DOI: 10.13009/EUCASS2022-6061
9TH EUROPEAN CONFERENCE FOR AERONAUTICS AND SPACE SCIENCES (EUCASS)

Multidisciplinary Design and Optimization of the Blended Wing Body Configuration SMILE

Julie Gauvrit-Ledogar, Arnault Tremolet*, Sébastien Defoort**, Franck Morel**, Romain Liaboeuf**, and Michaël Méheut****

** ONERA, Université Paris Saclay, Palaiseau, France*

julie.gauvrit-ledogar@onera.fr

arnault.tremolet@onera.fr

*** ONERA, Université de Toulouse, Toulouse, France*

sebastien.defoort@onera.fr

franck.morel@onera.fr

romain.liaboeuf@onera.fr

**** ONERA, Université Paris Saclay, Meudon, France*

michael.meheut@onera.fr

Abstract

Since 2015, ONERA has been developing a Multidisciplinary Design Analysis and Optimization (MDAO) process dedicated to Blended Wing Body configurations. ONERA used this process for the European Clean Sky 2 (ITD Airframe) ONERA-DLR project NACOR (Call for Core Partners Wave 1) to design and optimize a Blended Wing Body configuration for a short-medium range mission. This work resulted in the SMILE configuration presented in this paper.

The SMILE configuration proposed by ONERA represents a baseline for the European H2020 IMOTHEP project (dedicated to hybrid electric technologies for aviation) to explore the integration of a Distributed Electric Propulsion (DEP) architecture.

1. Introduction

The global aviation industry is currently facing a huge challenge for the design of future passenger transport aircraft with the aim of achieving substantial performance improvement and reduction of air transport environmental footprint (reduction of fuel consumption, reduction of pollutant emissions and reduction of noise emissions) compared with existing aircraft. In such a context, the Blended Wing Body (BWB) configuration appears to be one of the most promising new architectures to replace the classical Tube and Wing configuration [1][2].

The typical features of the BWB configuration is that each subsystem, as propulsion, control surfaces, pressurized cabin, etc. is integrated to a single wing shaped body. Thus, the design of such geometry imposes to consider, at the same level of the overall aircraft design process, disciplines all together such as aerodynamics, structure, propulsion, handling qualities, etc. Therefore, the use of multidisciplinary approaches is crucial in order to take into account the complex couplings between disciplines involved in its design and optimization, and provide consolidated figures of merit of the achievable performance.

Since 2015, ONERA has been developing a Multidisciplinary Design Analysis and Optimization (MDAO) approach dedicated to BWB configurations with the implication of experts in aerodynamics, structure, propulsion, handling qualities, aeroelasticity, acoustics, aircraft performance, aircraft overall architectures and MDAO [3][4][5][6]. This process was then 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 a BWB configuration for a short-medium range mission [7]. This work resulted in the Small - Medium range Integrated Light and Efficient (SMILE) configuration presented in this paper.

This SMILE configuration represents a baseline for the European Horizon 2020 IMOTHEP project to explore the integration of a Distributed Electric Propulsion (DEP) solution.

This paper presents the ONERA multidisciplinary approach dedicated to BWB configurations and details the results obtained about the SMILE configuration. The paper is organised as follows. The first section gives more insight in the

DOI: 10.13009/EUCASS2022-6061

BWB MDAO process with a description of all disciplinary modules integrated along with the design and optimization methodologies applied. The second section describes the SMILE configuration and details its performance. The third section presents the approach implemented in the frame of the European H2020 IMOTHEP project to explore the integration of a Distributed Electric Propulsion (DEP) solution on the SMILE configuration.

2. ONERA BWB MDAO Process

The ONERA approach involves experts in aerodynamics, structure, propulsion, handling qualities, aeroelasticity, acoustics, aircraft performance, aircraft overall architectures and MDAO [3][4][5][6]. This approach results in a MDAO process composed of six disciplinary modules, integrated within the NASA OpenMDAO framework [8].

This process consists of the addition of a Multidisciplinary Design Analysis (MDA) that chains all the disciplinary modules and producing a single consistent design, but not optimal, and an optimization algorithm that guides the MDA to find the optimal solution regarding a given objective function and considering constraints.

2.1 Multidisciplinary Design Analysis

Figure 1 illustrates the eXtended Design Structure Matrix (XDSM) of the MDA [9], created with an automatic generator [10].

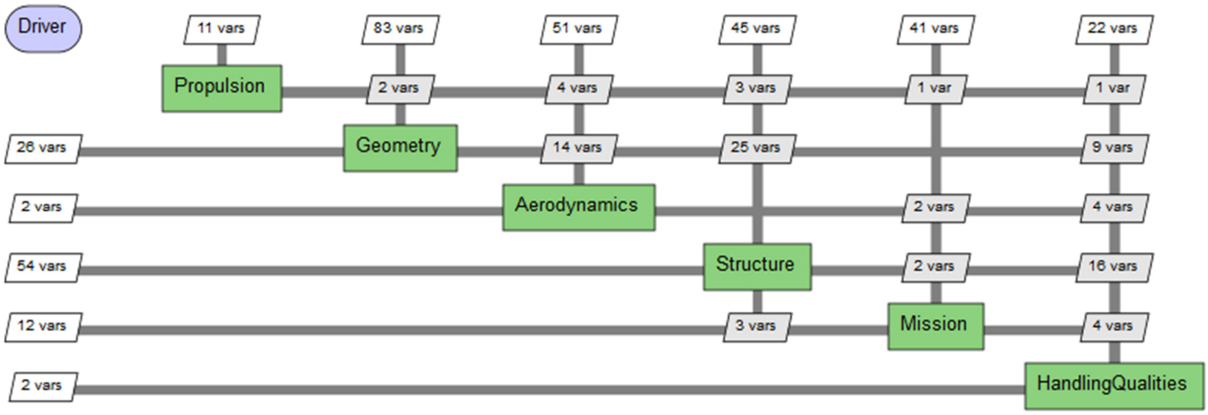

Figure 1: XDSM of the ONERA BWB MDA

The Propulsion Module models the thermodynamic cycle of typical turbofan engines in order to provide the engine performance (thrust, specific fuel consumption) within the aircraft flight envelope (Mach, altitude, engine T5[1]).

The Geometry Module sizes the internal pressurized area (passenger cabin and cargo hold) using typical operational data and certification specifications. Then, it defines the overall external airframe (central body, transition area, external wing, winglets) and the main internal elements (fuel tanks, landing gears, etc.). Finally, it provides a 3D model of the whole geometry including both external airframe and internal elements.

The Aerodynamics Module performs the aircraft aerodynamic performance evaluation within its flight envelope, using analytical formulations derived from both theory and data analysis and calibrated with high-fidelity aerodynamic computations and wind tunnel tests results. This module is extensively detailed in □[11].

The Structure Module sizes the primary structure through finite elements modelling and provides an estimation of the aircraft mass breakdown, centre of gravity location and inertia for several aircraft flight configurations. The aircraft subsystems masses are estimated with statistical formulations.

The Mission Module assesses the aircraft performance with regard to the specified mission, expressed by a detailed aircraft state vector. The mission flight profile is discretized in elementary flight phases and additional flight phases are included for reserve fuel weight assessment.

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

DOI: 10.13009/EUCASS2022-6061

Finally, the Handling Qualities Module evaluates the aircraft answers toward a set of handling qualities criteria. For that purpose, the aerodynamics characteristics assessed by the Aerodynamics Module are completed with data computed with the vortex-lattice based AVL software[2].

The consistency of the vehicle modelled is managed by a fixed point iteration introduced at the top level of the MDA on three mass variables □[5]□[6]: the aircraft Maximum Take-Off Weight (MTOW), the mission fuel weight, and the reserve fuel weight.

2.2 Optimization Algorithm

The optimal configuration is obtained using an Efficient Global Optimization (EGO) algorithm □[5]□[6]. This choice answers to the following considerations:

- The multidisciplinary process does not provide exact gradient of the objective function regarding the design variables, which excludes a large range of efficient and popular gradient based algorithms.
- Free gradient algorithms such as evolutionary algorithms could be considered but the multidisciplinary process running time is quite slow (from few seconds to 30 seconds, depending on the design point and the fixed point iteration convergence) and thus classic genetic algorithms that need thousands of converged designs would push the computation time to days.

Techniques such as EGO algorithm □[12] are able to manage these issues. The main idea of EGO is to optimize the concept using several Gaussian Processes (GP) surrogate models of the objective function and the constraints. During the optimization, the surrogate models are refined using the MDA in the areas of interest of the search space according to a criterion (Expected Improvement combined with Probability of Feasibility for constraints handling). This allows searching the optimal design using a limited number of multidisciplinary process runs.

3. SMILE Configuration

3.1 Optimization of the SMILE Configuration

The MDAO process presented in section 2 was 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 a BWB configuration for a short-medium range mission [7]. This work resulted in the Small - Medium range Integrated Light and Efficient (SMILE) BWB configuration, illustrated in Figure 2.

Figure 2: 3D view of the SMILE configuration

The SMILE configuration has been optimized considering top-level aircraft requirements derived from the Airbus A320NEO and summarized in Table 1. The design hypothesis consider an entry in service around the 2035 time horizon.

[2] https://web.mit.edu/drela/Public/web/avl/

DOI: 10.13009/EUCASS2022-6061

Table 1: SMILE configuration top-level aircraft requirements

Pax number	150 (economy class) @ 90 kg per pax
Sizing range	5100 km (2750 Nm)
Cruising Mach number	0.78
Top of climb altitude	12192 m (40000 ft)
Climb calibrated airspeed	130 m/s
ICAO Aerodrome Reference Code	ICAO Category C
Engines	2 SMR turbofans 2035, at the rear of the central body

The optimization is performed using the aircraft geometrical variable (chords, thickness ratios, sweep angles, etc.). In order to keep the aircraft overall geometry consistent throughout the design space exploration, the following relations are imposed between the geometrical variables:

- Same value of leading edge sweep angle along the central body and the transition area.
- Leading edge sweep angle of the first section of the external wing equal to the mean value of the central body leading edge sweep angle and the leading edge sweep angle of the second section of the external wing.
- Same value of thickness ratio along the external wing.
- Transition area width fixed to 2.5m.
- Kink of the external wing localized at 1/3.5 of the external wing total span.
- Chord at the kink of the external wing equal to 60% of the external wing root chord.

Considering the geometrical relations described above and using a sensitivity analysis performed on the aircraft geometrical variables [5][6], a total of seven design variables remains for the optimization, as detailed in Table 2.

Table 2: Design variables

Variable	**Variation range**	**Unit**
External wing root chord	[5, 10]	m
External wing taper ratio (2nd section)	[0.1, 0.5]	-
Central body leading edge sweep angle	[40, 60]	deg
External wing leading edge sweep angle (2nd section)	[30, 60]	deg
Central body thickness ratio	[0.14 , 0.19]	-
External wing thickness ratio	[0.08 , 0.15]	-
Main landing gear centre of gravity longitudinal position	[5, 20]	m

As indicated in section 2.2, the optimization is based on the EGO algorithm, using 300 points for the initial design space exploration and allowing the computation of 150 infilled points during the optimization process. The optimization aims at minimizing the fuel weight consumption for the mission and takes into account six constraints to guarantee that the optimal configuration is compliant with operational minimum requirements and aircraft overall consistency, as described hereafter:

- Maximal climb duration of 35 minutes.
- Maximal take-off distance of 2200 m.

DOI: 10.13009/EUCASS2022-6061

- Sufficient length behind the passenger cabin to accommodate the control surfaces.
- Maximum of 5500 tons of fuel to place outside of the external wing, in additional fuel tanks.
- Minimum wing tip of 1.5 m, as a minimum root chord for the winglet.
- Satisfaction of the handling qualities criteria.

Figure 3 illustrates the EGO algorithm iterations process that leads to the optimal solution.

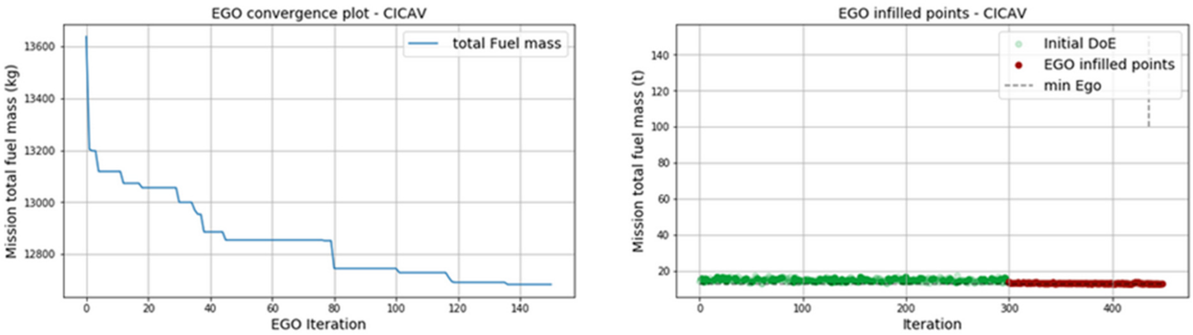

Figure 3: EGO algorithm iterations process

3.2 SMILE Configuration Detailed Results

The optimized SMILE configuration illustrated in Figure 2 is a 36 m wingspan and 19.7 m length aircraft. Table 3 gathers its main geometrical characteristics and Figure 4 illustrate its planform, compared with the Airbus A320neo planform.

Table 3: SMILE configuration geometrical data

	Central body	**Transition area**	**External wing**		
			Root	Kink	Tip
y position	0	5,5 m	8,0 m	10,8 m	18 m
Chord	19,7 m	11,4 m	5,2 m	3,1 m	1,5 m
Leading edge sweep angle	57°	57°	44°	31°	-

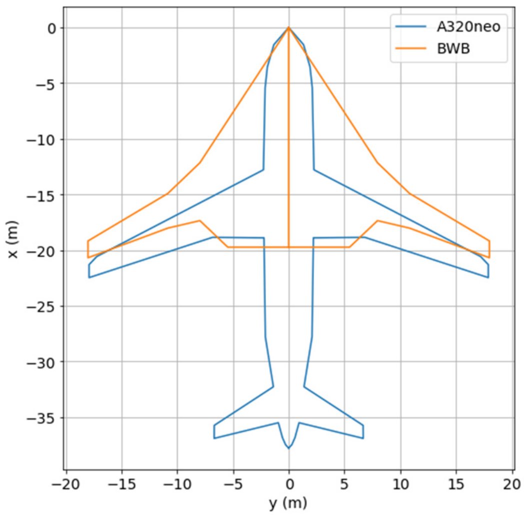

Figure 4: SMILE configuration planform and comparison with the Airbus A320neo (top view)

DOI: 10.13009/EUCASS2022-6061

The SMILE configuration is equipped with two turbofans of the 2035 generation. Those turbofans are modelled from the Central Reference Aircraft data System (CeRAS) model of the International Aero Engine V2527-A5 engine, which equipped the Airbus A320, with a projection of performance improvement at the 2035 horizon (18% reduction of the specific fuel consumption and adaptation of the mass to the current Safran LEAP-1A engine).
Two of this turbofan are localized at the rear of the central 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 modelled in the MDAO process.

The pressurized zone, localized in the central body is composed of the passenger cabin and two side cargo holds, as described in Figure 5. The passenger cabin is divided in two compartments, able to accommodate a total of 150 passengers with a 3-3 seats abreast full economy class configuration. The passenger cabin has four doors of Type I, two front doors are placed behind the cockpit and two rear doors are placed behind the seats rows, passing behind the side cargo holds. Two crossing aisles are placed for accessing the doors and have the galleys and toilets distributed on both sides. The dimensions of each elements of the passenger cabin (cockpit, seats, aisles, galleys, toilets, etc.) and the cargo holds (containers, etc.) are directly inspired by existing aircrafts internal layout [13] and are compliant with the certification specification CS-25, provided by the European Aviation Safety Agency (EASA).

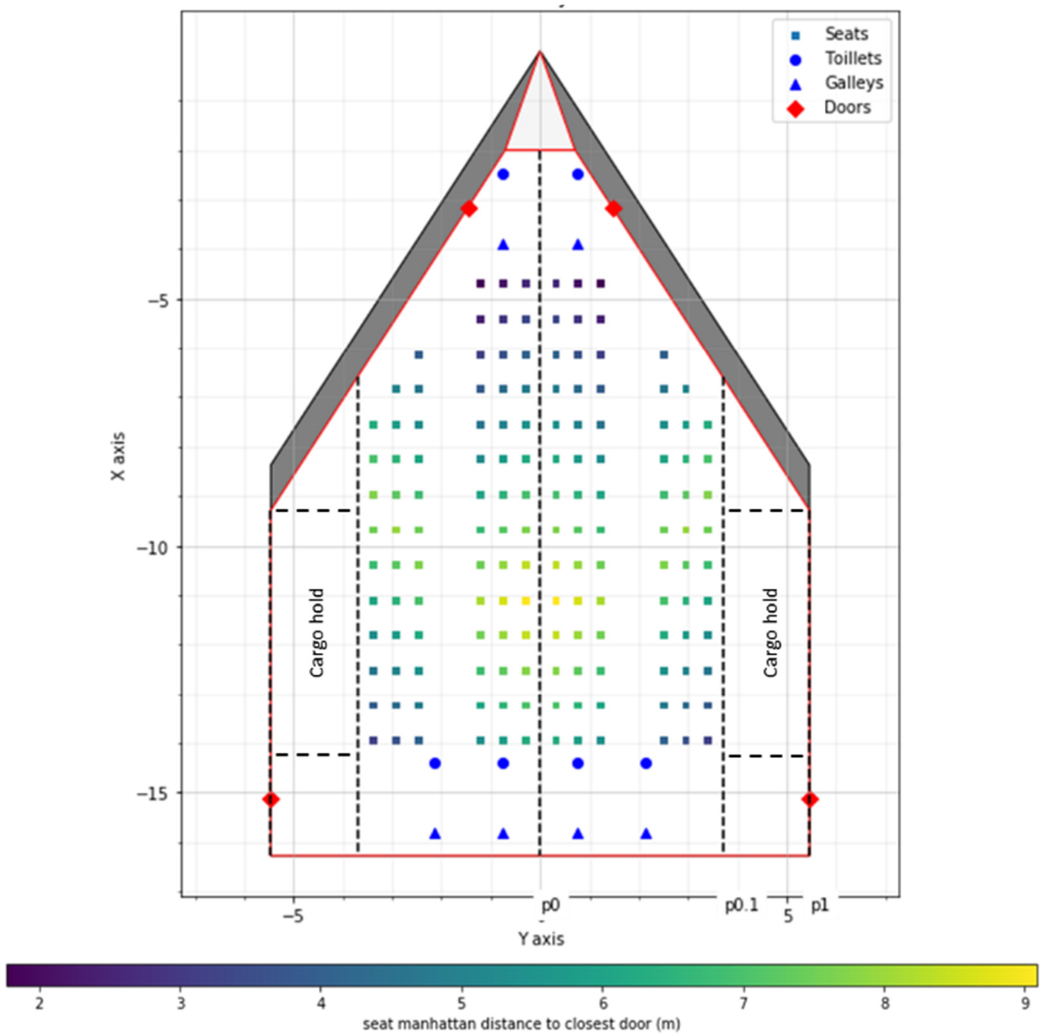

Figure 5: SMILE configuration pressurized part top view

The SMILE configuration has a MTOW of 61.3 tons, divided in 36.0 tons for the operational empty weight, 13.5 tons for the payload weight and 11.8 tons of fuel for achieving its mission (including 2.7 tons as reserve fuel weight), as detailed in Figure 6.

DOI: 10.13009/EUCASS2022-6061

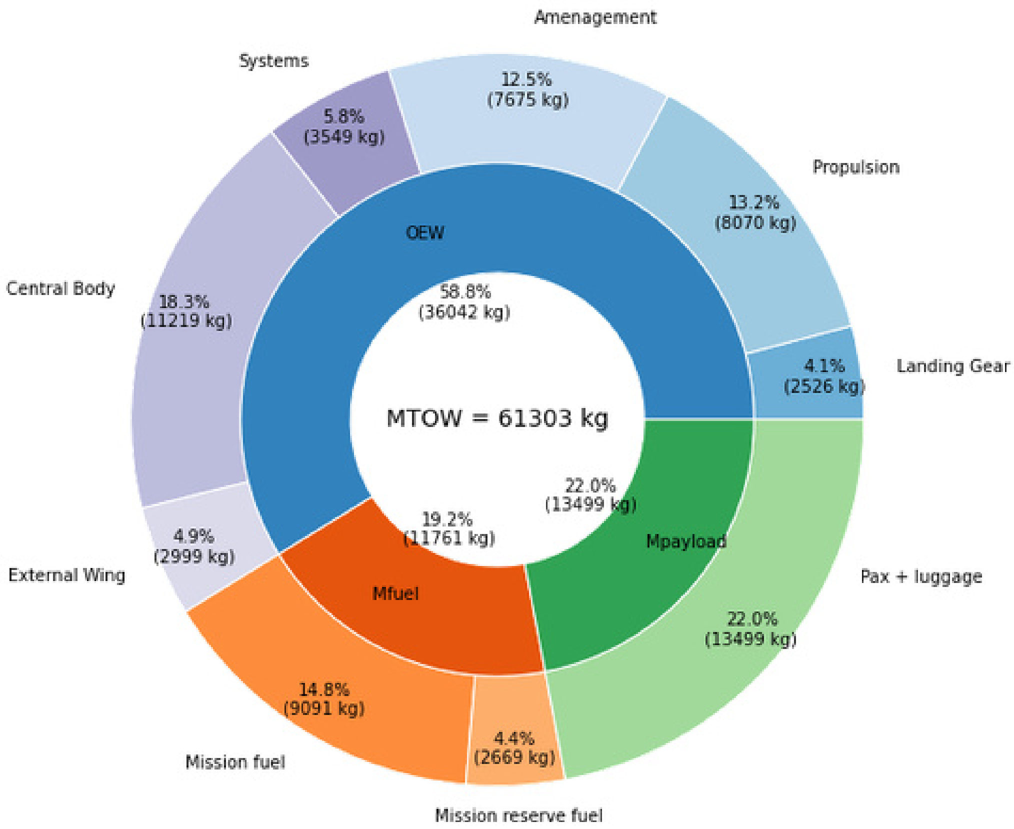

Figure 6: SMILE configuration mass breakdown

The aircraft centre of gravity location for several configurations (passenger cabin and fuel fillings) is illustrated in Figure 7 (left). This diagram highlights that the external wing cannot accommodate the whole fuel requirements and 4.4 tons of fuel have to be located in additional fuel tanks. The solution adopted proposes to place two fuel tanks at the front of the two side holds, as indicated in Figure 7 (right). This location improve the handling qualities characteristics of the aircraft.

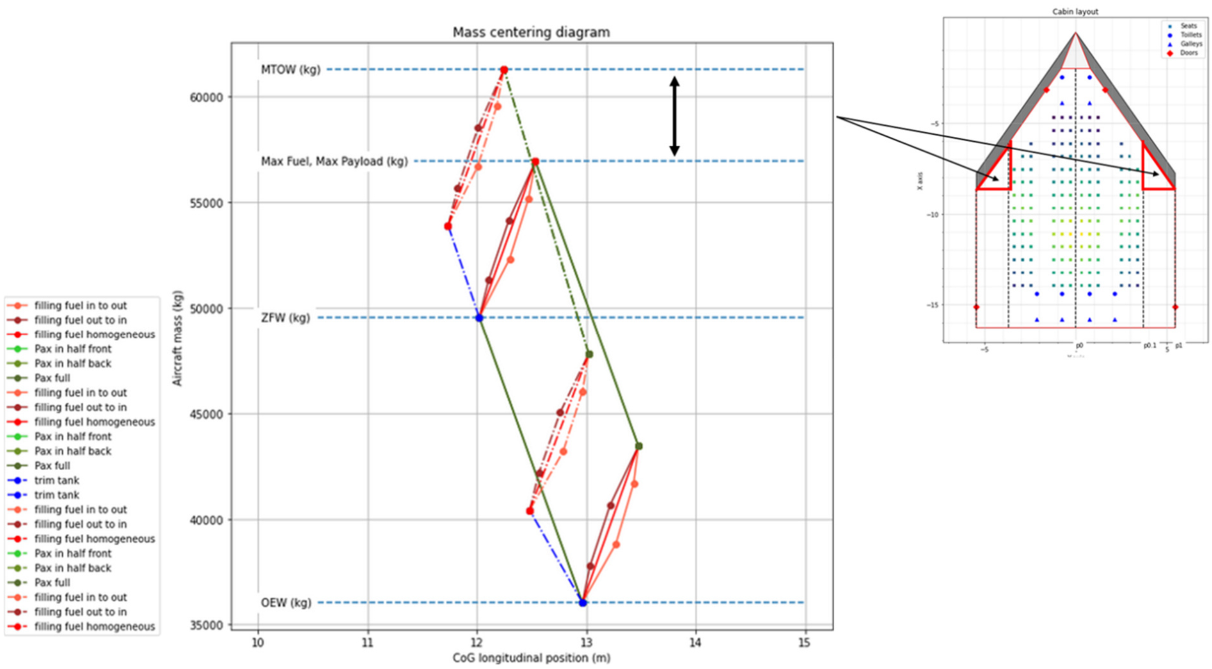

Figure 7: SMILE configuration centre of gravity location (left) and additional fuel tanks (right)

DOI: 10.13009/EUCASS2022-6061

The flight profile for the 5100 km short/medium-range mission is illustrated in Figure 8 and the mission characteristics are gathered in Table 4 (the values indicated for Mach and altitude are those reached at the end of the flight phase). The take-off distance (balanced field length) is assessed to 1899 m and the cruising segment is made at a lift over drag ratio of 20.5, very close to the maximal possible lift over drag ratio value of 20.8 estimated with the Aerodynamic Module.

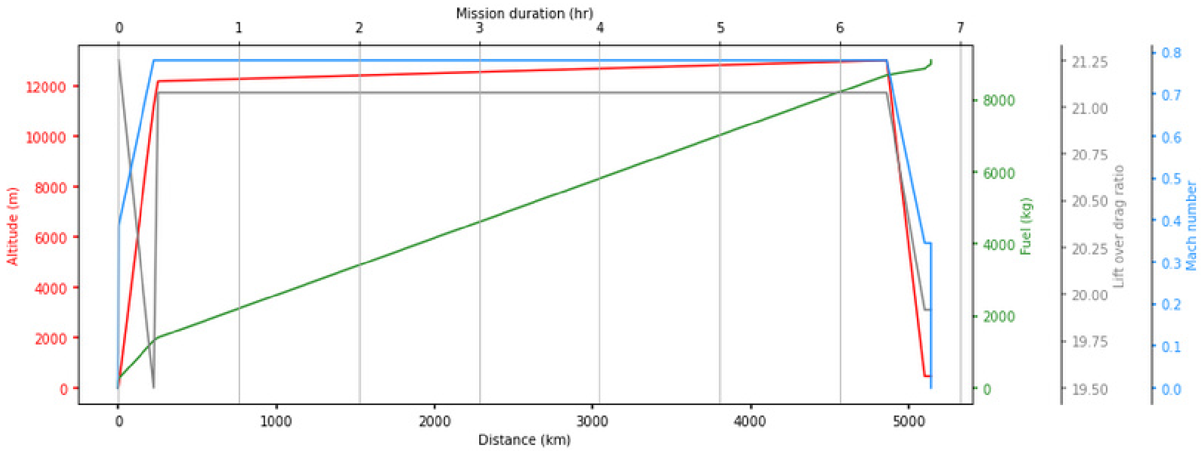

Figure 8: SMILE configuration flight profile

Table 4: SMILE configuration performance characteristics

	Range (km)	Fuel (kg)	Duration (min)	Mach	Altitude (m)
Taxi in	0.000	144.991	9.500	0.000	0.000
Take-off	3.157	113.170	0.682	0.387	101.555
Climb	247.721	1 135.309	23.381	0.780	12192.345
Cruise	4609.559	7291.832	333.785	0.780	13012.148
Descent	239.570	177.347	25.356	0.345	456.813
Approach	42.047	123.500	6.000	0.345	456.813
Taxi out	0.000	105.400	7.000	0.000	456.813
TOTAL MISSION	**5100.007**	**9091.547**	**405.704**		
Continued Cruise	507.306	749.464	36.735	0.780	13103.141
Overshoot	0.000	206.529	0.000	0.000	13103.141
Climb	69.736	363.71	9.125	0.490	4001.610
Cruise	231.438	570.281	24.246	0.490	4086.028
Descent	69.255	75.230	7.944	0.395	456.516
Hold	240.672	704.382	30.000	0.395	456.516
TOTAL RESERVES		**2669.595**			

DOI: 10.13009/EUCASS2022-6061

Finally, the SMILE configuration is compliant with the longitudinal handling qualities criteria integrated in the process and evaluated by the Handling Quality Module:

- Maximal and minimal loading of the nose landing gear compliant with the typical requirements.
- Ability to balance the aircraft in glide configuration.
- Ability to perform the take-off rotation.
- Stability at the manoeuvre point.

4. Integration of Distributed Electric Propulsion

4.1 Short Overview of the IMOTHEP Project

IMOTHEP is a Horizon 2020 European project, which stands for « Investigation and Maturation Of Technologies for Hybrid Electric Propulsion ». The main objective of the IMOTHEP project is to significantly improve the estimation of the potential offered by hybrid electric propulsion in order to reduce the fuel consumption and CO_2 emissions of civilian transport aircraft.
Four hybrid aircraft configurations are studied and compared to a reference turbofan aircraft representative of actual technology levels and a baseline aircraft representative of technology levels for Entry Into Service (EIS) 2035. They are distinguished between their target mission (REGional or SMR) and their level of disruption (CONventional or RADical). Figure 9 gives a notional view of these concepts, together with the partner responsible for their Overall Aircraft Design (OAD) integration.

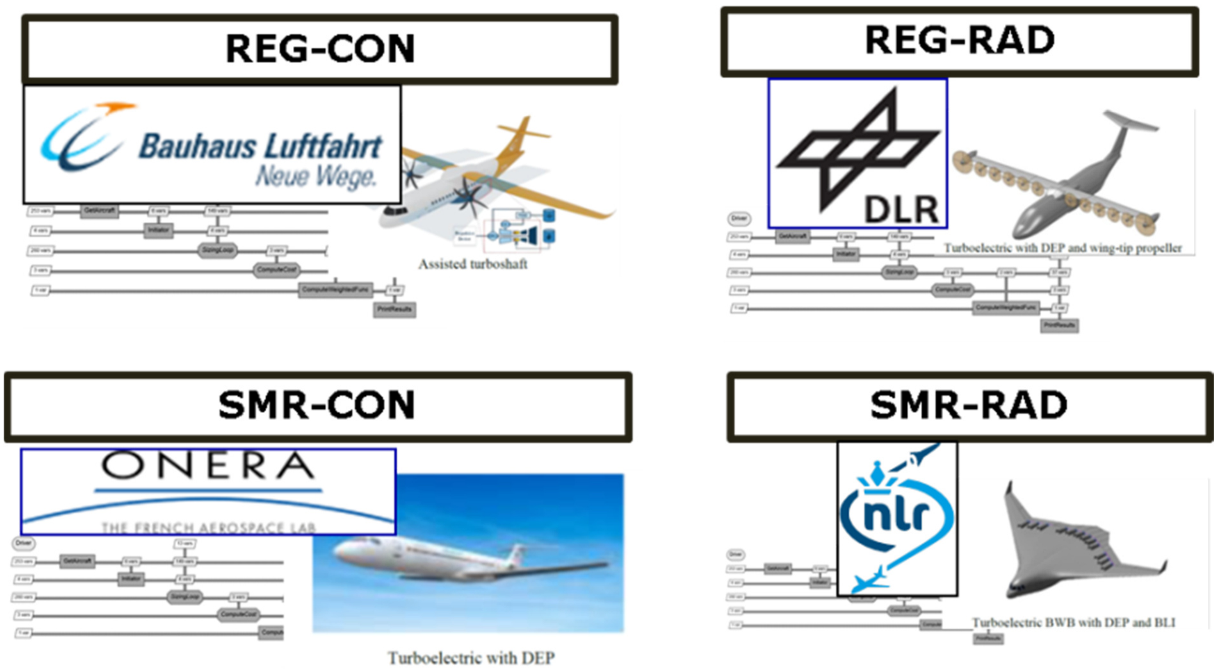

Figure 9: IMOTHEP project target configurations

IMOTHEP project is organized around three pillars: hybrid electric propulsion components (batteries, generators, e-motors, electrical power unit, cables, etc.), electric-enabled aero-propulsive integrations (Distributed Electric Propulsion (DEP), Boundary Layer Ingestion (BLI)), and aircraft integration. The convergence process is organized in three design loops as illustrated in Figure 10.

DOI: 10.13009/EUCASS2022-6061

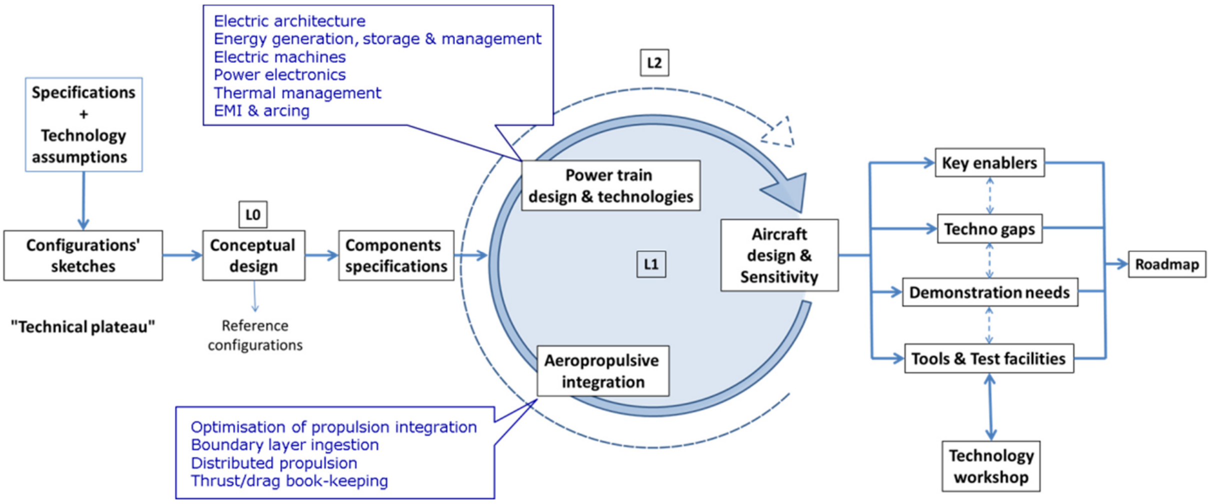

Figure 10: IMOTHEP project design logic

4.2 Towards a SMILE-based Radical Hybrid Concept for SMR Missions

The goal of the SMR-RAD concept introduced above is to demonstrate the potential of the BWB configuration to accommodate a distributed architecture with multiple electric fans, enabled by hybrid electric propulsion chains. The distributed architecture will in particular enable to ingest a large part of the aircraft boundary layer, improving the power efficiency of the propulsive system, at the cost of a distorted flow that can lead to fan losses. Therefore, a well-defined aeroshape is mandatory to be able to perform high fidelity computation (using CFD) and get an accurate estimate of the aeropropulsive performances (especially the Power Saving Coefficient □[14]).

To this end, ONERA decided to share the SMILE aeroshape with the IMOTHEP partners as a well-defined, OAD-converged aircraft suitable for CFD computations. Under the lead of NLR, partners are working on the refinement of the propulsion layout, and ONERA will be in particular in charge of the final CFD assessment of the aero-propulsive performances. Figure 11 illustrates on-going studies on this concept with associated partners [15][16].

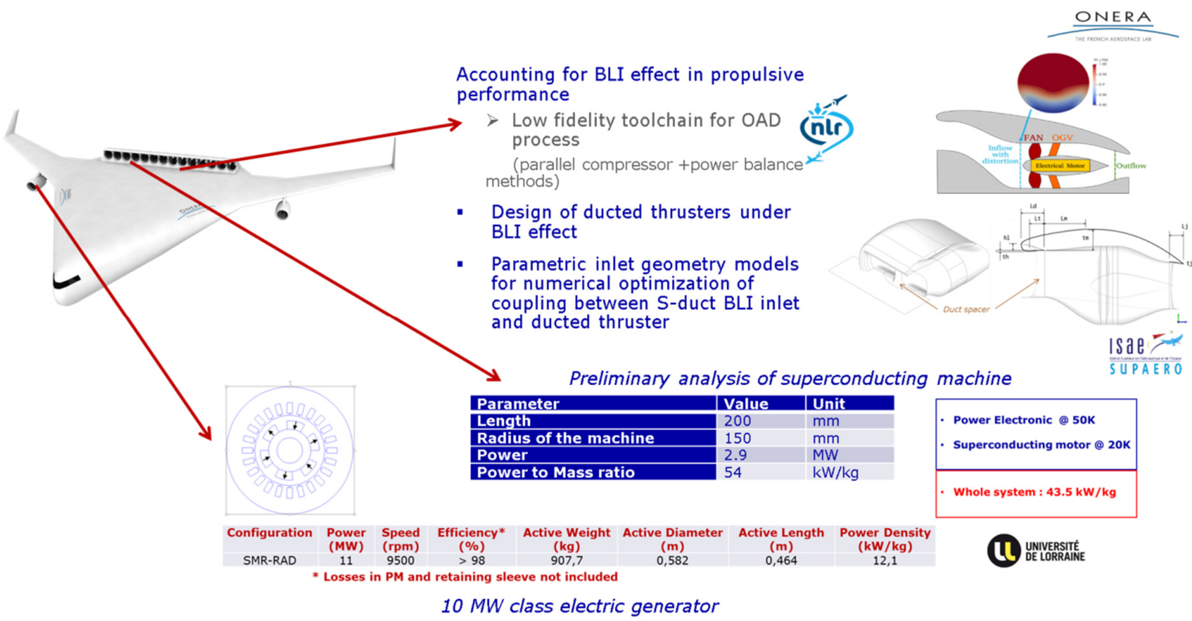

Figure 11: Works scheduled on the SMR-RAD concept using the SMILE airframe

Following this iteration on the propulsive system layout, an update of the multidisciplinary design of the SMILE configuration and aeroshape could be performed to tailor it to the needs of DEP with BLI.

DOI: 10.13009/EUCASS2022-6061

5. Conclusion and Perspectives

The MDAO process developed by ONERA for Blended Wing Body configurations has been used to propose the SMILE configuration as a possible substitute of the Airbus A320NEO aircraft in the next years. The SMILE configuration offers an operational empty weight reduction of 17% compared with the A320NEO and of 11% compared with the projection of what could be the A320NEO's successor in 2035 (considering the same hypothesis for the turbofan performances in 2035). In terms of fuel burn, the reduction is assessed at 35% compared with the A320NEO and 15% compared with the A320NEO's successor in 2035. This highlights the very high potential of the Blended Wing Body configuration.

Those improvements consider typical turbofans engines, but they could significantly increase with the use of new propulsion architectures, which become possible thanks to the Blended Wing Body configuration specific shape. Among the possible interesting solutions, Distributed Electric Propulsion (DEP) architectures are studied in the frame of the European H2020 IMOTHEP project and the SMILE configuration is used as a baseline for quantifying the possible gains and evaluating the technical difficulties associated to the integration of such propulsion architecture with an overall airframe.

Acknowledgements

The MDAO process presented in this paper was developed in the internal research project CICAV funded by ONERA from 2015 to 2019. This project involved 4 of the 7 ONERA scientific departments.

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.

The IMOTHEP project has received funding from the European Union Horizon 2020 research and innovation program under grant agreement No 875006 IMOTHEP. The authors thank the partners of this project for the fruitful collaboration (especially NLR, ISAE-Supaero and Safran Aircraft Engines).

References

[1] Liebeck, R. H. 2004. Design of the Blended Wing Body Subsonic Transport. *Journal of Aircraft*. Vol. 41, No 1, p. 10-25.
[2] Nickol, C. 2012. Hybrid Wing Body Configuration Scaling Study. In: *50th AIAA Aerospace Sciences Meeting including the New Horizons Forum and Aerospace Exposition*.
[3] Gauvrit-Ledogar, J., Defoort, S., Tremolet, A., and Morel, F. 2018. Multidisciplinary Overall Aircraft Design Process Dedicated to Blended Wing Body Configurations. In: *2018 Aviation Technology, Integration, and Operations Conference*.
[4] Gauvrit-Ledogar, J. 2018. Aile Volante. *Lettre 3AF*. No 32, p 22-29.
[5] Tremolet, A., Gauvrit-Ledogar, J., Brevault, L., Defoort, S. and Morel, F. 2019. Multidisciplinary Overall Aircraft Design and Optimisation of Blended Wing Body Configurations. In: *2019 European Conference for Aeronautics and Space Sciences*.
[6] Gauvrit-Ledogar, J., Tremolet, A., and Brevault, L. 2020. Blended Wing Body Design. *Aerospace System Analysis and Optimization in Uncertainty*. Springer, Cham, p. 385-419.
[7] Iwanizki, M., Wöhler, S., Froehler, B., Zill, T., Méheut, M., Defoort, S., Carini, M., Gauvrit-Ledogar, J., Liaboeuf, R., Tremolet, A., Paluch, B. 2020. Conceptual Design Studies of Unconventional Configurations. In: *3AF Aerospace Europe Conference 2020*.
[8] Gray, J., Moore, K. and Naylor, B. 2011. OpenMDAO: An Open Source Framework for Multidisciplinary Analysis and Optimization. In: *13th AIAA/ISSMO Multidisciplinary Analysis Optimization Conference*.
[9] Lambe, A. and Martins, J. 2011. A Unified Description of MDO Architectures. In: *9th World Congress on Structural and Multidisciplinary Optimization*.
[10] Lafage, R., Defoort, S., Lefèbvre, T. 2019. WhatsOpt: A Web Application for Multidisciplinary Design Analysis and Optimization. In: *AIAA Aviation 2019 Forum*.
[11] Moens F. 2022. A L0 Aerodynamic Model for Aircraft Multidisciplinary Design and Optimization Process. In: *56th 3AF International Conference on Applied Aerodynamics*.

DOI: 10.13009/EUCASS2022-6061

[12] Jones, D. R., Schonlau, M. and Welch, W. J. 1998. Efficient Global Optimization of Expensive Black-Box Functions. *Journal of Global Optimization*. Vol. 13, No 4, p. 455-492.
[13] Airbus. A320/A320NEO Aircraft Characteristics Airport and Maintenance Planning. Rev May 01/14.
[14] Atinault O., Meheut M., Defoort S. 2022. A Mixed Fidelity Conceptual Design Process for Boundary Layer Ingestion Concepts. In: *ECCOMAS Congress 2022*.
[15] Novelli, P., Defoort, S., Tantot, N., Zimmer, D., Lopez, J., Biaujaud, R., Lochot, C., Troiano, G. 2021. IMOTHEP: towards hybrid propulsion for commercial aviation: Project Overview & First Results. In: *3AF More Electric Aircraft 2021*.
[16] Vankan, W. J., Lammen, W. F., Defoort, S. 2022. Conceptual design study for a radical short-medium range hybrid aircraft. In: *EUCASS 3AF 2022*.