33RD CONGRESS
OF THE INTERNATIONAL COUNCIL
OF THE AERONAUTICAL SCIENCES
STOCKHOLM, SWEDEN, 4-9 SEPTEMBER, 2022

ICAS 2022 SWEDEN

MULTIDISCIPLINARY DESIGN ANALYSIS AND OPTIMIZATION PROCESS DEDICATED TO BLENDED WING BODY CONFIGURATIONS

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Abstract

The Blended Wing Body configuration offers very promising fuel consumption reduction and could represent a solution for the future of the aviation industry with regard to the reduction of its environmental footprint. To explore in depth the potential benefits of the Blended Wing Body configuration, ONERA – The French Aerospace Lab – develops since 2015 a dedicated multidisciplinary design analysis and optimization process. This process is composed of numerous disciplinary modules to take into account the broadest possible criteria or parameters that could affect the aircraft design towards a feasible and realistic final solution. The design and optimization of a long-range commercial transport mission aircraft with this process firstly confirm the good performance of the Blended Wing Body configuration and its credibility as a future existing solution and secondly highlight the improvement provided by the use of multidisciplinary approaches for bringing out optimal solutions in a constrained environment. The process has then been used in the frame of the European Clean Sky 2 (ITD Airframe) ONERA-DLR project NACOR (Call for Core Partners Wave 1) to design and optimize the SMILE Blended Wing Body configuration for a short/medium-range mission.

Keywords: blended wing body, transport aircraft, multidisciplinary, design, optimization.

1. Introduction

With the increasing concerns about the impact of human activity on the environment, the aviation industry faces a new challenge, which consists in drastically reducing its environmental footprint. This footprint addresses the fossil fuel consumption, the air pollution and the noise emission associated to the air operations. One of the major references currently considered for providing objectives about those items has been issued by the High Level Group on Aviation Research in Europe [1]. It defines targets of CO_2 emission reduction of 75% (emission expressed per passenger kilometer), NOx emission reduction of 90% and perceived noise emission reduction of 65% by 2050. Those targets are defined relatively to aircraft that entered into operation in 2000.

For achieving those objectives, the aviation industry is working on three topics, which can be implemented solely or in combination: design of more efficient aircraft configurations, application of new technologies to the aircraft and improvement of the air traffic management processes. On the first topic, several configurations undergo extensive studies and among them the Blended Wing Body (BWB) configuration seems to offer very promising fuel consumption reduction [2][3].

To explore in depth the potential benefits of the Blended Wing Body configuration, ONERA – The French Aerospace Lab – develops since 2015 a dedicated multidisciplinary design analysis and optimization process [4][5][6][7][8]. It is composed of numerous disciplinary modules, integrating the strong disciplinary expertise of ONERA, in order to take into account the broadest possible criteria or parameters that could affect the aircraft design to obtain a feasible and realistic final solution. Then, the ONERA methods and skills in the field of Multidisciplinary Design Optimization (MDO) are applied for optimization purpose. Finally, the ONERA experience about the BWB configuration, gained through numerous previous projects, is capitalized through the critical analysis of the results. Based on those three pillars, the ONERA approach provides consolidated figures of merit of the achievable performance of the BWB configuration.

This paper presents the consolidated version of the ONERA multidisciplinary design analysis and optimization process dedicated to BWB configurations. First, the process implementation and the disciplinary modules are fully detailed. Then, the results obtained with the use of this process for designing and optimizing a long-range commercial transport mission are detailed. Finally, the results obtained using this process for designing and optimizing a short/medium-range commercial transport mission are presented.

2. Multidisciplinary Design Analysis and Optimization Process

2.1 Multidisciplinary Design Analysis and Optimization Process Overall Features

Since 2015, ONERA is developing a multidisciplinary design analysis and optimization process dedicated to Blended Wing Body (BWB) configurations. This process has continually evolved due to the enrichment of the disciplinary modules integrated or the addition of new disciplinary modules. A description of the main development stages can be found in [4][5][6][7][8].

The consolidated version of the ONERA multidisciplinary process is composed of six disciplinary modules: Geometry, Propulsion, Aerodynamics, Structure & Weight, Mission & Performance and finally Handling Qualities. Those modules are integrated in the NASA OpenMDAO framework [9] to constitute the Multidisciplinary Design Analysis (MDA). Figure 1 illustrates the ONERA BWB MDA in its version 2.0.0, expressed through the eXtended Design Structure Matrix (XDSM) formalism defined by the MDO Lab at the University of Michigan [10]. This XDSM diagram is automatically generated by the ONERA WhatsOpt web application [11].

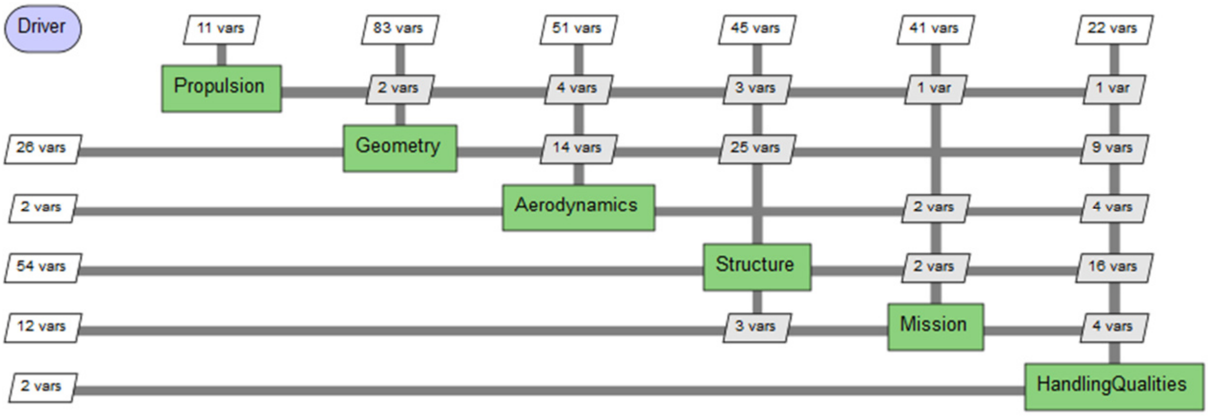

Figure 1 – XDSM of the ONERA BWB MDA (version 2.0.0).

The NASA OpenMDAO framework is here used to handle the data workflow through the numerous disciplinary modules that compose the process. The consistency of the vehicle modeled is managed by a fixed point iteration introduced at the top level of the process on three mass variables [5][8]: the aircraft Maximum Take-Off Weight (MTOW), the mission fuel weight, and the reserve fuel weight. The convergence of the three-abovementioned mass variables provides compliance of the structure sizing and the associated weight estimation with the aircraft mission simulation and the required fuel weight computation. This results in a coupling between both Structure and Mission Modules, which is typical in aircraft design processes, as illustrated in Figure 1 by the 3 variables feedback.

Finally, in order to find the best configurations that fulfills the aircraft mission specifications, an optimization formulation based on Efficient Global Optimization (EGO) algorithm [8][12] is applied to the MDA. This optimization formulation takes into account constraints to guarantee that the optimal configuration is compliant with operational minimum requirements.

Each disciplinary module composing the process is described in the following paragraphs.

2.2 Geometry Module

The Geometry Module is used in the process for performing three tasks.

First, it provides the sizing of both passenger cabin and cargo hold, which fit the payload specifications, expressed in the top-level aircraft requirements. Together, the passenger cabin and the cargo hold constitute the pressurized part of the aircraft. The passenger cabin sizing concerns the definition of its overall external dimensions and the definition and positioning of its internal elements (cockpit, partitions, seats, aisles, doors, galleys and toilets). In the same way, the cargo hold sizing concerns the definition of its overall external dimensions and the definition and positioning of its internal elements (partitions, standard containers, pallets and bulk volume). The sizing and internal arrangement of the pressurized part and in particular the passenger cabin are performed in order to stick to the applicable aircraft certification. The criteria considered are based on the Subpart D of the certification specification CS-25, provided by the European Aviation Safety Agency (EASA) [13] and applicable for large airplanes, which mainly aims to minimize the passenger hazard in case of emergency exit. The features of the internal elements present in the passenger cabin or the cargo hold are based on existing aircraft: the A350-1000 [14] is considered as the reference for long-range aircraft and the A320-NEO [15] is considered as the reference for short/medium-range aircraft. For the internal elements directly related to the emergency exit issues (i.e. doors and aisles), their features are based on the CS-25 requirements [13], adapted to the BWB configuration to ease passenger evacuation. Figure 2 illustrates two types of passenger cabin defined by the Geometry Module, respectively for long-range [5] and short/medium-range [6] BWB configurations. One of the solutions adopted to reduce the overall passenger cabin emergency evacuation time is inspired from the European project NACRE [16] and consists in doubling the width of some of the aisles for improving the passengers flow toward the doors (allowing the displacement of two passengers abreast). It has been applied to the transversal aisles and to the longitudinal aisles of the long-range passenger cabin internal compartments. Moreover, aisles along the central body leading edge are added in the passenger cabins in order to ease the doors access.

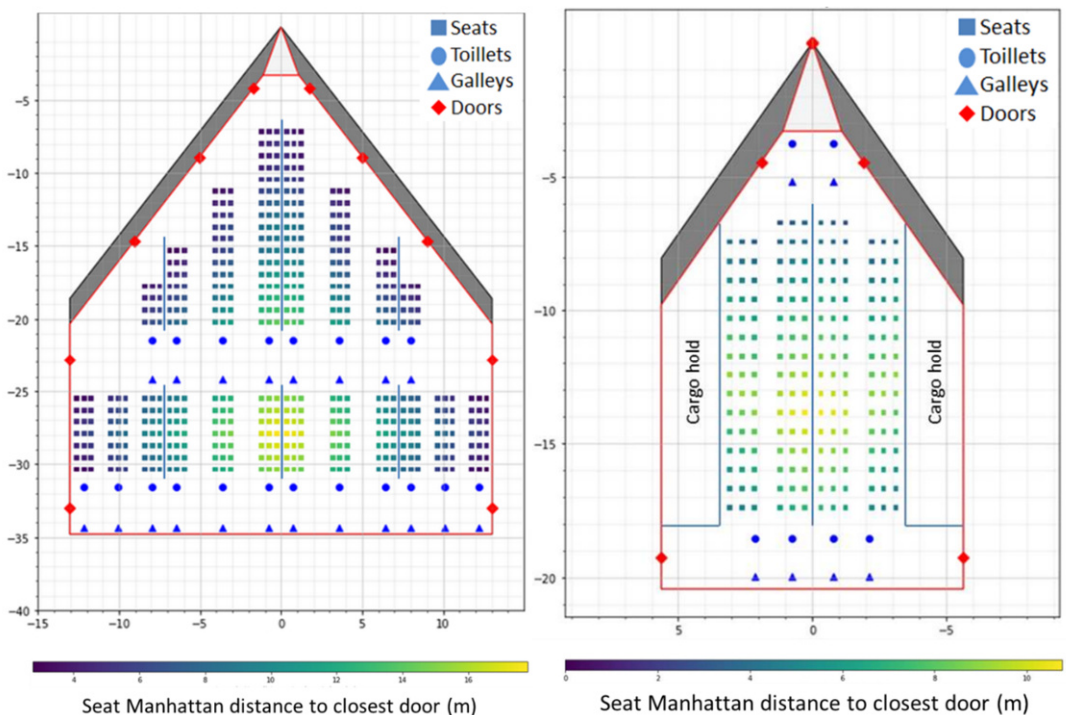

Figure 2 – Illustration of long-range (left) and short/medium-range (right) BWB passenger cabins.

Then, the Geometry Module gathers all the variables relative to the overall aircraft geometry. Those variables are based on a geometrical parameterization of the BWB configurations considered [4], which is shared with all the modules integrated in the MDAO process. To feed the modules with the required geometrical variables as inputs, the Geometry Module performs all the transformations.

Finally, the Geometry Module uses all the geometrical data to elaborate automatically an OpenVSP 3D model of the BWB configuration [17].

2.3 Propulsion Module

The Propulsion Module models the thermodynamic cycle of the turbine engines considered for the aircraft and computes their performance through the complete flight envelope, which is expressed in term of Mach, altitude and engine T5 (T5 represents the temperature of the engine combustion chamber and can be assimilated to the throttle). The thermodynamic cycle implemented is based on a typical turbofan engine.

The Propulsion Module provides the engine performance through thrust and fuel consumption evolution tables for the complete flight envelope. Results are calibrated on existing turbofan engines, respectively the GE-90 85B for long-range applications and the CFM56-5 for short/medium-range applications.

Beside the performance results, the Propulsion Module also provides an estimation of the weight and dimensions of the engine modelled, computed from the engine maximum thrust.

Finally, in order to model a range of turbofan engines around the two above-mentioned reference engines, the Propulsion Module can consider an engine scale factor as an input, which scales the thrust and derives new mass and dimension data without changing the thermodynamic cycle.

2.4 Aerodynamic Module

A dedicated Aerodynamic Module, based on analytical formulations derived from either theory or data analysis of past and present aircraft, has been developed for a fast evaluation of the aerodynamic performance of standard Tube and Wing, Flying Wing, or Blended Wing Body configurations, considering subsonic flight conditions. It is fully detailed in [18].

The principle adopted in the Aerodynamic Module is to start from the reference wing, assuming an optimum elliptical span loading, and then to consider the different elements (fuselage, winglets, nacelles, etc.) as extra components that affect the overall wing performance. Geometrical details, as the airfoil shape, camber or twist, are not taken into account at this stage of the aerodynamic evaluation and are considered in a next step of the design process using more advanced methods (vortex lattice method and Computational Fluid Dynamics (CFD)).

The Aerodynamic Module considers an elliptic span loading on the wing and the CL(α) computation uses the Polhamus formulation [19], with the effects of fuselage taken into account [20].

The drag formulation retained for the Aerodynamic Module is derived from [21]:

$$C_{D\,Total} = C_{D\,Induced} + C_{D\,Friction} + C_{D\,Additional} + C_{D\,Wave} + C_{D\,Parasitic} \qquad (1)$$

The lift induced drag coefficient is based on the standard formulation with a combination of both Anderson [22][23] and Hörner [23] methods for the estimation of the Oswald factor: validations performed with several CFD results analyzed by a far-field drag decomposition tool have showed that a mean value between these two formulations leads to excellent agreement. Fuselage or winglets are considered according to Nita formulations [22]. The contribution of the tail surfaces to the lift induced drag is not considered in the Aerodynamic Module.

The friction and pressure drag of the different aircraft elements are calculated using the methodology described in [20] and [21]. It considers a turbulent flat plate friction drag (obtained by the compressible Schlichting relation [20]) combined with a form factor for the given element (using [20] for the fuselage, [24] for the wing, the tail surfaces and the winglets and [25] for the nacelles).

For the wing, an additional profile drag due to lift is considered, based on [25].

Due to the transonic flight conditions of the aircraft mission the drag increase due to compressibility effects is considered using the Korn equation [21].

Finally, an additional parasitic drag due to protuberances, antenna, probes, paint, etc. is assessed, considering a ratio of 0.025 over the friction and pressure drag.

2.5 Structure & Weight Module

The Structure & Weight Module is used in the MDAO process to provide the aircraft mass breakdown, balance and inertia. Those elements are determined through a two-step process.

In a first step, the Structure & Weight Module performs a Finite Element (FE) model of the aircraft primary structure. For BWB configurations, this primary structure is composed of the pressurized part (which accommodates both passenger cabin and cargo hold) and the wing fuel tanks. The FE model of the primary structure is based on a structural architecture specifically defined for the BWB configuration. The primary structure is delimited by leading edge and trailing edge spars, which encompass both the pressurized part and the wing fuel tanks. Figure 3 highlights the spars that constitute the primary structure contours on a typical BWB configuration planform.

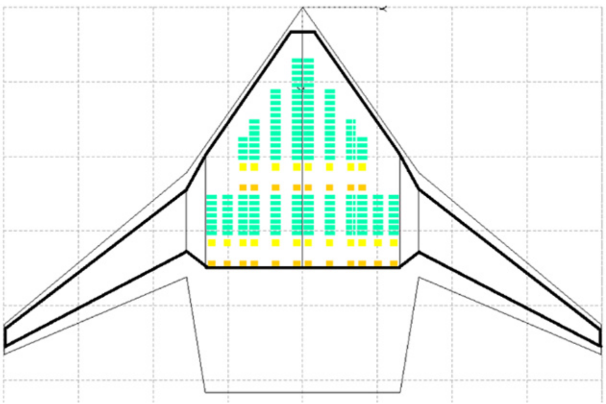

Figure 3 – Primary structure contours on a typical BWB configuration planform (top view).

The primary structure of the pressurized part is composed of a thin composite shell reinforced with stringers for the upper and lower skins, which withstand both the pressurization efforts applied inside of the pressurized part and the aerodynamic loads applied outside of the overall structure. The stringers are distributed along both longitudinal and wingspan directions. The upper and lower skins are linked by structural rods, which act as partition walls.

The primary structure of the wing fuel tanks is based on typical aircraft wing boxes with ribs.

Using the FE model, the primary structure is sized with regard to, on the one hand, the pressurization efforts and, on the other hand, the typical flight load cases of the certification specification CS-25 [13] (maneuvers, gusts, etc.) considering the most critical aircraft weights and flight configurations. Based on the FE model, the mass breakdown, balance and inertia of the sized primary structure are directly extracted.

In a second step, all the typical aircraft subsystems (power units, landing gears, systems, furnishing, operator items, etc.) are spread through the overall BWB configuration geometry. Their weight, balance and inertia are assessed using expert rules and statistical formulations from existing aircraft.

The primary structure and subsystems weight, balance and inertia are then gathered to compute the overall aircraft data corresponding to the specific aircraft weights along the mission (take-off weight, cruising weight, landing weight, operational empty weight, etc.). In addition, the wing fuel tank weight, balance and inertia are computed for several filling conditions.

2.6 Mission & Performance Module

The Mission & Performance Module computes the aircraft performance for the specified mission. It is based on the mission flight profile breakdown in elementary flight phases. During each phase, the flight mechanics equations are integrated in order to evaluate the state of the aircraft. This allows, in particular, evaluating the fuel consumption and the flight time of each phase and finally, combined to the Structure Module, to estimate the take-off weight of the modeled configuration.

In order to integrate the flight mechanics equations, the Mission & Performance Module needs tabulated engine and aerodynamic performance.

The engine performance is modeled by two tables, provided by the Propulsion Module:

- The maximum thrust table function of the altitude and the Mach number for the take-off, climb and cruise phases.

- The consumption table function of the altitude, the Mach number and the thrust for the same three phases.

The aerodynamic performance is modeled by a table that contains the drag coefficient CD (with its decomposition as described in section 2.4) as a function of the altitude, the Mach number, the lift coefficient CL, and the configuration of the aircraft (cruise, take-off, approach, landing, with landing gear retracted or extended). This table is provided by the Aerodynamic Module.

For the Mission & Performance Module integrated in the ONERA BWB MDAO process, a three part mission profile was created, as illustrated in Figure 4.

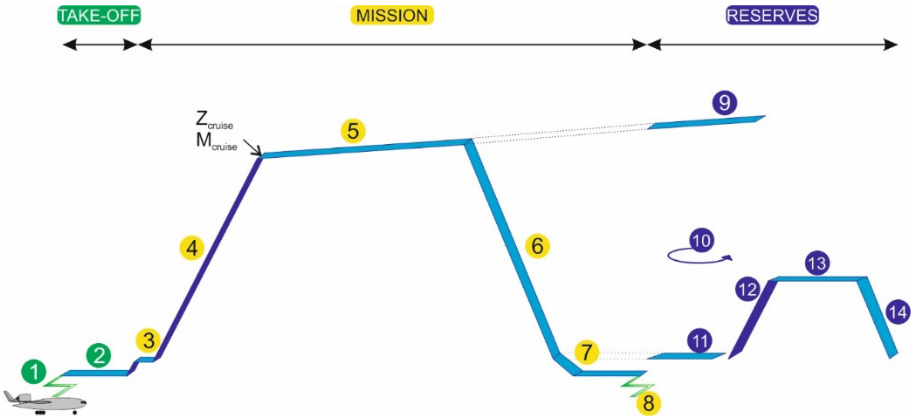

Figure 4 – Mission flight profile modeled with the Mission & Performance Module.

- The take-off part, which is composed of two phases (number 1 to 2 in Figure 4):
  - A taxying phase (1). The fuel consumption during this phase is supposed to be equivalent to the engines consumption at 150% of the minimum thrust during 600s.
  - A take-off phase (2). It is composed of four segments: acceleration at maximum thrust, rotation, lift off and initial climb to an altitude of 100 meters. In this part the different characteristic parameters at take-off are determined (take-off field length, take-off speed, stall speed, etc.). Computations consider some engine failure cases during take-off to calculate the decision speed and the accelerate stop distance.
- The mission part, which is subdivided in six phases (number 3 to 8 in Figure 4):
  - An acceleration phase (3) at constant altitude in order to reach the desired conventional air speed of the following climb phase.
  - A climb phase (4) performed at a constant calibrated air speed and constant gradient.
  - A climbing cruise phase (5) at constant lift-over-drag ratio and Mach number. The beginning of this phase is defined by the cruise segment specifications (altitude and Mach number).
  - A descent phase (6) performed similarly to the climb phase until the hold altitude.
  - An approach and landing phase (7) where the fuel consumption is supposed to be equivalent to the consumption of a 300s flight level at the hold altitude.
  - A taxying phase (8) where the fuel consumption is supposed to be equivalent to the consumption of the engines at 150% of the minimum thrust during 420s.

The mission range is the distance between the beginning of the take-off and the end of the descent.

- The reserve part, corresponding to the regulation fuel reserves, which is divided in six phases (number 9 to 14 in Figure 4):
  - A continued cruise phase (9), at the same conditions of the mission cruise phase. The duration of this phase is equal to 10% of mission flight duration.
  - An overshoot phase (10). In this phase, only the fuel consumption is calculated and is supposed to be equal to 80% of the take-off fuel consumption.
  - A hold phase (11). This phase is a 30 minutes constant air speed level flight that

begins at the end of the mission descent.

- A climb phase (12) performed in the same way as the mission climb phase, until the altitude of 4000m and Mach 0.6.
- A climbing cruise phase (13) at constant lift-over-drag ratio and Mach number.
- A descent phase (14) performed in the same way as the mission descent phase.

The last three phases constitute the diversion step. The distance of this diversion, which is the distance between the beginning of the climb and the end of the descent is equal to 200Nm.

The Mission & Performance Module provides for each phase, the aircraft state vector detailing the distance travelled, the fuel consumed, the duration, the final Mach and speed, the final altitude, and the final lift and drag coefficients. Beside those data, the Mission & Performance Module also provides information about the aircraft overall performance, such as the maximal take-off distance, the climb duration, etc.

2.7 Handling Qualities Module

The Handling Qualities (HQ) Module aims at evaluating if the aircraft is safely operable and how a given modification affects its flying qualities. Those flying qualities are defined by the aircraft ability to be safely and efficiently handled by the pilot. They are the result of the compromise between stability and maneuverability.

The HQ Module takes as inputs the aircraft geometry, its aerodynamic characteristics, its mass distribution and the loading scenarios. These data are then used to compute the selected criteria evaluation. The aerodynamic characteristics are completed by data obtained with the vortex-lattice based AVL software [26], especially for what concerns aerodynamic derivatives.

The HQ Module consists in a flight simulator that puts the aircraft in a given set of flight conditions in order to evaluate a set of HQ criteria. Criteria, that come from either regulation or industry good practices, fall into two categories: the longitudinal ones that affect the size of horizontal surfaces and the lateral ones that influence vertical surfaces.

Each longitudinal criteria defines a Center of Gravity (CoG) range in which they are satisfied. Some of them set a forward limitation to the CoG location and are called forward criteria. The others, called aft criteria, set an aft limitation. A general rule is that forward criteria are linked with aircraft maneuverability while aft criteria are related to its stability.

Regarding the lateral handling qualities criteria, the module computes them at a given CoG location, the most unfavorable one, in order to get a metric (a numerical value) of its satisfaction.

For the BWB configuration, the evaluated criteria are:

- Longitudinal dynamic criteria:
  - Trim Glide (forward and aft): The aircraft ability to be balanced with sufficient actuator margin at approach speed with landing configuration and following a glide slope path. The forward limitation is linked with the maximal downlift the control surfaces are able to produce. The aft limitation that corresponds to the maximal uplift the control surfaces can produce is not a concern for conventional aircraft but, due to the low efficiency of the BWB control surfaces, it is specifically considered for the BWB configurations evaluation.
  - Trim Turn (forward and aft): Same conditions as the Trim Glide adding a steady turn.
  - Trim Takeoff (forward): Ability of the aircraft to produce enough pitch acceleration during takeoff. For BWB configurations, this criterion is a very challenging one.
  - Maneuver Point (aft): The maneuver point is an extension of aircraft’s neutral point that takes into account the dynamic effects. If the aircraft CoG is more aft than this point, the aircraft is unstable. This criterion looks for the maneuver point most forward position.
- Longitudinal static criteria:
  - Nose landing gear minimal and maximal loads: In order to have enough weight on the nose landing gear to ensure steering but not too much which can cause the nose

landing gear to collapse.

No lateral criteria are considered in the presented MDAO process as the focus is made on the longitudinal issues, but they could be added in a future evolution.

The flight simulator is coupled with a Design of Experiments (DoE) feature that aims to explore some parameters. The explored parameters are (in this order): zero-lift pitching moment, take-off speed over stall speed ratio, engine vertical location, control surfaces efficiency ratio, main landing gear longitudinal position. For each parameter, the design space is explored and the criteria margins are returned. A longitudinal criterion is satisfied if its CoG range is compatible with the aircraft CoG range, providing thus a positive margin. For each design, the HQ Module returns an n.m matrix where n is the number of criteria and m the number of tested masses. The MDAO process uses this matrix as a constraint to be satisfied in the optimization problem.

3. Long-Range Blended Wing Body Configurations Design and Optimization

The multidisciplinary design analysis and optimization process described in section 2 has been used to generate typical long-range Blended Wing Body (BWB) configurations. Table 1 summarizes the top-level aircraft requirements considered, based on the A350-1000 aircraft [14]:

Requirement	Value
Pax number	440 pax
Hold volume	208 m^3
Bulk volume	11.3 m^3
Maximum number of LD3 container	44
Maximum number of pallets	14
Range	14800 km (8000 Nm)
Top of climb altitude	10058 m (33000 ft)
Cruising Mach number	0.84

Table 1 – Long-range mission top-level aircraft requirements.

A reference geometrical parameterization is defined for the long-range BWB configurations [4][5][7][8], through three main subparts: the central body, the transition area and the external wing, as illustrated in Figure 5 (a). The passenger cabin is located in the central body and the cargo hold is placed under the passenger cabin. This internal layout leads to a partition of the central body in two sections. The external wing geometrical parameterization considers a double trapeze, leading also to a partition in two sections. Figure 5 (b and c) represents the five sections considered to model long-range BWB configurations.

A total of six control surfaces are considered through the planform, as illustrated in Figure 6: two for the central body, one for the transition area and three for the external wing.

3.1 Reference Case for Long-Range Missions

An initial set of aircraft geometrical values, used as inputs of the multidisciplinary process, provides a reference BWB configuration that fulfills the above-mentioned top level aircraft requirements but is non optimal. The reference BWB has a wingspan of 80m and a length of 43.4m. Table 2 gathers the main geometrical data of the reference BWB configuration.

Figure 7 illustrates both internal passenger cabin and cargo hold arrangement performed by the Geometry Module. The passenger cabin layout is composed of four compartments able to accommodate 450 passengers with a 3-3-3 seats layout, for a total floor surface of 602 m^2. Ten doors are distributed among the passenger cabin: six doors are located along the central body leading edge and four doors are located at the junction area between the central body and the external wing (assuming exit path accommodated over the external wing). The cargo hold layout illustrates the maximum capability able to accommodate a maximum of 48 LD3 containers or 16 standard 96” pallets, within a total volume of 315 m^3.

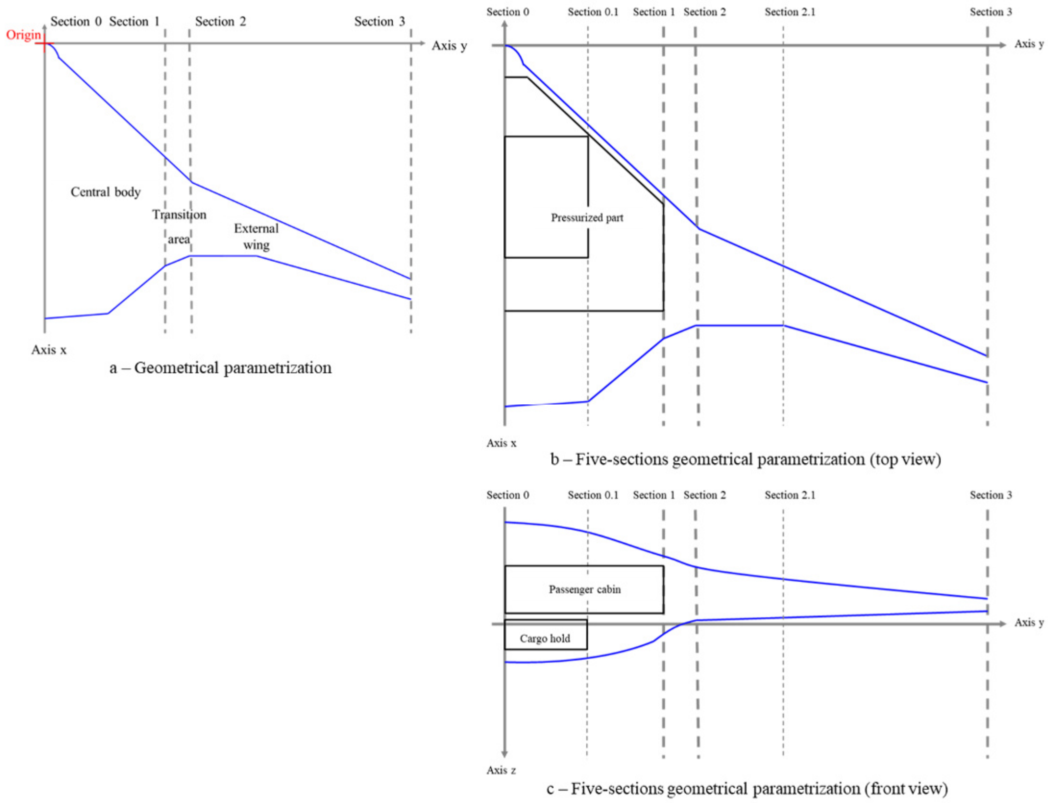

Figure 5 – Geometrical parameterization of the long-range BWB configurations.

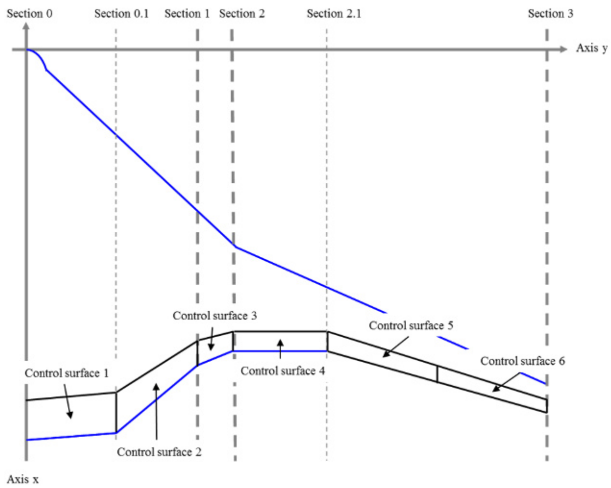

Figure 6 – Control surfaces arrangement.

The reference BWB configuration performance is computed using a model of the Rolls-Royce Trent XWB-97 engine, which is selected to power the A350-1000. This engine is reproduced through the application of an engine scale factor of 1.2 on the GE-90 85B reference engine mentioned in section 2.3. The reference BWB configuration uses two of this turbofan, each located under the external wing, at the kink section. Another possibility would be to mount the engines at the rear of the central wing body. Such a solution would lead to move the overall aircraft center of gravity backward, what is less suitable with regard to its controllability. In addition, the resulting high engines position, upper than the aircraft overall center of gravity, would penalize the take-off rotation. Thus, handling qualities considerations would prefer to have engines located under the external wing than upper the rear central wing body. Furthermore, ONERA experts in structural design have highlighted that mounting engines on pylons would have significant impacts on the engine installation mass. Such a solution indeed requires building a pylon structure able to resist to the compression and flexion efforts generated by the combination of the engine weight and the engine thrust, which lead to unstable loading conditions. This critical aspect of the engines location would be mitigated with solutions where the engines are buried or partially buried in the central body, because the engines installation can be collocated with the central body internal structure elements (spars, etc.). Nevertheless, such architecture leads to deeply consider the integration of the engines with the overall airframe, using boundary layer ingestion solutions, which is not yet modeled in the MDAO process presented here. This will represent a major area of improvement of the process itself, including its constituting disciplinary modules and the associated Blended Wing Body configurations.

Geometrical parameter	Value
Wingspan	80 m
Central body length ($chord_{section\_0}$)	43.4 m
Central body leading edge sweep angle ($\varphi_{LEsection\_0}$)	60°
External wing leading edge sweep angle ($\varphi_{LEsection\_2}$)	40 °
External wing root chord ($chord_{section\_2}$)	13 m
External wing tip chord ($chord_{section\_3}$)	4 m
Longitudinal section thickness ratio ($t/c_{section\_0}$)	15.5 %
External wing thickness ratio ($t/c_{section\_2}$)	8 %

Table 2 – Reference BWB configuration main geometrical data.

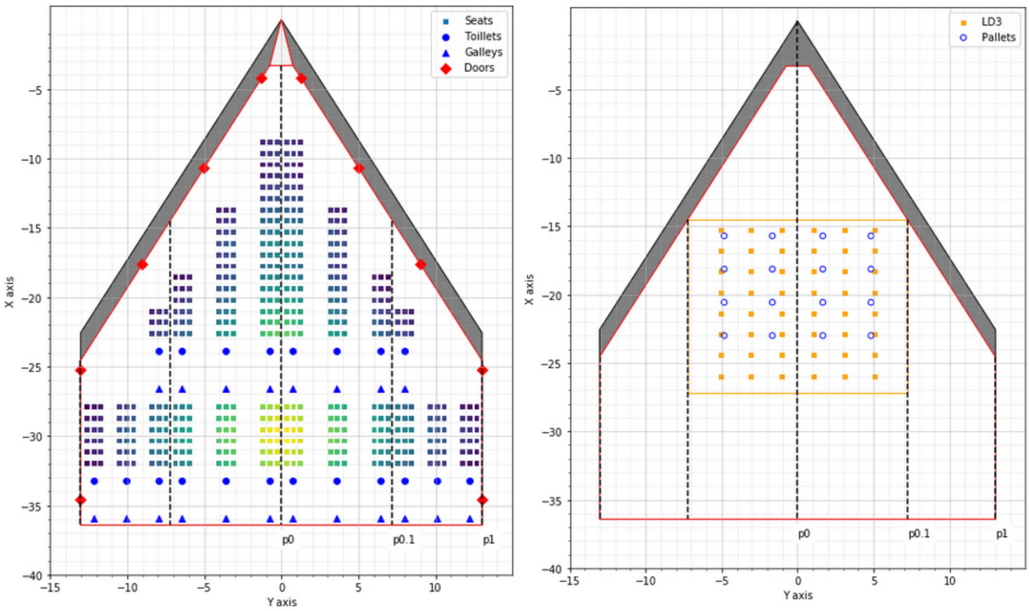

Figure 7 – Reference BWB configuration passenger cabin (left) and cargo hold (right) layout.

The geometry presented above leads to a MTOW of 323.5 tons and requires 126.4 tons of fuel for achieving its long-range mission (including 14.6 tons as reserve fuel weight). Table 3 gathers the main performance characteristics obtained with the reference BWB configuration with regards to its 14800km long-range mission. Those results confirm the very good potential of the BWB configuration able to reach a lift-over-drag ratio value of 22.2. Nevertheless, the cruise lift-over-drag ratio appears to be about three points below this value, indicating important potential benefits achievable with the optimization process.

For each section, the control surfaces are defined through the ratio of their relative chord to the total local chord. The values considered for the reference BWB configuration are described in Table 4.

Using the optimization method described in section 2.1, this reference BWB configuration has been optimized with the objective of reducing its fuel consumption. The following paragraph describes the optimization procedure and the related results.

Performance characteristics	Value
MTOW	323.5 tons
Mission fuel weight	126.4 tons
Payload weight	40.5 tons
Take-off distance	3181 m
Climb duration	22 min
Mission duration	1031 min
Maximum lift-over-drag ratio	22.2
Cruise lift-over-drag ratio	19.2

Table 3 – Reference BWB configuration main performance characteristics.

Control surfaces characteristics	% total chord
Control surface chord at section 0	0.15 %
Control surface chord at section 0.1	0.15 %
Control surface chord at section 1	0.15 %
Control surface chord at section 2	0.2 %
Control surface chord at section 2.1	0.2 %
Control surface chord at section 3	0.25 %

Table 4 – Reference BWB configuration control surfaces characteristics.

3.2 Optimized Blended Wing Body Configurations for Long-Range Missions

In order to improve the BWB configuration performance, an optimization formulation based on Efficient Global Optimization (EGO) algorithm [8][12] is applied to the overall aircraft design process. The optimization is made considering the long-range mission top-level aircraft requirements defined in Table 1. The optimization problem aims at minimizing the mission fuel weight required to perform the mission. The optimization problem takes six constraints into account in order to guarantee that the optimal configuration will remain compliant with operational minimum requirements and feasibility criteria. Three of the constraints concern minimum requirements to stick to typical long-range aircraft operations: a maximum take-off distance of 3200m, a maximum climb duration of 28 min and a maximum mission duration of 18 hours. Three of the constraints concern feasibility criteria about the overall aircraft: a sufficient distance behind the passenger cabin to accommodate central body control surfaces, a minimum external tip chord of 2.5 m to have a sufficient winglet surface and the satisfaction of the considered handling qualities criteria. Equation 2, where z represents a group of design variables, summarizes the optimization problem:

$$\text{minimize:}\ mission\ fuel\ weight\ (z)$$

$$\text{subject to:} \begin{array}{l} distance_{take-off}\ (z) \leq 3200\ m \\ duration_{climb}\ (z) \leq\ 28\ min \\ duration_{mission}\ (z) \leq 18\ h \\ central\ body\ rear\ length\ (z) \geq central\ body\ control\ surfaces\ chord(z) \\ external\ wing\ tip\ chord\ (z) \geq 2.5\ m \\ handling\ qualities\ criteria\ (z) \leq 0 \end{array} \quad (2)$$

In order to both reduce the number of design variables manipulated within the optimization and keep the BWB configuration overall geometry consistent, the following relations are imposed:

- Continuity of the wing leading edge sweep angle through the central body:

$$\varphi_{LE\,section\_1} = \varphi_{LE\,section\_0.1} = \varphi_{LE\,section\_0} \quad (3)$$

- Continuity of the wing leading edge sweep angle through the external wing:

$$\varphi_{LE\,section\_2.1} = \varphi_{LE\,section\_2} \quad (4)$$

- Continuity of the thickness ratio through the external wing:

$$t/c_{section\_3} = t/c_{section\_2.1} = t/c_{section\_2} \tag{5}$$

- External wing kink fixed according to the other external wing geometry characteristics:

$$Y_{section\_2.1} = Y_{section\_2} + \frac{Y_{section\_3} - Y_{section\_2}}{4} \tag{6}$$

$$chord_{section\_2.1} = chord_{section\_2} + distance_{section\_2 \rightarrow section\_2.1}(-tan(\varphi_{LE\,section\_2.1})) \tag{7}$$

- External wing tip chord fixed with a taper ratio:

$$chord_{section\_3} = \varepsilon_{section\_2.1 \rightarrow section\_3} . chord_{section\_2.1} \tag{8}$$

The design variables considered for the optimization have been selected according to their impact on the overall aircraft performance. This selection is based on a sensitivity analysis performed on the main aircraft geometrical variables [5][8]. With this selection and considering the six relations described above (Eq. 3 to 8), a total of six variables remains as independent optimization variables, as detailed in Table 5.

Geometrical variables	Variation range	Unit
Wing chord at section 2 : $chord_{section\_2}$	[12.0, 18.0]	m
External wing taper ratio : $\varepsilon_{section\_2.1 \rightarrow section\_3}$	[0.20, 0.50]	-
Central body leading edge sweep angle : $\varphi_{LEsection\_0}$	[45.0, 62.0]	deg
External wing leading edge sweep angle : $\varphi_{LEsection\_2}$	[35.0, 55.0]	deg
Central body thickness ratio : $t/c_{section\_0}$	[0.14, 0.18]	-
Main landing gear center of gravity longitudinal position	[24.0, 32.0]	m

Table 5 – Geometrical variables used for the optimization.

The ONERA MDAO process has been used to perform several optimizations of Blended Wing Body configurations for long-range missions, according to different design hypothesis and using the same engine hypothesis and model as for the reference BWB configuration.

The first design set of hypothesis considers that the optimized Blended Wing Body configuration stick to the current aircraft operational features about wingspan and top of climb altitude:

- It is assumed that the optimized Blended Wing Body configuration belongs to the ICAO Aerodrome Reference Code letter F category with a maximal wingspan fixed to 80 m.
- It is supposed that the optimized Blended Wing Body configuration cruise segment is typical of current aircraft operations with a top of climb altitude fixed to 33000 ft.

Then, in order to quantify what could be the results obtained when relaxing those two hypothesis, new optimizations have been made with new set of hypothesis:

- Optimized wingspan in the [80, 110] m variation range.
- Extended top of climb altitude to 39000 ft.
- Optimized wingspan in the [80, 110] m variation range and extended top of climb altitude to 39000 ft.

Name of the configuration	Wingspan (m)	Top of climb altitude (ft)
BWB1	80	33000
BWB2	Optimized through [80, 110]	33000
BWB3	80	39000
BWB4	Optimized through [80, 110]	39000

Table 6 – Design sets of hypothesis used for the optimizations.

Figure 8 illustrates the optimized BWB configurations obtained with the optimizations mentioned above and Table 7 gathers their main characteristics.

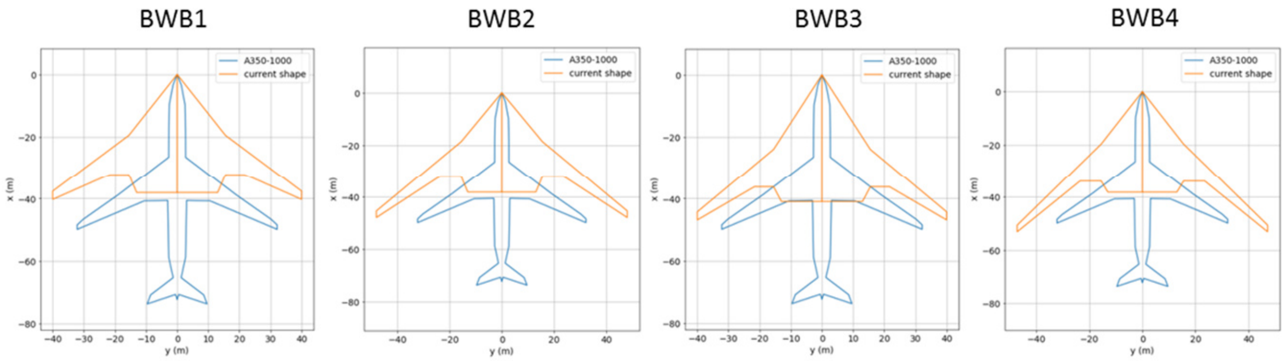

Figure 8 – Optimized BWB configurations planforms.

Optimized BWB configurations characteristics	Unit	BWB1	BWB2	BWB3	BWB4
Wingspan	m	80	96	80	94
Wing Area	m2	1192	1272	1187	1245
Wing chord at section 2 : chordsection_2	m	12.7	13.5	12.3	14.2
External wing taper ratio : εsection_2.1→section_3	-	0.33	0.37	0.36	0.39
Central body leading edge sweep angle : φLEsection_0	deg	51	50	57	52
External wing leading edge sweep angle : φLEsection_2	deg	37	40	40	44
Central body thickness ratio : t/csection_0	%	17.6	17.6	16.4	17.6
Main landing gear center of gravity longitudinal position	m	24.2	25.6	27.3	27.1
Top of climb altitude	ft	33000	33000	39000	39000
Climb duration	min	21	21	28	27
Mission duration	min	1030	1030	1036	1035
Take-off distance	m	2740	2967	2909	2992
MTOW	t	305.5	313.6	296.3	304.2
ZFW	t	189.6	199.8	189.0	201.8
Mission fuel weight	t	115.9	113.8	107.3	102.4
Additional fuel tank requirement	t	35	-	33	-
Cruise lift-over-drag ratio	-	19.6	20.7	21.3	23.1

Table 7 – Optimized BWB configurations characteristics.

3.2.1 BWB1 Optimized Blended Wing Body Configuration Detailed Description

The BWB1 optimized configuration has a wingspan of 80m and a length of 38.1m. Table 8 gathers its main geometrical data.

Geometrical parameter	Value
Wingspan	80 m
Central body length ($chord_{section\_0}$)	38.1 m
Central body leading edge sweep angle ($\varphi_{LEsection\_0}$)	51°
External wing leading edge sweep angle ($\varphi_{LEsection\_2}$)	37 °
External wing root chord ($chord_{section\_2}$)	12.7 m
External wing tip chord ($chord_{section\_3}$)	2.7 m
Longitudinal section thickness ratio ($t/c_{section\_0}$)	17.6 %
External wing thickness ratio ($t/c_{section\_2}$)	8 %

Table 8 – BWB1 optimized configuration main geometrical data.

Figure 9 illustrates both passenger cabin and cargo hold internal arrangements. The passenger cabin layout is able to accommodate 450 passengers, for a total floor surface of 586 m2. The cargo hold layout illustrates the maximum capabilities able to accommodate a maximum of 48 LD3 containers or 16 standard 96” pallets, within a total volume of 315 m3. Figure 10 offers a 3D view of the overall BWB1 optimized configuration geometry with its main internal elements: central body, external wing, winglets, engines, passenger cabin, cargo hold, landing gears.

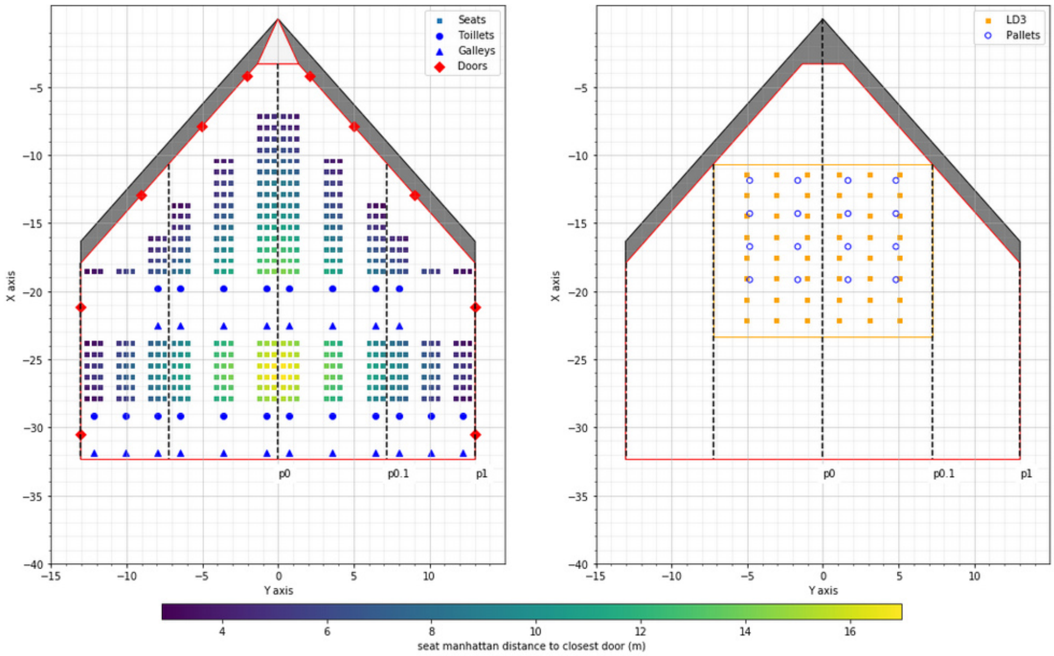

Figure 9 – BWB1 optimized configuration passenger cabin and cargo hold internal layout.

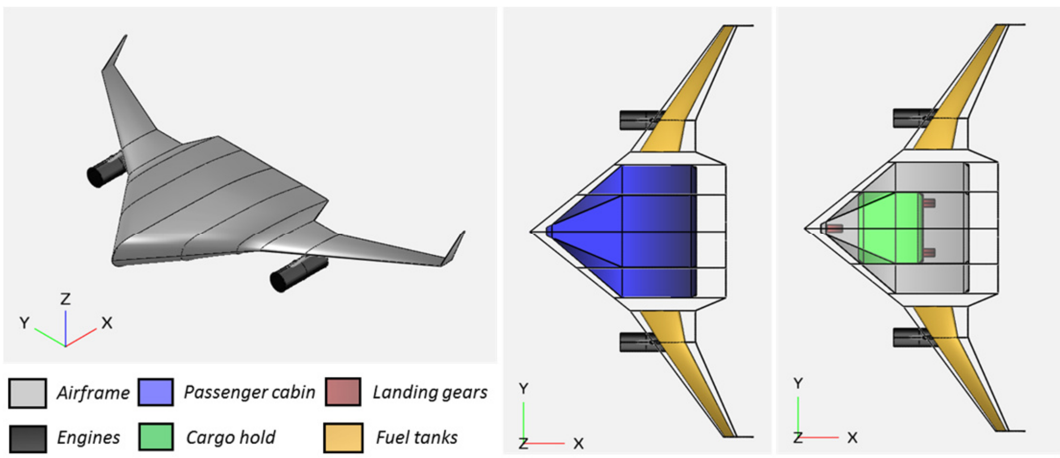

Figure 10 – BWB1 optimized configuration 3D view.

This geometry leads to a MTOW of 305.5 tons and requires 115.9 tons of fuel for achieving its long-range mission (including 13.6 tons as reserve fuel weight). Figure 11 details the reference BWB configuration mass breakdown provided by the Structure Module.

The BWB1 optimized configuration offers a fuel reduction of 10.5 tons in comparison with the reference BWB configuration presented in section 3.1 for achieving the same long-range mission. It means that, considering the same design set of hypothesis, the optimization of the geometrical characteristics can provide a reduction of 8.3% of the fuel consumption. Table 9 illustrates the operational and performance gains of the BWB1 optimized configuration in comparison with the reference BWB configuration.

It has to be noted that the BWB1 optimized configuration can accommodate 81.4 tons of fuel in the wing fuel tanks, which means that 34.5 tons have to be placed in an additional fuel tank. This fuel tank can be located just in front of the cargo hold, under the passenger cabin, as illustrated in Figure 12. As a comparison, the reference BWB configuration could accommodate 84.8 tons of fuel in its wing fuel tanks and required 41.6 tons in an additional fuel tank.

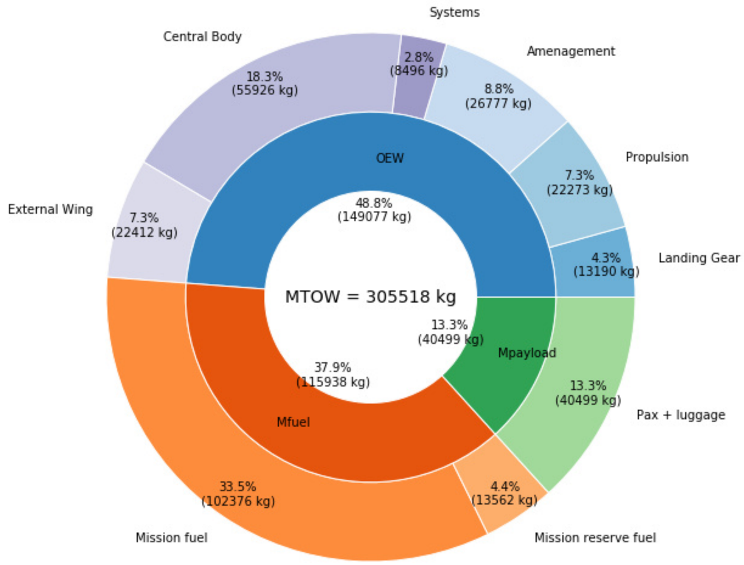

Figure 11 – BWB1 optimized configuration mass breakdown.

	Unit	BWB1 Optimized configuration	Reference BWB configuration	Gains
Wingspan	m	80	80	=
Wing Area	m^2	1192	1264	-5.7%
Top of climb altitude	ft	33000	33000	=
Climb duration	min	21	22	-4.6%
Mission duration	min	1030	1031	+0.1%
Take-off distance	m	2740	3181	-13.9%
MTOW	t	305.5	323.5	-5.6%
ZFW	t	189.6	197.2	-3.9%
Mission fuel weight	t	115.9	126.4	-8.3%
Cruise lift-over-drag ratio	-	19.6	19.2	+2.1%

Table 9 – BWB1 optimized configuration VS reference BWB configuration.

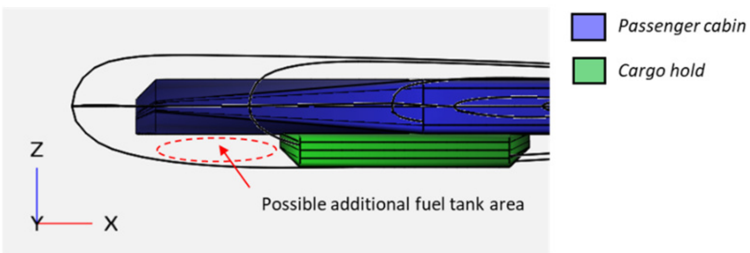

Figure 12 – Possible zone for an additional fuel tank in the front part of the central body.

3.2.2 Impacts of the Design Hypothesis Relaxation

As detailed in Table 6 and Table 7, three other configurations have been optimized according to the relaxation of design hypothesis about on the one hand the wingspan and on the other hand the top of climb altitude. Figure 13 gathers the main results of the optimized configurations, compared to the reference configuration.

It is remarkable to note that the top of climb altitude increase offers a very important fuel saving, with a required fuel weight reduction of respectively 15.1 % for the BWB3 optimized configurations and 19.0 % combined with the wingspan increase for the BWB4 optimized configurations compared to the reference BWB configuration. For those two configurations, the top of climb altitude increase leads to respectively 7 and 6 additional minutes for performing the climb segment, which seems quite reasonable and stays below the operational limit of 28 minutes. Considering those results, it appears interesting to consider possible modification of the flight operation and mainly the possibility of performing the cruise segment at a higher altitude. Indeed, a higher cruise altitude allows flying at a better lift-over-drag ratio, as found for both BWB3 and BWB4 optimized configurations with respectively 21.3 and 23.1 cruise lift-over-drag ratios. It is also to be noted that the chosen engine ceiling is enabling this higher cruise altitude.

In a second way of improvement, the wingspan (and thus the wing aspect ratio) increase also offers a great fuel saving potential, with a required fuel weight reduction of respectively 10.0 % alone for the BWB2 optimized configurations and 19.0 % combined with the top of climb altitude increase for the BWB4 optimized configurations compared to the reference BWB configuration. It has to be noted that the expected gains on the overall MTOW are nevertheless quite mitigated by the ZFW increase due to the wingspan extension. In a more operational point of view, the optimized wingspan values obtained for both BWB2 and BWB4 optimized configurations lead to higher values than the category F of the ICAO Aerodrome Reference Code letter, with respectively 16 and 14 m above the 80 m actual limitation. Such an increase of the wingspan could limit the potential accessibility of existing airports and would require adaptation of airports infrastructures to welcome such new configurations. Finally, it is remarkable that the wingspan increase leads to configurations for which no more additional fuel tanks are required. This reflects a combination of the required fuel weight reduction and the wing fuel tank capacity extension, both related to the wingspan increase. However, as the aspect ratio of the external wing is significantly increased compared to existing wings, these results would have to be confirmed by detailed aero-structural sizing including dynamic criteria (flutter, gust response, etc.).

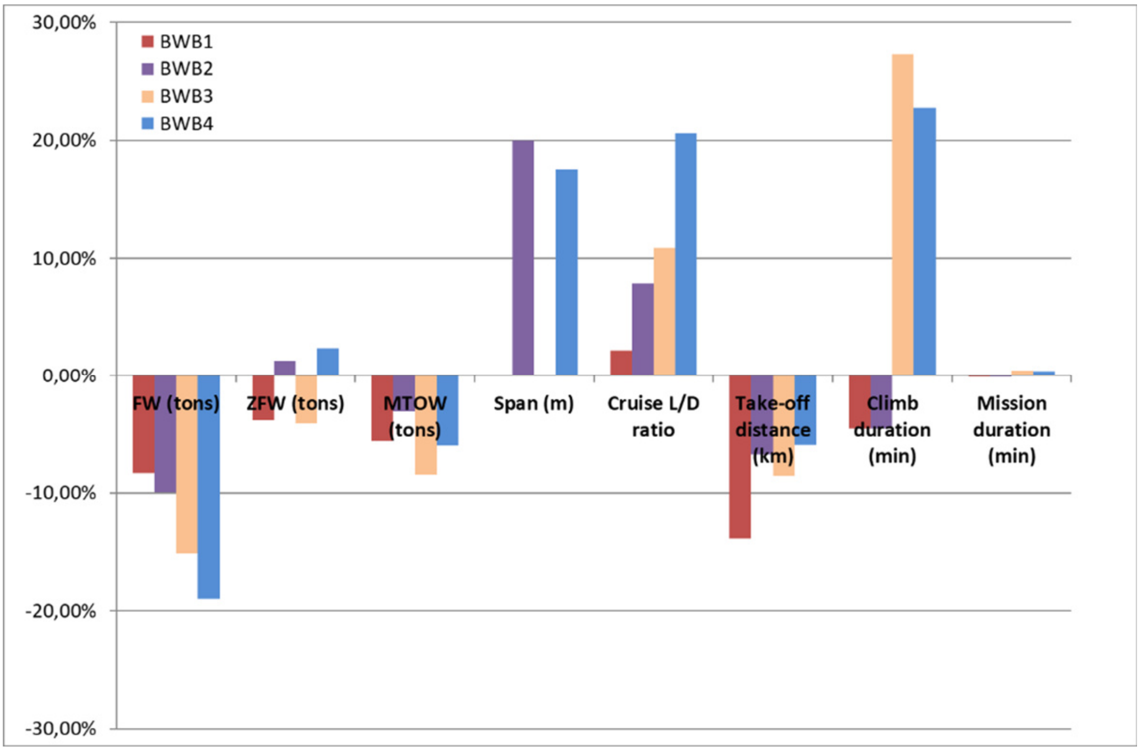

Figure 13 – Comparison of the optimized configurations with the reference configuration.

4. Short/Medium-Range Blended Wing Body SMILE Configuration

In the frame of the European Clean Sky 2 (ITD Airframe) ONERA-DLR project NACOR (Call for Core Partners Wave 1), ONERA uses the MDAO process described in section 2 to design and optimize a BWB configuration for a short/medium-range mission [6]. This work results in the SMILE BWB configuration illustrated in Figure 14 and detailed in [27]. The mission considered, summarized in Table 10, is based on the A320 short/medium-range aircraft [15].

Figure 14 – 3D view of the ONERA SMILE BWB configuration.

Requirement	Value
Pax number	150 pax
Range	5100 km (2750 Nm)
Top of climb altitude	12192 m (40000 ft)
Cruising Mach number	0.78
ICAO Aerodrome Reference Code	ICAO Category C

Table 10 – Short/medium-range mission top-level aircraft requirements.

The SMILE configuration has a wingspan of 36m and a length of 19.7m. Figure 15 illustrates its pressurized part internal arrangement. The passenger cabin is composed of two compartments able to accommodate 150 passengers with a 3-3 seats layout. Two front doors are located behind the cockpit and two rear doors are located at the end of the passenger seats. The cargo hold is divided in two equal parts placed on the flanks of the passenger cabin, constituting two side cargo holds.

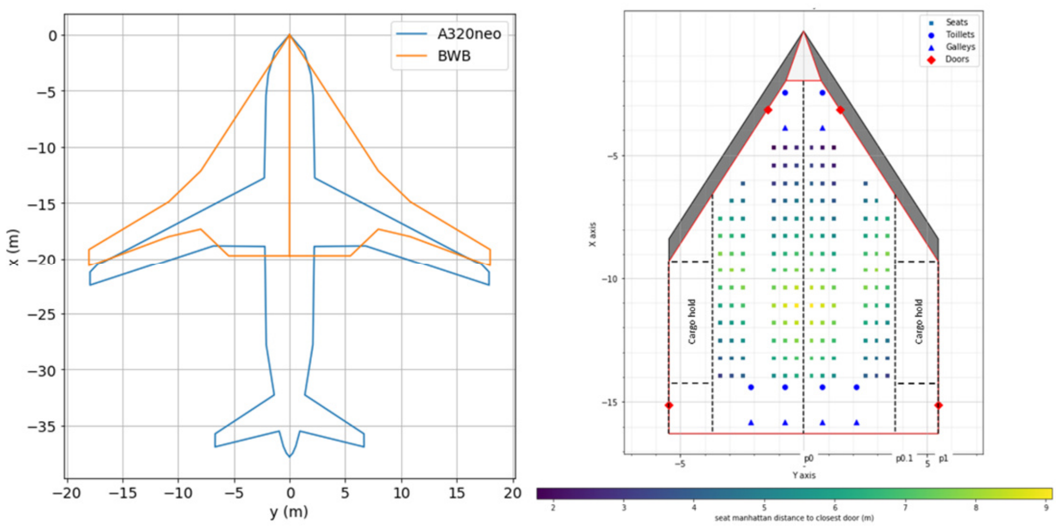

Figure 15 – SMILE configuration top view (left) and pressurized part internal layout (right).

The engine performance is based on the CeRAS model of the International Aero Engine V2527-A5 engine that has been modified to integrate the performance improvement expected for the 2035 target entry into service date considered for the SMILE configuration. A reduction of 18% is applied on the specific fuel consumption, representative of both the already demonstrated improvement of the Airbus NEO engine families (such as the Safran LEAP-1A engine) and some additional improvement to anticipate the effect of new technologies from now to 2035 engines. The mass was meanwhile adapted to the current Safran LEAP-1A engine.

Two of these turbofans are located at the rear of the central wing body, in a semi-buried position. This solution represents a first step toward integration of the engines to the airframe but the boundary layer ingestion effects are not yet modeled by the MDAO process.

The SMILE configuration has a MTOW of 61.3 tons and requires 11.7 tons of fuel for achieving its mission (including 2.7 tons as reserve fuel weight). Table 11 gathers its main performance characteristics concerning the 5100 km short/medium-range mission and Figure 16 illustrates its mass breakdown.

Performance characteristics	Value
MTOW	61.3 tons
Mission fuel weight	11.7 tons
Payload weight	13.5 tons
Take-off distance	1899 m
Climb duration	23 min
Mission duration	406 min
Maximum lift-over-drag ratio	20.8
Cruise lift-over-drag ratio	20.5

Table 11 – SMILE configuration main performance characteristics.

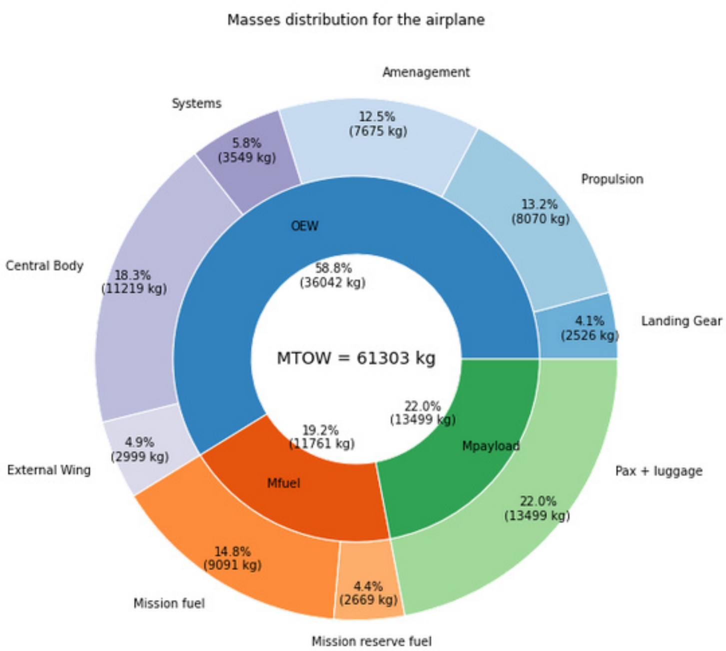

Figure 16 – SMILE configuration mass breakdown.

The SMILE configuration represents a baseline for the evaluation of the boundary layer ingestion effects. A first evaluation conducted at ONERA using high fidelity aerodynamics methods and tools [28] will contribute to the next evolution of the MDAO process in order to be able to model semi-buried engines BWB configurations.

5. Conclusion, Lessons Learned and Perspectives

The effort made by ONERA since 2015 led to a fully operational Multidisciplinary Design Analysis and Optimization (MDAO) process dedicated to Blended Wing Body (BWB) configurations. This process is composed of six disciplinary modules developed by ONERA experts (Geometry, Propulsion, Aerodynamics, Structure & Weight, Mission & Performance, and finally Handling Qualities) and has inherited ONERA competences in the MDAO field.

This MDAO process has been used to optimize a BWB configuration devoted to long-range missions, aiming at minimizing the mission fuel weight required and considering constraints to guarantee that the optimal configuration remains compliant with operational minimum requirements and feasibility criteria (maximum take-off distance, maximum climb duration, maximum mission duration, sufficient distance behind the passenger cabin to accommodate central body control surfaces, minimum external tip chord to have a sufficient winglet surface, and satisfaction of handling qualities criteria). A fuel consumption reduction of 8.3% (configuration BWB1) is obtained thanks to the optimization process, which represents 10.5 tons of fuel saving.

The optimization has been repeated considering several sets of hypothesis in order to quantify the impact of relaxing some of the design hypothesis (wingspan and top of climb altitude). Additional fuel saving can be expected:

- 10% with the wingspan extension above the ICAO Aerodrome Reference Code letter F category (configuration BWB2).
- 15% with the top of climb extension to 39000 ft (configuration BWB3).
- 19% with the combination of those two modifications (configuration BWB4).

Facing those results and in particular the possible benefits of the top of climb extension would lead to reconsider the typical long-range mission profile. It appears indeed that the specific geometry of the BWB configuration could take advantage of performing the cruise segment at a higher altitude than today. In another way, the wingspan extension would also represent a potential source of fuel saving. Nevertheless, such a solution would have significant impact on the BWB configuration overall dimensions and thus on the airport infrastructures.

The BWB configurations modeled by the MDAO process consider typical engine arrangement where the engines are located under the external wing. A major area of improvement of the overall design and optimization presented here would be to extend capabilities toward new engine technologies and architecture integrations on BWB configurations. This would cover new solutions about energy sources with electric solutions introduction and new engines layout from semi-buried engines to distributed propulsion. Those alternative solutions are currently under investigation and the associated disciplinary modules will be integrated into the process in the coming months.

As a first step toward those objectives, the SMILE configuration has been optimized for a short/medium-range mission, considering semi-buried engines positioning but with no integration of the boundary layer ingestion effects in the MDAO process performance estimation. Those effects will be integrated later in a next evolution of the process.

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7. Funding sources

The developments and results presented in this paper come from the internal research project CICAV funded by ONERA from 2015 to 2019. The authors would like to specifically thank the ONERA contributors to the MDAO process development and the BWB configurations design and optimization: Baptiste Dutrieux, Jean-Michel David, Ingrid Legriffon and Laurent Sanders from the Aerodynamics Aeroelasticity Acoustics Department, Mathieu Balesdent, Loïc Brévault, Carsten Döll and Clément Toussaint from the Information Processing and Systems Department.

The project leading to the SMILE configuration has received funding from the Clean Sky 2 Joint Undertaking under the European Union's Horizon 2020 research and innovation program under grant agreement N°CS2-AIR-GAM-2020-2021-01. The authors would like to thank the project partners from DLR, Dassault Aviation and Airbus Commercial Aircraft for the collaboration.

8. Copyright Statement

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