}_P = k_P \cdot SFC \cdot (N_c \cdot P_c + N_m \cdot P_m) \quad (16)$$

where P_c and P_m are the power consumption of camera and monitor respectively.

2.4 Numerical implementation

In order to evaluate the saved fuel due to the reduction in weight, the fuel fraction method is used by calculating the required fuel for each segment of the flight mission through an iterative process.

Figure 5 shows the block diagram of the code used to implement the whole method. Aircraft parameters, as sizes and cruise information, 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 operating costs. The termination criterion of the iterative processes is a tolerance depending on the weight of the aircraft or on the maximum number of iterations.

The code starts sizing the reinforcements, through the neutral hole theory, Eqs. (6) and (7), panes, Eq. (5), the added material, Eqs. (8) and (9), and the visual system, through Eqs. (10) and (11). Afterwards it is possible to estimate the direct reduction in weight due to the removal of windows. The indirect reduction can be calculated either as a sum of the saved weight in each system or approximated as 25% of the direct reduction ("snowball effect"). Through the fuel fractions method, the reduction in fuel consumption is obtained (considering a fuel density of $0.804 \text{ kg}/\text{m}^3$), as well as saved emissions (supposing that one liter of burnt fuel produces 2.531 kilograms of carbon dioxide²) and operating costs with a global medium price of jet fuel of $0.401 \text{ $}/\text{l}$.³ Exploiting a chosen atmosphere model, as ISA 76, it is possible to know how much the service ceiling is increased. The code can be applied to turbofan or turboprop aircraft, with the necessary changes in the fuel fraction method equations. It is also possible to estimate the consumption due to monitors and cameras, Eqs. (15) and (16).

² From EIA (Energy Information Administration), official energy statistics from the U.S. Government https://www.eia.gov/environment/emissions/co2_vol_mass.php.

³ It is a mean, in fact the jet fuel price has not a constant value, see <https://www.iata.org/en/publications/economics/fuel-monitor/>.

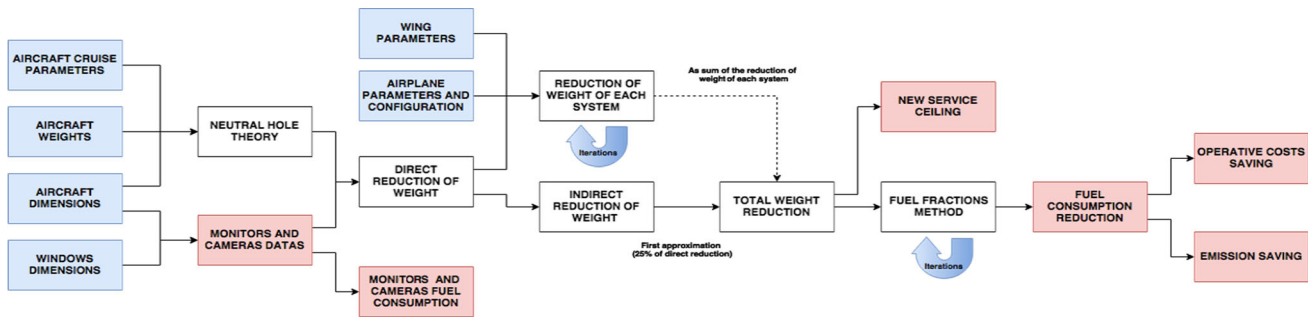


Fig. 5 Methodology block diagram

Table 1 Aircraft models’ data with windows

	ATR72	E190	A320	B737
Take-off weight [kg]	22800	47790	73500	79015
Max. Range [km]	1528	4445	6100	7400
Cabin length [m]	19.21	25.76	27.51	29.27
Fuselage width [m]	2.77	3.01	3.95	3.76
Number of windows	54	50	76	80

Table 2 Data of the visual system

	ATR72	E190	A320	B737
Number of monitors	20	24	32	34
Number of cameras	108	100	152	168
Visual system weight [kg]	60.1	69.5	94.6	100.6
Fuel mass flow [g/s]	8	9	13	14

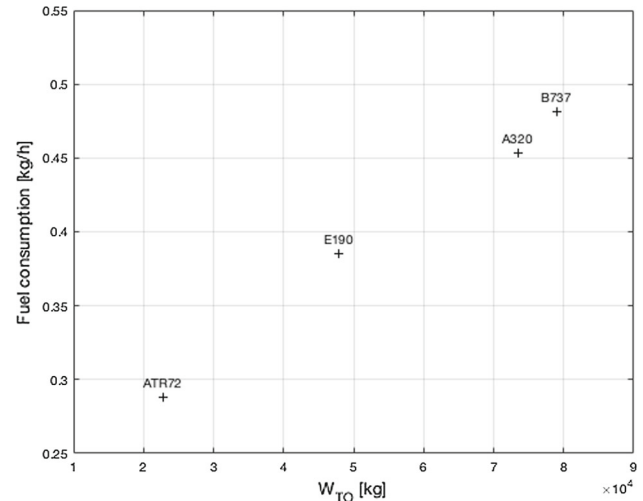


Fig. 6 Fuel consumption caused by the visual system

3 Discussions

3.1 Case studies

The reduction in weight is calculated for four common short-medium range aircraft models: Airbus 320 and Boeing 737–800, ATR-72 and Embraer 190. Table 1 shows the most important parameters. All windows are removed, except those of the emergency exits, and replaced with 77” OLED screens (weight of 1.9 kg and power consumption of 96 W) connected with small external cameras (weight of 0.076 kg and power consumption of 2.8 W), the data of the visual system are already shown in Table 2. The weight of the cables is conservatively considered 30% of the weight of the visual system. The fuel consumption of the visual system after one hour, considering all cameras and monitors on, is reported in Fig. 6.

The direct reduced weight is 392 kg for A320, 351 kg for B737, 162 for E190 and 102 kg for ATR72 so the fuselage is almost 20% lighter. It has to be considered that for each kilogram saved in the preliminary design, approximately 1.25 kilograms are saved in the final project (“snowball effect”).

Table 3 Systems weight reduction

	ATR72	E190	A320	B737
$\Delta W_{wing\ group}$ [kg]	13.8	21.9	56.2	50.3
$\Delta W_{landing\ gear}$ [kg]	4.7	7.5	20.3	19.8
$\Delta W_{control\ surfaces}$ [kg]	2.1	3.2	5.6	5.3
ΔW_{total} [kg]	127.4	202.8	489.4	439.2

The total reduced weight is 492 kg for A320, 444 for B737, 175 for the E190 and 127 for ATR72. Table 3 shows the results, for the three systems affected, and the total reduction in weight. Despite the great number of windows and the long passenger cabin, the B737 presents a lower reduced weight due to the narrower fuselage, which is the most influencing parameter. The results are more predictable for the ATR and the Embraer models, that are smaller than the Boeing and the Airbus models. As expected, the bigger it is the aircraft the higher is the advantage provided by a windowless configuration. In Fig. 7, the reduction in weight is compared as a function of the Max Take-off Weight W_{TO} .

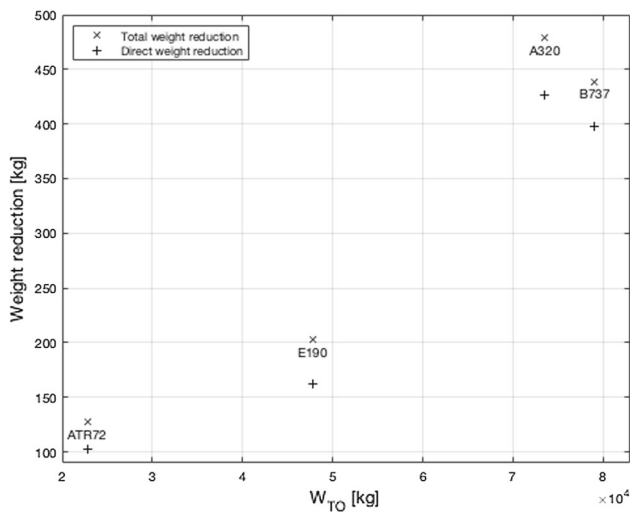


Fig. 7 Weight reduction: direct and total (direct and other aircraft system)

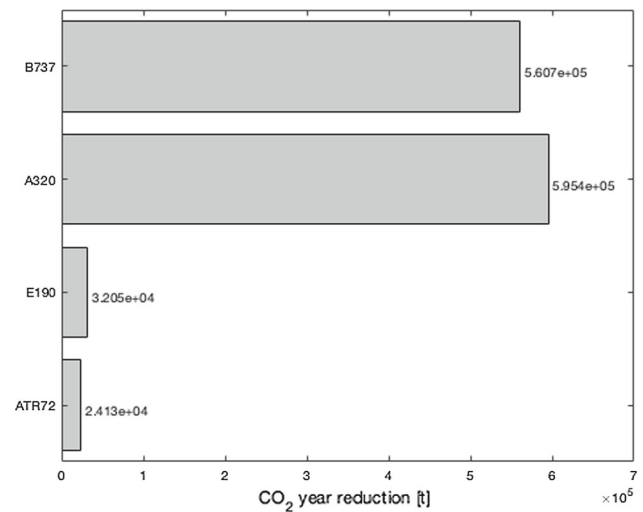


Fig. 8 Carbon dioxide year reduction for each model operational fleet [t]

3.2 Emissions and costs

The reduction in fuel consumption is assessed using the fuel fraction method. The A320 saves 0.024 liters per kilometer, the B737 0.022 l/km, the ATR72 0.009 l/km and the E190 0.010 l/km. Furthermore, assuming that for one liter of fuel, 2.53 kilograms of CO₂ are emitted, a windowless A320 approximately saves 0.06 kilograms of CO₂ per kilometer, the B737 0.55 kg/km, the ATR72 0.02 kg/km and the E190 0.03 kg/km. These results become encouraging considering the number of aircraft currently in operation. There are 4111 A320s, 4258 B737s, 991 ATR72s and 546 E190s, consequently the daily emission saving would be 1.89 million kilograms of CO₂ for the A320, 1.78 million for the B737, 76.6 thousand kilograms for the ATR72 and 101.9 thousand for the E190. The annual emission reduction for the number of aircraft of each model currently in operation is reported in Fig. 8.

In terms of operating costs, flying with a windowless A320 and B737 would be cheaper by respectively 0.01 and 0.009 dollars per kilometer, with the ATR72 by 0.0038 \$/km and with the E190 by 0.0042 \$/km. A medium-haul aircraft, exploiting a windowless configuration, as average of A320 and B737, produces 0.70% less polluting emissions than a traditional one and it is 0.72% cheaper. A regional turboprop, such as the ATR72, is 0.5% cheaper. A short-range aircraft, such as the E190, is 0.34% cheaper. Considering the number of aircraft currently in operation, the daily dollar saving is around 309 thousand for A320s and 292 thousand for B737s; for the ATR72 and E190, a saving of 12 and 16 thousand respectively can be considered. The annual operating cost saving for the number of aircraft of each model currently in operation is reported in Fig. 9.

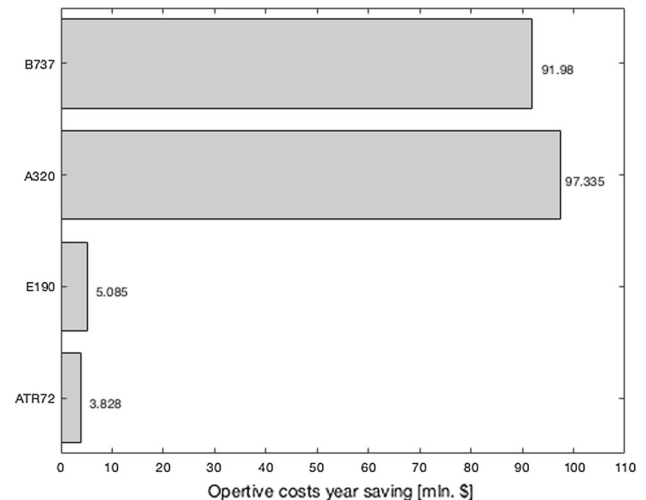


Fig. 9 Operating costs year saving for each model operational fleet [mln. \$]

Table 4 Final results, in terms of operating costs and emission saving

	ATR72	E190	A320	B737
Operating costs [mln. \$]	3.83	5.09	97.33	91.98
Emissions [kt]	24.13	32.05	595.35	560.7

Table 4 shows the annual saving. Emissions account for almost 0.46% of the pollution caused by domestic flights.

For the four aircraft models, the value of fuel consumption due to monitors and cameras is very low and consequently negligible.

4 Conclusions

This paper proposes an analysis on the preliminary design of a windowless concept with the aim to assess the reduction in fuel consumption and the associated emissions, limiting the passenger discomfort due to the absence of real windows. Important findings are obtained, both in terms of numerical and analytical results:

- there is an effective reduction in weight (and, consequently, in fuel consumption), considering both the removed and added elements from the fuselage;
- the method could easily estimate the weight reduction for different short-medium range aircraft models, with negligible computational costs and using accessible data.

In fact, this work has tried to highlight the advantages of a windowless concept applied to a traditional fuselage, filling the gap of knowledge, understood as the lack of reliable methods and results, on this particular configuration.

Moreover, much deeper analysis may find other advantages for this configuration and find a way to overcome some of its major issues:

- the dynamic effect on the window reinforcements and interactions between windows and other openings, such as doors, referring to the analysis [15], moreover dynamic analyses on the monitors must be performed to understand if there is the need to add reinforcements against vibrations;
- the fatigue effects on aircraft without openings;
- the modifications to aerodynamic performance. In fact, aside from the drag reduction due to the removal of windows (likely negligible), the wing surface could be decreased, choosing to embark less fuel, with a lower aerodynamic drag;
- reduction in noise inside the cabin, increasing the passenger comfort. A first study, at low frequency and for a regional turboprop aircraft, was already conducted by Moruzzi et al. [16];
- tailored interiors design could help passengers to accept the new configuration, with wider and interactive screens;
- in the mid-term future, the visual system concept could be improved with eye tracker devices or augmented reality devices till a complete removal of monitors;
- from a manufacturing point of view a fuselage without holes is cheaper than one with a hole. Further studies could quantify this saving. Moreover, a windowless aircraft could have less maintenance costs.

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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