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Multidisciplinary Overall Aircraft Design and Optimization of Blended Wing Body Configurations

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Abstract

The Blended Wing Body (BWB) configuration seems to be one of the most promising concepts to replace the current passenger transport aircrafts with substantial improvement of their performance and reduction of their environmental footprint. However the expected gains still need to be precisely evaluated with airplanes to design. BWB concept is a highly coupled system because every sizing discipline is connected to a single system: the wing. This paper presents the multidisciplinary design analysis and optimization process of a blended wing body and its application to a long-haul commercial transport mission.

1. Introduction

The commercial aviation industry is seeking to global aircraft performance improvements combined with environmental impact reduction. The current Tube and Wing (T&W) concept is well known and fully optimized so it becomes now difficult to obtain significant performance improvements. The overall performance and specially the fuel consumption reduction would not evolve with one order of magnitude without an innovative and game changing solution like new propulsion technologies, new aircraft configurations or new flight procedures. Among the various innovative solutions, the Blended Wing Body (BWB) configuration is one of the most promising within the possible new aircraft configurations.

The BWB shape allows minimizing the drag contributors. The overall aircraft can be assimilated to a single wing that becomes the main element. All subsystems such as engines, passenger cabin, cargo hold, control surfaces are integrated within the wing.

Studies performed about BWB [1][2][3][4][5][6] highlight this concept as one of the most promising configuration for long-haul commercial transport missions with medium to large passengers capacity (300 to 500 pax). Expected improvements compared to T&W are an increase up to 15% of the lift over drag radio and a reduction of the take-off weight by about 10% for a similar mission. Those two performance improvements would participate to reduce fuel consumption and also CO_2 and NO_X emissions. Moreover, the large central body allows new propulsion integration concepts leading to noise ground print reduction, boundary layer ingestion or distributed propulsion architectures.

The figures mentioned above still remain estimations and the sizing of a realistic BWB configuration allowing to precisely compute the gains and drawbacks is a complicated exercise. BWB solution is a highly coupled system where the classical sizing disciplines (aerodynamics, structure, propulsion, etc.) have numerous interactions between them within the design process. For instance, the design of the cabin is strongly constrained by the design of the wing and vice versa. In the same way, modifying the shape of the wing has a direct impact on the control surfaces shape and positions, thus altering the handling qualities. The design and the optimization of a BWB require to solve the numerous coupling and so to consider multiple discipline outputs in the same sizing process. The Multidisciplinary Design Analysis and Optimization (MDAO) methodologies and tools are elaborated to solve this kind of highly coupled problem as they assess the impact of each subsystem on each other.

Starting in 2015, the ONERA CICAV project aims to develop a MDAO process dedicated to study BWB configurations. This project gathers a wide range of ONERA expertise: aerodynamics, structure, propulsion, handling qualities, aero-elasticity, acoustics and aircraft performance experts who have to fully cooperate with aircraft architects, MDAO and applied mathematics experts.

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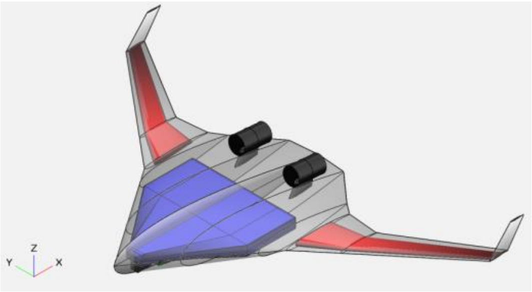

Figure 1: Illustration of a Blended Wing Body configuration designed within the CICAV process

2. Blended wing body multidisciplinary process

The BWB is a highly coupled system with numerous connexions between disciplines. It is natural to use a Multidisciplinary Design Analysis and Optimization (MDAO) framework. This last gives a canvas to gather multiple disciplines, objectives, constraints and design variables. This approach has been discussed in the references [7].

The CICAV process is build following two steps. The first one establishes the geometrical parametrization of the aircraft. It allows putting in place the main geometrical variables able to create the external shape and internal layout of the aircraft. Then, the second step of the process construction defines an exhaustive disciplines and variables list to connect with the geometrical description. The list of disciplines and their goal is the following:

- Geometry module: internal pressurized part sizing and overall airframe definition
- Propulsion module: engines performance assessment
- Structure module: primary structure sizing and weight and balance computation
- Aerodynamics module: aerodynamic characteristics assessment
- Mission module: performance assessment with regard to the specified mission
- Handling Qualities module: longitudinal handling qualities assessment

Few additional modules help to complement the aircraft performance as acoustics and aero-elasticity but they are not directly integrated in the design loop at the moment and their evaluation is done offline.

2.1 Geometry

The geometry module defines the aircraft overall external dimensions, its internal layout and the main sub-systems dimensions. The external shape is composed of plans or sections cutting the wing along the span. The figure 2 illustrates the different sections considered. For each section, several geometrical parameters allow to draw the wing shape. They are summarized in the table 1. About 40 variables are used to describe the wing but the entire Geometry module treats about 100 variables and parameters.

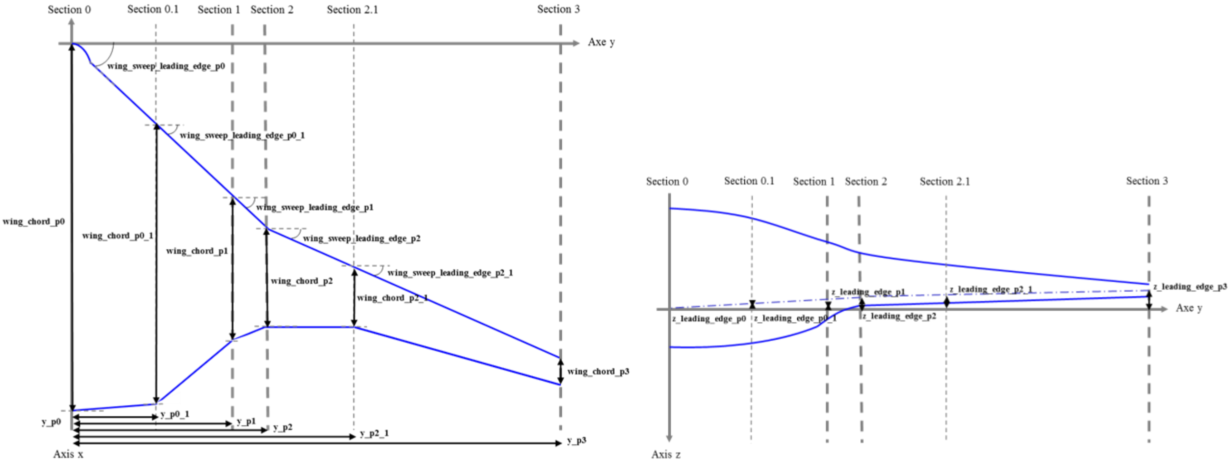

Figure 2: Sections of the BWB geometry, top view (left) and front view (right)

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Table 1: main wing parametrization variables

Variables
Wing sweep leading edge, sections: 0, 0.1, 1, 2, 2.1
Wing sweep trailing edge, sections: 0, 0.1, 1, 2, 2.1
Leading edge longitudinal, lateral, vertical position, for each section
Wing chord, for each section
Wing thickness ratio, for each section
Twist angle, for each section

The Geometry module first sizes the internal layout of the passenger cabin, in order to place seats, toilets, galleys, aisles, doors, etc. and the cargo hold. Both passenger cabin and cargo hold overall shape depend on the central wing body shape inputs, and specially the central body wing sweep leading edges. This geometry sub-process helps to define the maximal length of the airplane, represented by the chord in the section 0, as the cabin length depends on the section 0, 0.1 and 1 wing sweeps leading edges. The figure 3 shows a typical internal layout considered here. The computation details are not indicated here but do take into account common tube and wing cabin arrangement such as the seats dimensions and step in between. The passenger cabin internal arrangement and especially the doors and aisles definition are made using guidelines based on the certification specifications for large aeroplanes CS-25 provided by the European Aviation Safety Agency [8].

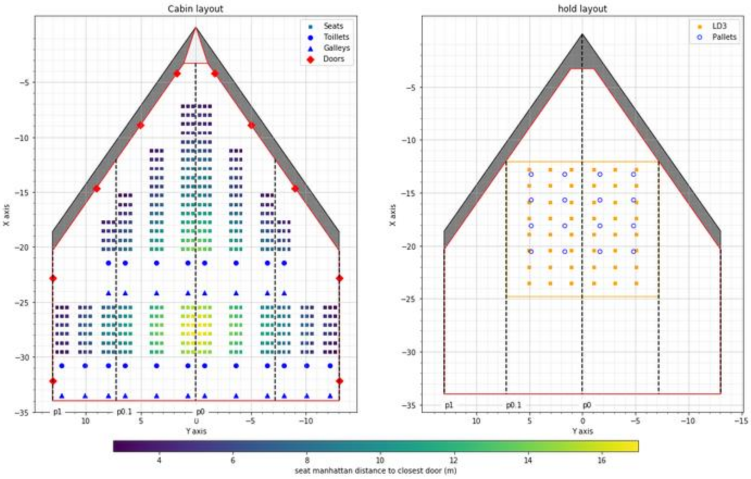

Figure 3: Typical internal layout of a blended wing body (passenger cabin on the left and cargo hold on the right)

After the passenger cabin and cargo hold internal layout definition, the wing geometry is completed. All the subsystems (landing gears, engines, fuel tanks and control surfaces) are then positioned in function of user inputs.

2.2 Aerodynamics

The Aerodynamics module has to provide the aircraft drag and lift coefficients at a given flight point within the mission flight domain (altitude: 0 to 14000 meters, Mach: 0.0 to 0.9). In the current process we use a model based on semi-empirical formulations from theory and statistics which is validated via high fidelity CFD results. The main output provided is a table that gives the aircraft drag coefficient C_x in function of the Mach number, the altitude and the aircraft lift coefficient. The module inputs are mainly coming from the Geometry module and use numerous expert parameters for characterizing the aircraft aerodynamic overall performance. They are not detailed here. More advanced model using Euler CFD methods will be integrated later this year in order to supplement the initial Aerodynamics module with high fidelity characterization for the cruise segment.

2.3 Propulsion

The propulsion module builds a performance table that give the engine thrust and consumption in function of the Mach number, the altitude and the engine T5[1]. It is based on the computation of the complete thermodynamic cycle of a turbofan engine. The results of the current module have been confronted and validated with engines available off

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[1] The T5 represents the temperature of the engine combustion chamber, which can be assimilated as the throttle.

the shelf (GE-90 85B for the long range applications and CFM-56 5C1 for the short-to-medium range applications). The propulsion module also estimates the weight and dimensions of the modelled engine.

2.4 Structure

The Structure module assesses the aircraft mass breakdown, balance and inertia. First, the Structure module sizes the aircraft primary structure using a parametric Finite Element Model (FEM). It is composed of all the elements that sustain the mechanical strength of the aircraft. For instance, the central body primary structure encompasses the passenger cabin and cargo hold. Load cases defined according the aircraft flight domain, pressurization constraints and certification specifications CS-25, are used to size the primary structure with a realistic set of hypothesis. Then, the primary structure weight, balance and inertia are assessed. The module also provides constraints points for the airfoils definition. The figure 4 shows the BWB structure decomposition through its FEM.

After evaluating the primary structure, the Structure module computes the weight, balance and inertia of all the other subsystems present on-board (landing gears, engine pylons, power units, systems, furnishing, operator items weight, etc.). It uses reference data or statistic formulations from already existing aircrafts. The module results have been confronted with different references [9][10] and showed a quite good accordance (deviation less than 10% of the operational empty weight). This is very significant because the overall aircraft weight estimation is of primary importance on its performance and fuel consumption assessments.

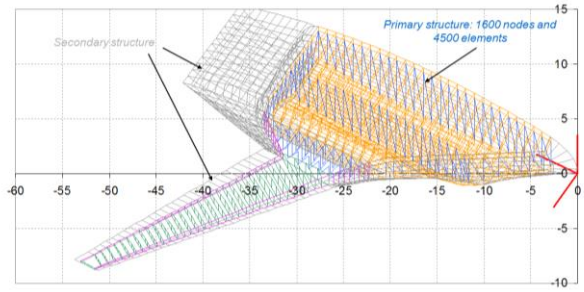

Figure 4: Illustration of the primary structure FEM generated by the Structure module

2.5 Mission

The Mission module computes the performance and the required Fuel Weight (FW) of the aircraft through a typical commercial transport mission profile. The mission profile is composed of several segments: take-off, climb, cruise, descent and landing and additional segments for fuel reserves assessment. The figure 5 illustrates the mission decomposition considered. The aerodynamic and propulsion tables generated by the modules previously presented are used to feed classical flight mechanics equations in order to assess the fuel consumption at each flight point throughout the overall mission. The Mission module also takes into account performance constraints based on the certification specification CS-25: the minimal required performance for the take-off and climb segments, including one (or more) engine(s) inoperative, and the operational ceiling.

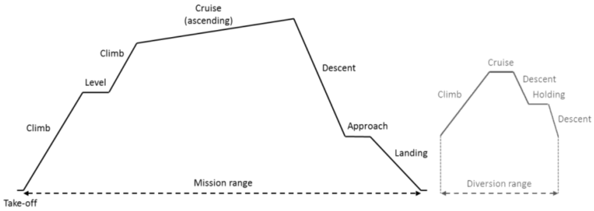

Figure 5: Representation of the mission profile for a long-haul commercial transport aircraft.

2.6 Handling Qualities

The Handling Qualities module provides complementary information about the aircraft designed with the evaluation of its stability and controllability. It checks the aircraft longitudinal behaviour for the ground and take-off segments through several criteria. The compliance of the aircraft longitudinal behaviour with regard to those criteria can be expressed as the relative positioning of the aircraft loading vector (evolution of the longitudinal Center of Gravity

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(CoG) position while adding passengers and fuel within different possible orders) with regard to bounds representing each criterion. More details about the handling qualities will be provided in the Section 6.

2.7 Multidisciplinary analysis

The 6 disciplines / modules: Geometry, Aerodynamics, Propulsion, Structure, Mission and Handling Qualities (Control) are connected together through the NASA openMDAO framework [11]. The MultiDisciplinary Analysis (MDA) is presented in the figure 6. The MDAO pattern presently used is a classical single level method, Mutli-Discipline Feasible (MDF), which has the advantage to be quick and easy to implement. The figure 6 illustrates the XDSM view of the process [12], created with an automatic generator developed at ONERA [13][14].

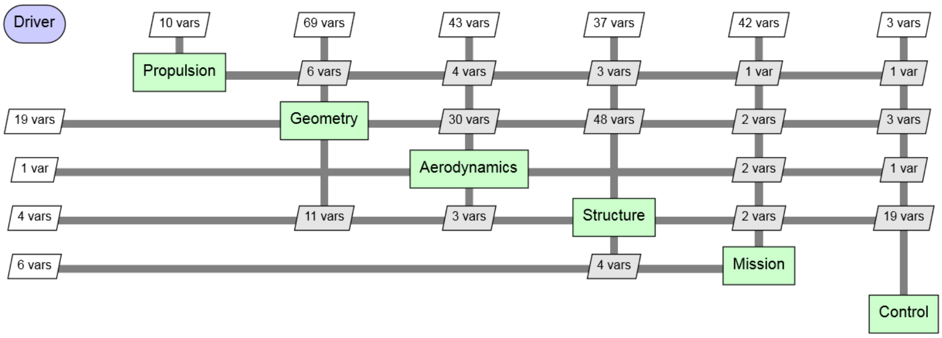

Figure 6: XDSM view of the CICAV Blended Wing Body MDA.

The figure 6 highlights a very typical interaction for aircraft design processes between the weight estimation and the mission analysis. As the modules are not run at the same time, inputs between the Structure module and the Mission module are not consistent. On one hand, the Structure module computes the primary structure sizing with a Fuel Feight (FW) hypothesis as the mission have not yet been computed. On the other hand, the Mission module uses a Maximal Take-Off Weight (MTOW) which is not yet well estimated by the Structure module because of ignorance of the required fuel weight. The consistency of the weights considered respectively by the Structure and Mission modules is ensured by the convergence of both MTOW and FW through a fixed point method introduced at the top level of the process, over the MDA. The fixed point method helps to find an equilibrium weight point for both MTOW and FW. The figure 6 illustrates this loop: 4 variables are exchanged from the Mission module to the Structure module: MTOW, FW and Reserve Fuel Weight (RFW). The fourth variable concerns a deviation applied on the weight computed by the Structure module and is relative to an uncertainty propagation analysis not presented in the following results.

Other couplings have been identified. For instance, interactions could be implemented between the primary structure sizing and the shape of the aerodynamic airfoils around it or the positioning of the landing gears, the engines and the control surfaces in function of handling qualities criteria. These couplings are not yet present in the current process but they will be introduced for the next evolution of the MDAO process.

3. Reference case

Prior to the optimization of a system, it is convenient to establish a reference baseline in order to measure the possible gains. As no BWB has ever flown the first available comparison point is to use a classical operative T&W aircraft. For the current generation of aircraft placed on long-haul commercial transport missions, the Airbus A350-1000 which entered in service in February 2018 appears to be a good candidate. The starting point of the comparison is to establish common Top Level Aircraft Requirements (TLAR). They are summarized in the table 2 and based on the A350-1000 [15][16][17].

These TLAR and ONERA experience about BWB design are used to build a reference baseline that initialize the optimization process. This first iteration of the complete MDA without any optimization can be use as reference baseline.

Table 2: ONERA BWB long-haul commercial transport mission TLAR

Top Level Aircraft Requirements	
Passengers capacity	440 pax
Hold capacity	208.2 m^3, composed of : • LD3 containers : 44 (hypothesis: 100% LD3 containers) • 96" pallets : 14 (hypothesis of full cargo filling with) • bulk volume : 11.3 m3
Mission range	14800 km
Top of climb altitude	9448 m (31000 ft)
Cruising Mach number	0.84

The reference baseline leads to an 80 meters wingspan blended wing body with a length of 45 meters and a MTOW of 307 tons. The figure 7 illustrates the configuration obtained. The table 3 shows the main aircraft features and their comparison with the A350-1000.

The reference BWB uses more powerful engines than the reference engine modelled by propulsion module (based on the GE-90 85B). A scale factor of 1.2 has been considered in order to model a turbofan of the Rolls-Royce Trent XWB class, which currently equips the Airbus A350-1000.

The engines are podded under the external wing, as typical engines integration. At the beginning of the BWB studies within the CICAV project, the reference case considered engines mounted over the rear part of the central wing body [5]. Such configuration, very common among the numerous BWB concepts found in the literature, appeared to be interesting in order to reduce the engines noise ground propagation. Nevertheless, the lessons learned from previous studies about engine structural integration highlight some disadvantages about such configuration. First, having an engine mounted on top of a pylon imposes to rigidify the structure in order to withstand the compression and buckling effects. Having such resistance causes a significant increase to the engine attachment structure mass including the pylon itself which is several meters height. Then, the rear engines position does not favor the aircraft longitudinal handling qualities as it move back the overall aircraft center of gravity. The introduction of longitudinal handling qualities criteria naturally encourages moving the engines position forward. Finally, the ground operations and specially the engines maintenance operations might be more complex when the engines are located over the wing body. For all these reasons, it has been decided to consider engines podded under the wing despite the expected acoustics gains. However this configuration asks questions about lateral control capability in case of inoperative engine.

Such thought highlight the interest of integration solutions related to semi-buried engines with regard to engines acoustics emissions reduction objectives because the pylons do not exist anymore and the height of the engine attachment structure is very low. Futures studies performed within the CICAV project are planned to deal with semi-buried engines

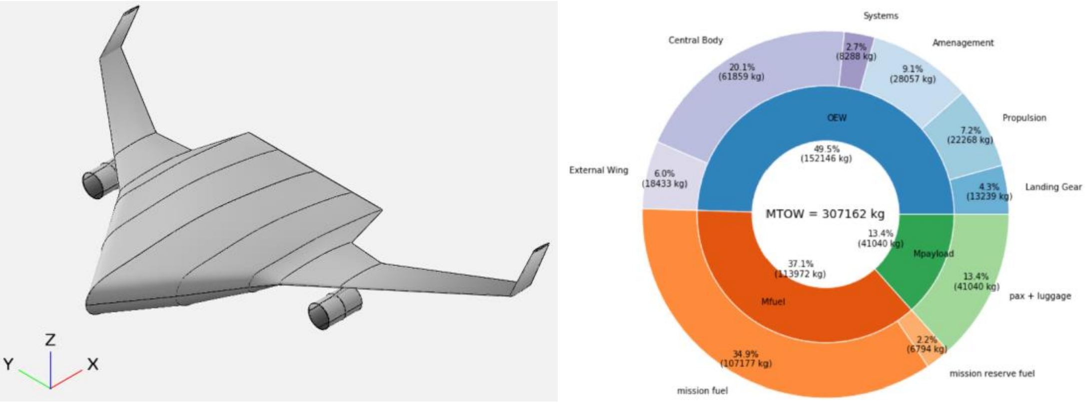

Figure 7: 3D isometric view and mass breakdown of the reference blended wing body

Table 3: CICAV baseline BWB compared with the A350-1000

	A350-1000 [16]	CICAV baseline BWB
Pax	440	456
LD3 / Pallets 96 ’’	44 / 14	48 / 16
Wingspan	64.8 m	80.0 m
Overall length	73.8 m	44.8 m
MFW	125 t [2]	114 t
MTOW	308 t	307 t

4. Sensitivity analyses

The optimization problem consists of minimizing the Fuel Weight (FW) required to perform the mission with respect to five constraints.

Three constraints concern operational limitations for ensuring a good compatibility of the BWB designed with the existing airport infrastructures and the typical air traffic management procedures. First, the take-off distance is limited to 3200 m in order to comply with the typical runways length. Then, the climb duration and the mission duration are limited respectively to 28 min and 18 hours in order to meet the typical durations for similar long-haul missions.

The two other constraints concern geometrical criteria. First, the rear length of the central body, located just at the rear of the passenger cabin, is limited by the minimal chord required to integrate the control surfaces specified as inputs. Then, the external wing volume is limited by the minimal volume required to integrate all the fuel needed for performing the specified mission.

The optimization problem is summarized in the equation 1.

$$\begin{array}{rl} \underset{z}{\text{minimize:}} & FW(z) \\ & distance_{take-off}\,(z) \leq 3200\,m \\ & duration_{climb}(z) \leq \ 28\,min \\ \text{subject to:} & duration_{mission}(z) \leq 18\,h \\ & central\ body\ rear\ length(z) \leq central\ body\ control\ surfaces\ chord(z) \\ & external\ wing\ fuel\ tank\ volume(z) \leq FW(z) \end{array} \qquad (1)$$

The z symbol represents a group of design variables.

The total list of inputs and parameters in the MDA is about one hundred variables. Most of them are not useful in the optimization process and their optimization can be discarded. A reduced list of 12 variables has been identified as variables of interest and is presented in the table 4. A preliminary step consists in a parametric study to eliminate the variables with a small impact on the optimization objective. To preserve the overall aircraft plan form consistency, the wing sweep leading edge is kept equal along the central body (from the section 0 to the section 1), and along the external wing (from the section 2 to the section 2.1). The same logic is applied for the external wing thickness ratios (from the section 2 to the section 3).

Table 4: List of design variables considered for the parametric study

Design variables	Range	Optimized
top_of_climb_altitude	[8500, 10750]	yes
cruising_mach_number	[0.75, 0.89]	yes
distance_y_p1_to_y_p2	[1.0, 4.0]	yes
distance_y_p2_to_y_p2_1	[5.0, 8.0]	no
wing_chord_p2	[5.0, 20.0]	yes
wing_chord_p2_1	[5.0, 11.0]	yes
wing_chord_p3	[2.0, 6.0]	no
wing_span	[65.0, 80.0]	yes
wing_sweep_leading_edge_p0 [3]	[45.0, 70.0]	yes
wing_sweep_leading_edge_p2 [4]	[30.0, 50.0]	no
wing_thickness_ratio_p0	[0.12, 0.16]	yes
wing_thickness_ratio_p2 [5]	[0.08, 0.10]	no

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[2] Computed from the A350-1000 usable fuel quantities [16], with the hypothesis of a fuel density of 0.8 g/cm^3.

[3] wing_sweep_leading_edge_p0 = wing_sweep_leading_edge_p0_1 = wing_sweep_leading_edge_p1

[4] wing_sweep_leading_edge_p2 = wing_sweep_leading_edge_p2_1

The influence of these variables is confronted to the optimization objective and constraints. A sensitivity analysis is done using a Latin Hypercube Sampling (LHS) of 500 points. The figure 8 represents the Sobol [18] indices relative to those 12 variables with regard to the FW minimization objective.

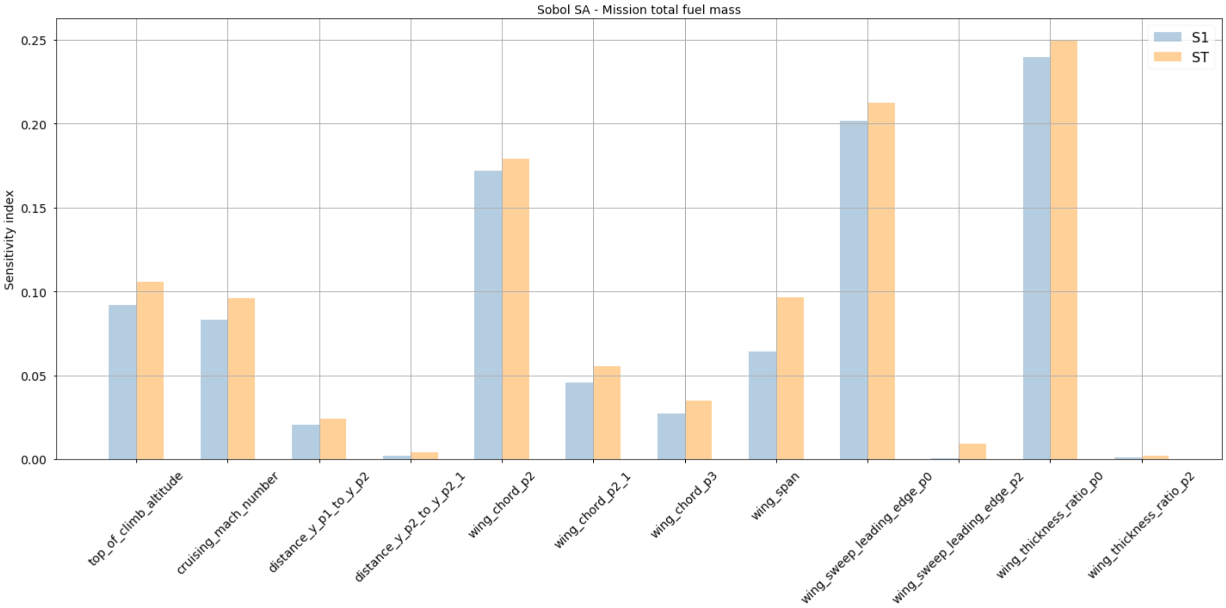

Figure 8: Sobol indices relative to the FW

4.1 Mission type variables

The two variables relative to the mission profile, i.e. the top of climb altitude and the cruising Mach number, have significant impacts on the FW minimization objective.

The figure 9 illustrates the sensitivity of the optimization objective and the five constraints to the top of climb altitude. The FW minimization objective leads to increase the top of climb altitude. The maximal top of climb altitude is found with the upper bound considered for the sensitivity analysis, which is fixed to order of magnitude considered for long-haul missions in order to stay within typical air traffic management procedures. Those results could lead to review the typical cruising altitude for new configurations such as BWB and adapt the air traffic management procedures to their performances.

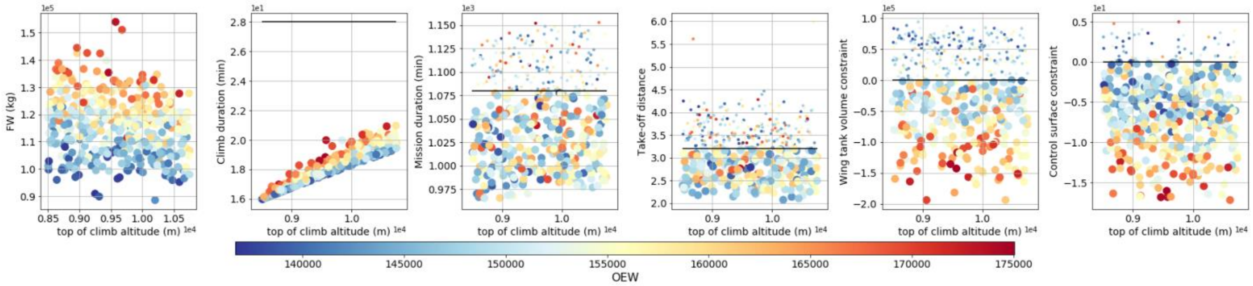

Figure 9: Optimization objective and constraints versus top of climb altitude
(The black line corresponds to the constraints limits)

The figure 10 illustrates the sensitivity of the optimization objective and the five constraints to the cruising Mach number. The FW minimization objective leads to reduce the cruising Mach number, but meet a limitation brought by the constraint considered about the mission duration.

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[5] wing_thickness_ratio_p2 = wing_thickness_ratio_p2_1 = wing_thickness_ratio_p3

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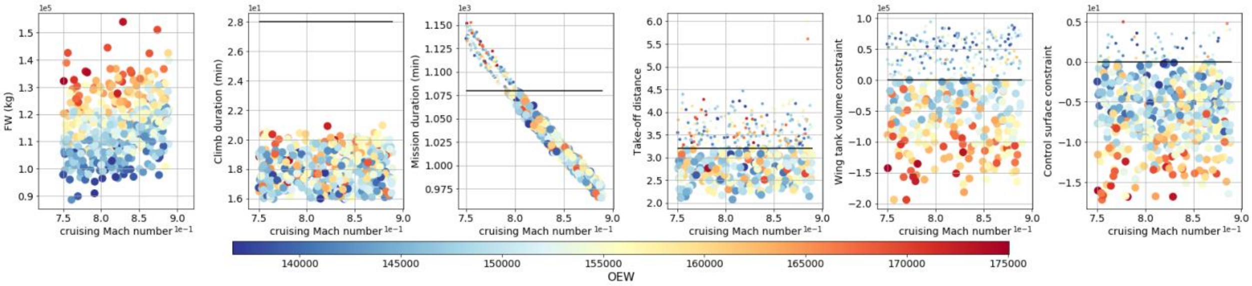

Figure 10: Optimization objective and constraints versus cruising Mach number
(The black line corresponds to the constraints limits)

4.2 Geometrical type variables

The three variables relative to the aircraft geometry that have the greatest impact on the FW minimization objective are the wing thickness ratio in the section 0, the wing sweep leading edge in the section 0 and the wing chord in the section 2. The figure 11 illustrates the impact of the wing thickness ratio in the section 0. The FW minimization objective leads to increase the wing thickness ratio in the section 0, but meet a limitation brought by the constraint considered about the sufficient rear length of the central body to accommodate control surfaces.

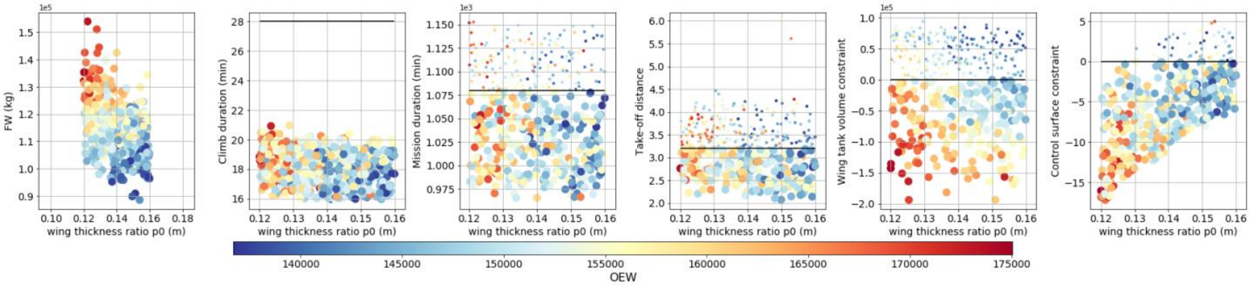

Figure 11: Optimization objective and constraints versus wing thickness ratio in the section 0
(The black line corresponds to the constraints limits)

The figure 12 illustrates the impact of the wing sweep leading edge in the section 0. The FW minimization objective leads to increase the wing sweep leading edge in the section 0, but meet a limitation brought by the constraint considered about the sufficient rear length of the central body to accommodate control surfaces.

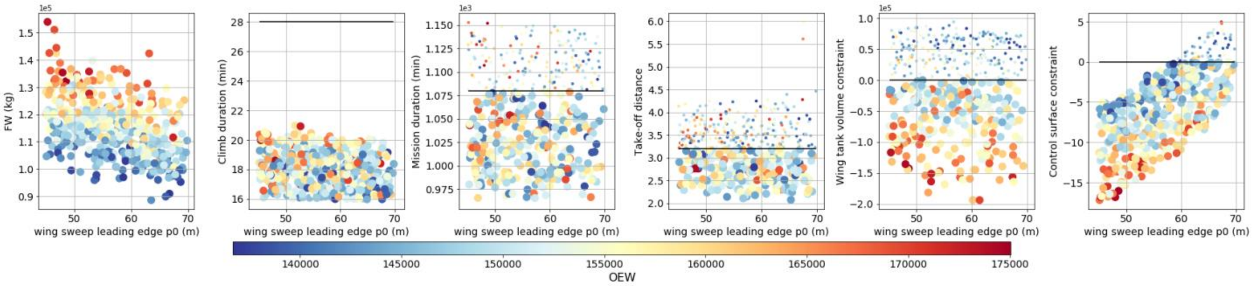

Figure 12: Optimization objective and constraints versus wing sweep leading edge in the section 0
(The black line corresponds to the constraints limits)

The figure 13 illustrates the impact of the wing chord in the section 2. The FW minimization objective leads to decrease the wing chord in the section 2, but meet a limitation brought by the constraint considered about the sufficient external wing volume to accommodate the fuel required.

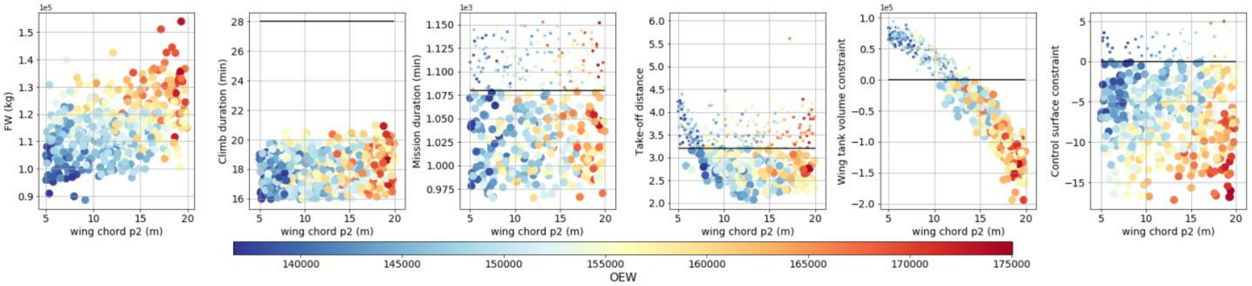

Figure 13: Optimization objective and constraints versus wing chord in the section 2
(The black line corresponds to the constraints limits)

Due to their poor impacts on the optimization objective, the distance between the section 2 and the section 2.1, the wing sweep in the section 2, and the wing thickness ratio in the section 2 are discarded from the optimization. It is also decided to not use the wing chord in the section 3 as a design variable because of its crucial effect on the winglet sizing, which is not yet taken into account in the optimization loop. In a first hypothesis, it means that the winglet is the same for all the configurations defined and only modification of the wing plan form is considered. This decision is also confirmed by the poor effect of the wing chord in the section 3 variation with regard to the FW.

5. Optimization

5.1 The optimization method

Due to the computational cost of the multidisciplinary coupled simulation and the absence of exact gradient information, traditional optimization algorithms are not a viable option for such process. For this reason, surrogate model based optimization is considered in this paper. More specifically, Efficient Global Optimization (EGO) algorithm [19] is used to solve this MDO problem. The underlying idea of EGO consists in creating Gaussian Processes (GP) of the objective and constraint functions by relying on a limited finite dataset. These surrogate models are subsequently refined using a sequential approach by evaluating the exact functions in the areas of interest of the search space, determined according to a given criterion, until a stopping condition is met. In this paper, the criterion used is the Expected Improvement combined with Probability of Feasibility for the constraints handling [19]. This enables to find the optimum of the MDO problem using a limited number of calls to the exact MDA.

5.2 Optimization results

An initial dataset of 80 exact function evaluations (MDA simulations) is carried out using a LHS and then 70 EGO iterations are performed to converge to the obtained optimal solution. The algorithm converges after a total of 100 iterations (80 initial + 20 EGO), as illustrated in the figure 14. The figure 15 represents a synthetic view of the results through the optimization process. Each set of design variables are connected to the objective and constraints results. The parallel plot shows that some variables are hitting the boundaries. It may reflect the lack of a constraint or a too narrow variation domain. The sensitivity analysis already highlighted to interest to investigate higher flight altitude. The thickness ratio also hit a boundary. The optimization leads to decrease the wing sweep leading edge of section 0 while keeping the highest possible thickness ratio regarding the control surface space (15% of the overall length). The aerodynamic performance tends to favour short airplane length and so higher thickness ratio.

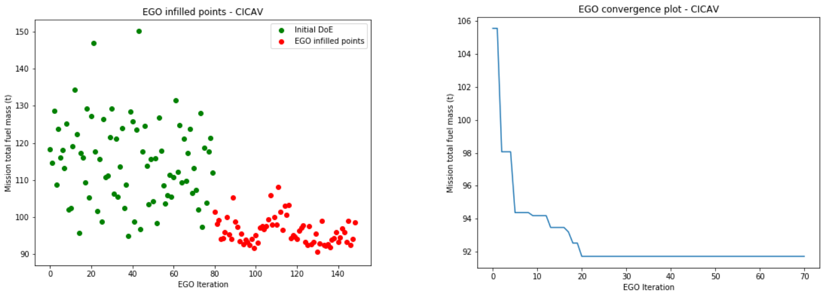

Figure 14: EGO convergence plots

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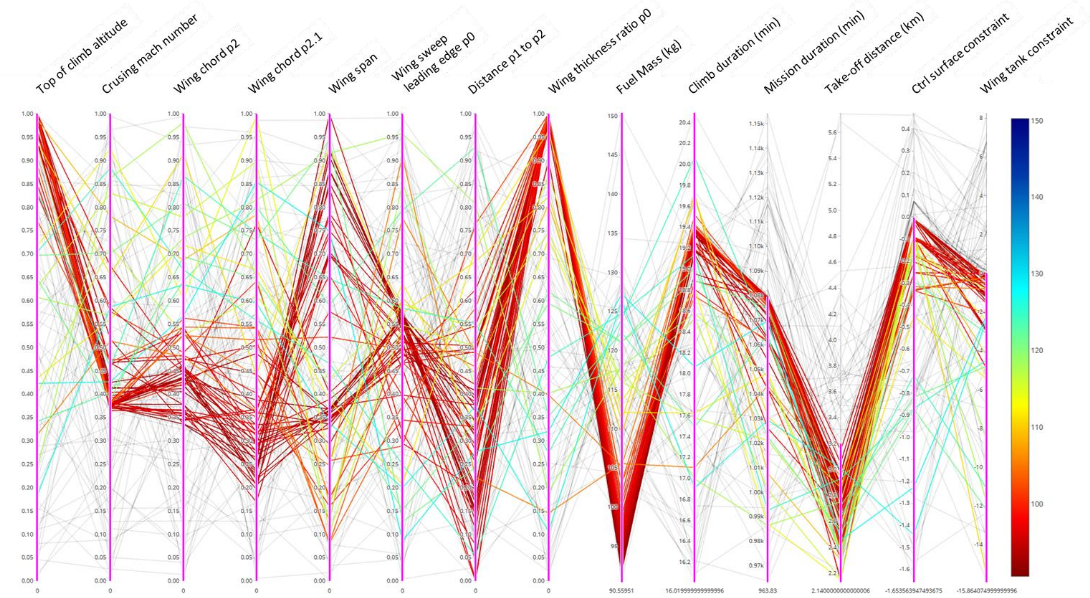

Figure 15: Parallel axis plot. Variables are without dimension and displayed between 0 and 1 where 1 is the maximum of variable variation range and 0 the minimum.

The optimization loop achieved to an optimized BWB which is 78.2 meters wingspan blended wing body with a length of 42.0 meters and a MTOW of 275 tons. The figure 16 (left) illustrates the configuration obtained and the pie chart (right) gives details about the mass breakdown.

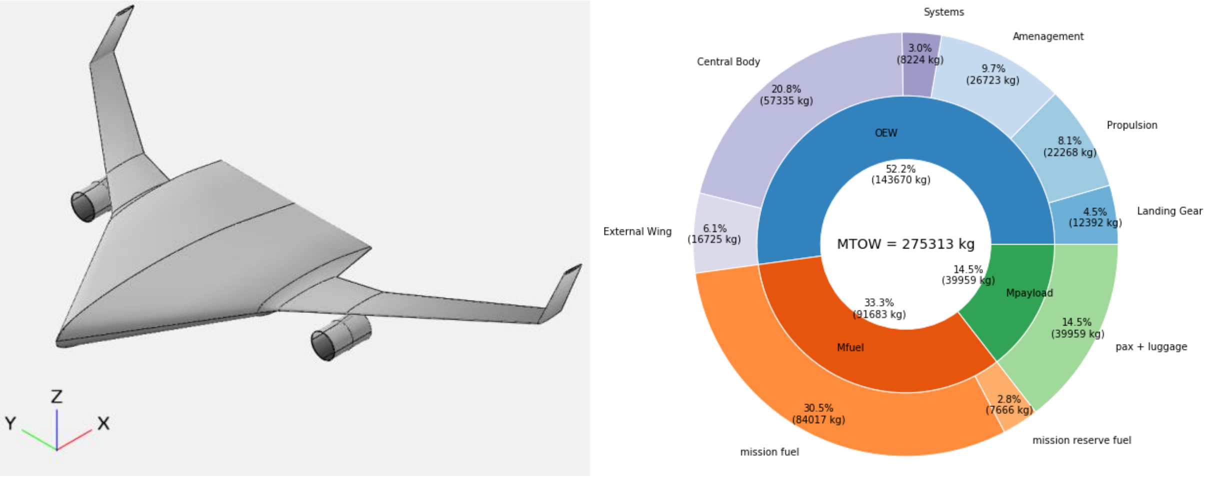

Figure 16: 3D isometric view and mass breakdown of the optimized blended wing body

The figure 17 illustrates the mission profile and indicates that the cruise is made at a high lift over drag ratio which reflects a well optimization of the overall aircraft geometry with regard to its mission. However the performances seem optimistic compared to past evaluations [1][2][3][4][5][6]. The fuel mass gain compared to the CICAV baseline and the A350-1000 is about 22 tons (24% better) and 33 tons (36% better) respectively. This small fuel mass comes from very good aerodynamic performances at cruise speed. The aerodynamic module is able to provide a good first evaluation but does not catch the real physics of a complex 3D shape. Thus it needs to be corrected on the loop with higher fidelity models currently integrated.

The structure module currently works with fewer sections than the other modules. This is why the rear central body leading edge is flat. Further improvements will allow optimizing the rear shape of the wing central body.

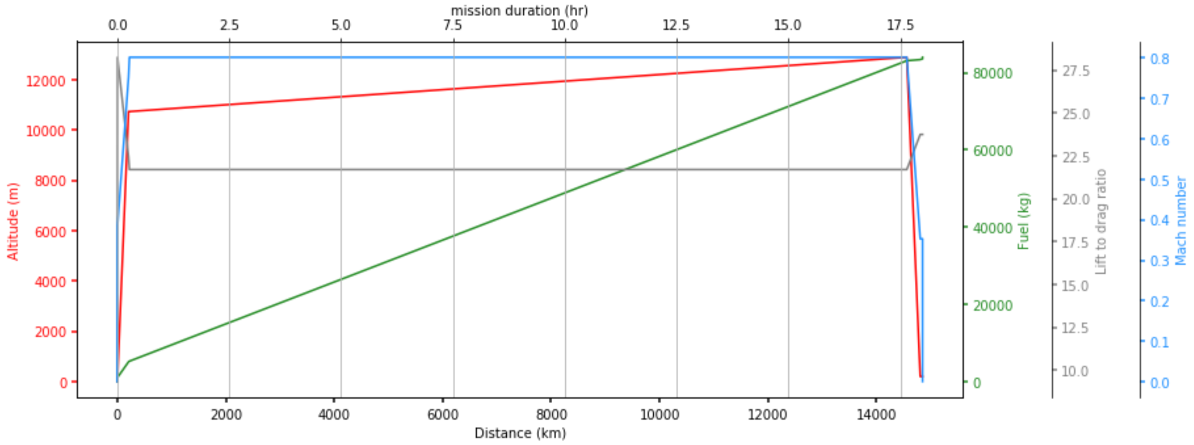

Figure 17: Mission profile of the optimized blended wing body

The table 5 shows the main aircraft features and their comparison with the reference case presented in Section 3 and the A350-1000. The figure 18 illustrates both BWB reference case and optimized BWB plan form compared to the A350-1000.

Table 5: CICAV optimized BWB compared with the baseline and the A350-1000

	A350-1000 [16]	CICAV baseline BWB	CICAV optimized BWB
Pax	440	456	444
LD3 / Pallets 96 ’’	44 / 14	48 / 16	48 / 16
MFW	125 t	114 t	92 t
MTOW	308 t	307 t	275 t

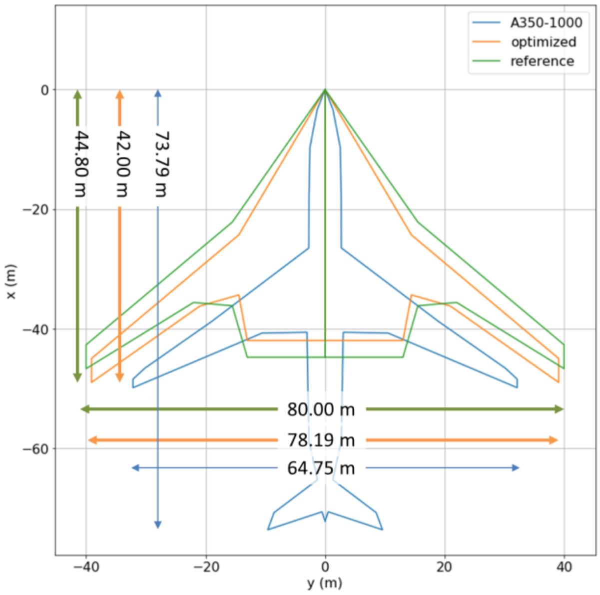

Figure 18: A350-1000, BWB reference case and optimized BWB plan form comparison

6. Handling Qualities considerations

The longitudinal handling qualities analysis deal with 5 criteria which are relative to the rolling, the take-off and the approach phases. The aircraft loading vector represented in figure 19 is built with several hypotheses about payload and fuel filling. During the mission, the payload remains unchanged and the fuel is emptied along the trajectory. The aircraft loading vector thus moves within the boundaries located on the left part. This part of the aircraft loading vector must be compliant with the criteria observed.

Two first criteria concern the nose landing gear loading and are relative to the rolling phase (NLG_load_min/max in the figure 19). A minimal loading of the nose landing gear is considered in order to ensure sufficient ground manoeuvrability and a maximal loading is considered following the typical landing gears sizing requirements. The evolution of the aircraft loading vector must stay within the boundaries representative of those two criteria. Two other criteria concern the aircraft manoeuvrability in glide during the approach phase (Trim_glide_fwd/aft) and a last criteria concern the ability of the aircraft to perform the take-off rotation (Trim_TO_rotation). The compliance with those three criteria depends on the adequacy of the elevators sizing and features with regard to the overall aircraft pitching characteristics.

The figure 19 indicates that the aircraft loading vector is compliant with the two nose landing gear loading criteria for a longitudinal position of the main landing gear around 29 m from the aircraft nose. The figure 19 also indicates that the aircraft loading vector is not well compliant with the three manoeuvrability criteria. A solution for improving the aircraft manoeuvrability would be to move the aircraft loading vector forward. Without any modification of the overall geometry, this could be done by adding a fuel tank at the front part of the wing central body. This solution will be investigated in more details within the CICAV project, in addition to the fitting of some parameters about the elevator authority, the engine vertical position, the overall aircraft Cm0 and the take-off speed.

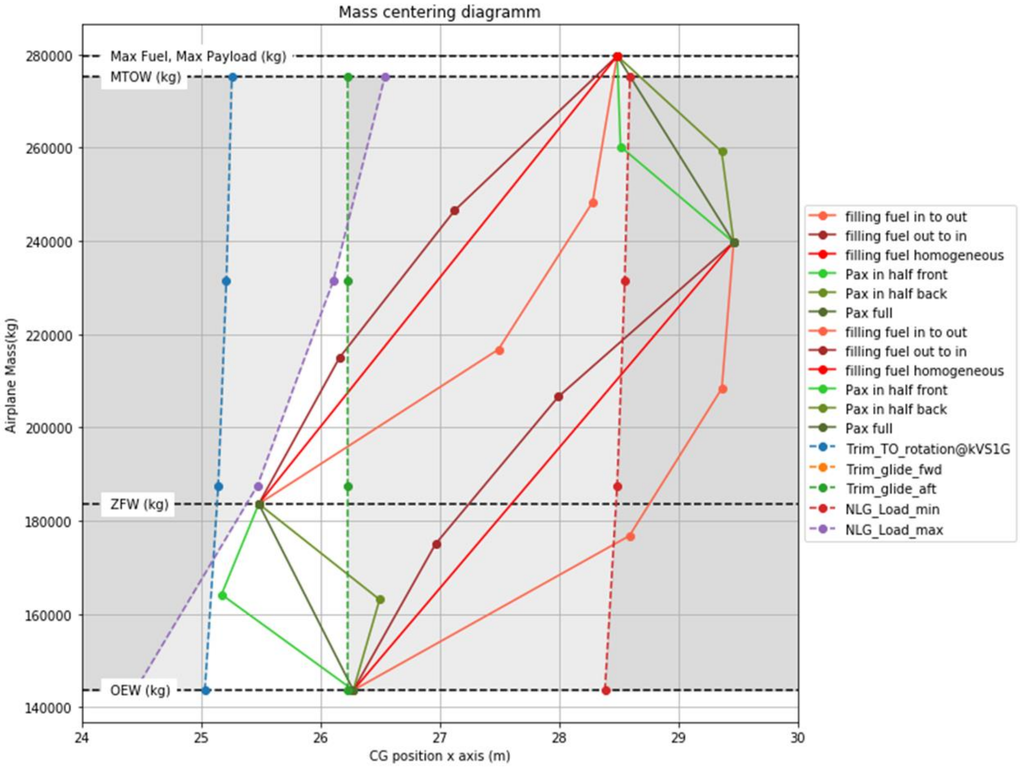

Figure 19: Aircraft loading vector diagram and handling qualities criteria (the white region fulfils all criteria).

7. Further works and conclusions

Multiple evolution of the current MDAO process is planned within the CICAV project.

First handling qualities have a significant impact on the design optimization. The criteria to fulfil might change some design variables. The next step is to integrate the handling qualities criteria in the optimization loop as constraints to orient the design optimization toward feasible designs. Beside the longitudinal, the lateral handling qualities will be also considered.

Disciplines precision will be improved with highest fidelity physics. Optimization results show very optimistic aerodynamic performances, cruise lift to drag ratio is higher than expected. The solution considered is to use an ONERA internal tool [20] relying on SU2 [21]. This software allows considering properly airfoils, twists evolution law along the wing span. The integration of high fidelity computation to the MDA will give more physical results and a better definition of the wing shape. However the addition of the airfoils optimization capability implies new

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feedback loops in the process with the structure and geometry module. It will increase the processes complexity and the computation time.

The overall geometry of BWB configurations and especially the wide central body offers opportunities to integrate innovative propulsion solutions. Among them semi-buried propulsion architecture benefiting of Boundary Layer Ingestion (BLI) is the most promising. Several studies [4][22][23] indicates that a significant reduction of fuel weight could be achieved thanks to a reduction of the engine pylons wet area suppression, and the overall airframe drag reduction because of BLI effects. However BLI could also decrease the fan performances and degrade the thermodynamic efficiency thus the overall gains still has to be estimated. ONERA is currently investigating this topic for all kind of airframe concept and resulting models will be integrated in the CICAV process.

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