Model Based Collaborative Design & Optimization of Blended Wing Body Aircraft Configuration : AGILE EU Project

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Novel configuration design choices may help achieve revolutionary goals for reducing fuel burn, emission and noise, set by Flightpath 2050. One such advance configuration is a blended wing body. Due to multi-diciplinary nature of the configuration, several partners with disciplinary expertise collaborate in a Model driven 'AGILE MDAO framework' to design and evaluate the novel configuration. The objective of this research are :

- **To create and test a model based collaborative framework using AGILE Paradigm for novel configuration design & optimization, involving large multinational team. Reduce setup time for complex MDO problem.**
- **Through Multi fidelity design space exploration, evaluate aerodynamic performance**
- **The BWB disciplinary analysis models such as aerodynamics, propulsion, onboard systems, S&C were integrated and intermediate results are published in this report.**

Nomenclature

AGILE = **A**ircraft 3rd **G**eneration MDO for **I**nnovative Col**l**aboration of Heterogeneous Teams of **E**xperts
MDO = Multi Disciplianry Optimization
CPACS = Common Parametric Aircraft Configuration Scheme
BWB = Blended Wing Body
KA = Knowledge Architecture
CA = Collaborative Architecture
CMDOWS = Common Multidisciplinary Design Optimization Workflow Schema

Figure 1. BWB Deisgn Concepts for AGILE EU Project

Agile Paradigm is used for BWB design. The Design approach is stated as below using a Model Based Agile Framework and Central Data model CPACS:

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1) Design space exploration of BWB shape and sizing using low-medium & Hi fidelity Aerodynamic analysis.
2) Engine cycle design for the desired thrust and mission performance, while considering subsystem offtake, noise & emission constraints
3) Aircraft subsystem design and analysis for Novel configuration, to derive subsystem weight and power offtakes from Engines and its impact on aircraft performance
4) Engine location, Integrated BLI and Nacelle system design and analysis for BWB configuration
5) Flight dynamics and handling analysis for BWB configuration through control surface sizing
6) Finally, Mission simulation for evaluating fuel burn considering mission parameters

I. Model Based Collaborative MDO framework

A. AGILE Paradigm

A collaborative framework to solve complex aeronautics problem is created during AGILE EU Project 2015-2018. In order to enable and to accelerate the deployment of model based collaborative, large scale design and optimization activity, the “AGILE Paradigm” [1] , a novel methodology, has been formulated during the project.The goal of the method is to reduce the MDO setup time and being in more knowledge to earlier stages of the design [Figure 2]. The main elements composing the AGILE Paradigm [Figure 3] are the Knowledge Architecture (KA) [2], and the Collaborative Architecture (CA) [3] which accelerate the deployment of complex MDO problems. The current paper is focused on the application of using the AGILE Paradigm to solve design of novel aircraft configuration to meet the future environment goals. The first phase of the project involved, creation of the model based collaborative MDO approach and Second phase involved evaluating different collaborative and MDO approach for conventional configuration and Third phase is to expand the approach for novel configurations. In this collaborative framework, the disciplinary analysis modules from multiple organizations, involved in the optimization are integrated within a distributed framework through a Model based approach. The disciplinary analysis tools are not shared, but only product and process data are distributed among partners through a secured network of framework. The interaction of multiple distributed disciplinary analysis is handled via CPACS [4] and CMDOWS [5] data standards.

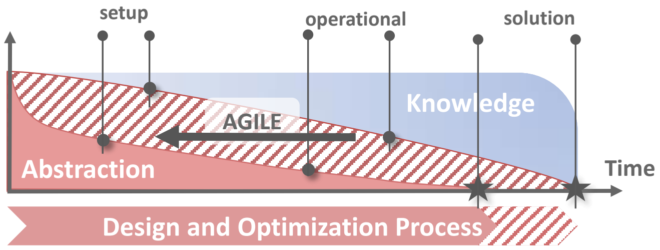


Figure 2. 3rd Generation MDO Pardigm Shift

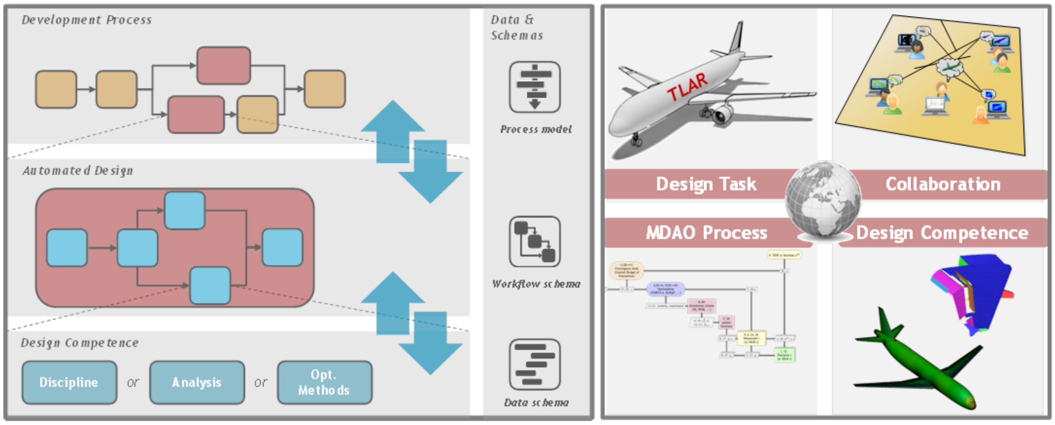


Figure 3: AGILE paradigm framework: Model based design enabler

B. Inter-Disciplinary Central Data Model or Communication Standard

For large scale distributed multidisciplinary optimization problems involving several partners, one fundamental requirement is to be able to efficiently communicate across organizations, exchange data between the individual disciplinary analysis tools and design modules, by making use of a common language as described by Nagel et al[6]. Common Parametric Aircraft Configuration Scheme (CPACS) is used for interdisciplinary exchange of aircraft data between heterogeneous analysis codes. The CPACS data schema contains standard structure of information on the aircraft model such as geometry description, airframe design masses, performance requirements, aerodynamic polar, structural details, engine parameters, mass properties, subsystem architecture details, and process data to control parts of a design process, which is necessary to initialize and trigger the disciplinary analysis modules. Figure 4 shows the concept of CPACS interface between various tools for this research.

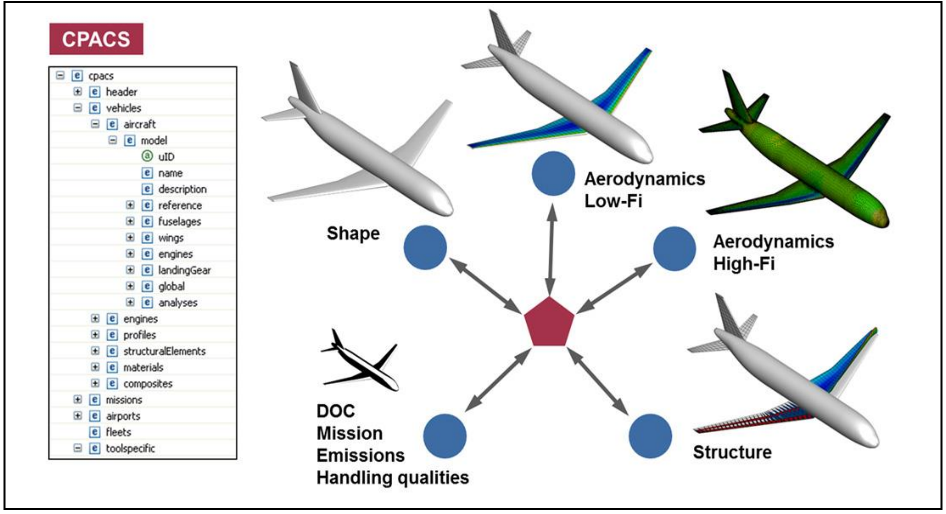


Figure 4. Centralized CPACS data structure for Multi-Disciplinary Framework

II. Disciplinary analysis models and Organizations involved

Several Analysis (Competency) modules/models from multiple organization, geographically distributed, is involved for BWB design and optimization. Each organization with their competency uses one central CPACS data model containing Process and product data [Figure 4, Figure 7]. The competency model uses the information for the disciplinary analysis and uploads the results, which is further used by other organizations for their analysis. Thereby, no sharing of analysis codes but only results which the analysis specialist choose to share. The Disiplinary analysis modules and organizations are listed below

1) Design Synthesis : VampZERO from DLR, To initialize a design from TLAR provided in Table 1
2) Aerodynamics :
    i. Preliminary Hi-Fi CFD analysis and Lo-Fi Aerodynamic Design space exploration: UNINA
    ii. Hi Fi Full configuration CFD : TsAGI, CFSE, Airinova and UNINA
    iii. Local Aerodynamics for BLI and propulsion system integration: TsAGI (Not covered in this paper)

NOTE : 1 and 2 modules are used for Initial Design space Exploration Loop

3) Aircraft On Board Systems Design : Politecnico di Torino, To explore the OnBoard subsystem design architecture
4) Propulsion system design for BWB : CIAM, Evaluate, siye and match the Engine and airframe for the configuration
5) Propulsion System-Airframe Aerodynamic Integration : TsAGI, Aerodynamic optimization of Nacelle and Aerodynamic integration of Airframe- Propulsion is carried out in this Analysis Module
6) Mission Performance : DLR, Mission simulation considering Drag and Mass esitimation to evaluate fuel consumption
7) Flight Dynamics and Handling : TU Delft, Airframe is evaluated for stability and better handeling qualities.

Table 1: TLAR for BWB Design Studies

Category	*Name*	*Unit*	*Description*	*Cond*	*BWB*
Payload, range	#Pax	[-]	number of passengers	=	450
	$m_{payload\ max}$	[t]	maximum payload	=	59
	range	[nm]	maximum range @ $m_{payload\ max}$	>	8500
	m_{cargo}	[t]	amount of cargo	=	5
performance targets	M	[-]	Mach number in cruise at ICA	=	0.85
	H_{max}	[ft]	maximum operating altitude	>	43000
	V_{appr}	[kts]	approach speed (@MLW, SL, ISA)	<	166
airport compatibility	b	[m]	maximum wing span	<	80
	TOFL	[m]	take-off field length (@MTOW, SL, ISA + 15deg)	<	2950

III. Design and Optimization Workflow Formulation

From the individual modules , the Design Space Exploration and MDO is formulated as shown below [Figure 5] to evaluate the BWB aircraft for minimum fuel burn and technology integration on optimum configuration.

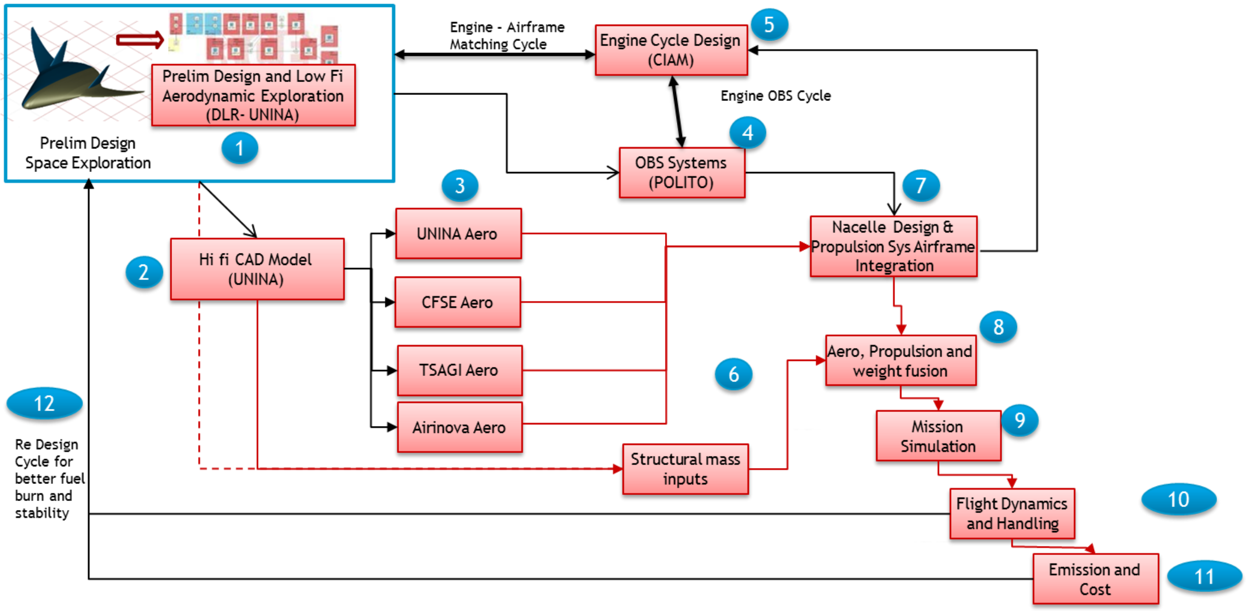


Figure 5: BWB MDAO workflow formulation

The Design Structure Matrix shows the disciplinary interrelations and AGILE Framework provides suitable IT frontend to modify the formulation based on the analysis module requirement and MDO objective.

The corresponding formulation in AGILE Framework is shown below in [Figure 6]

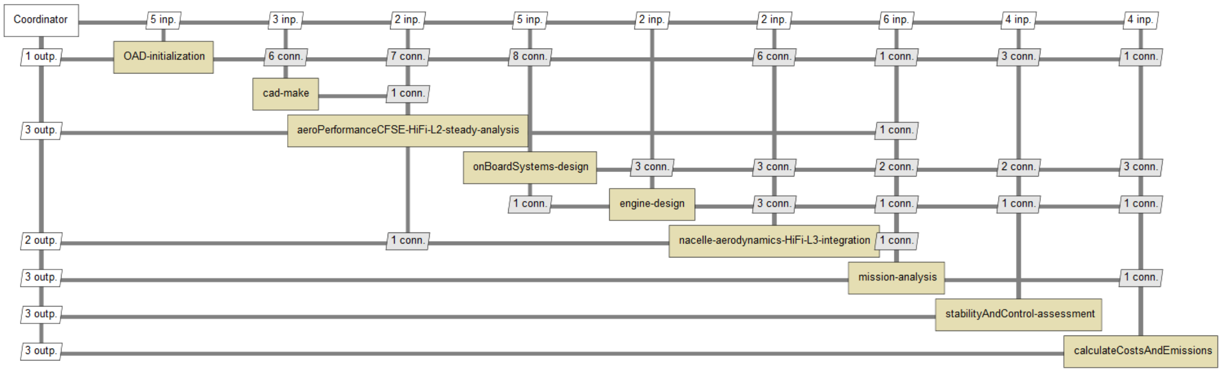


Figure 6: BWB Design Structure Matrix in AGILE Framework

IV. Disciplinary Analysis Model Details and Results

The Disciplinary analysis model communicates using Standard CPACS data model. Each model reads the input from the central data model and writes output in the same central mdoel according to CPACS schema (www.cpacs.de). The AGILE framework uses KE Chain , KADMOS , CMDOWS and VISTOMS for model based approach. The details of these enablers are in papers V Gent et al [5]

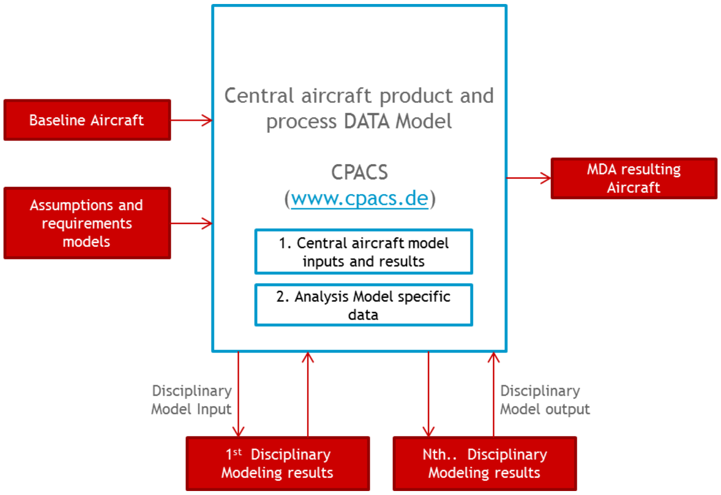


Figure 7: Model Based Approach for Data Handling : Central Data Model

Each Disciplinary analysis methods and results are discussed in the following section.

C. Aerodynamics Modelling

1. Low Fidelity Aerodynamic Design Space Exploration (University of Naples, UNINA)

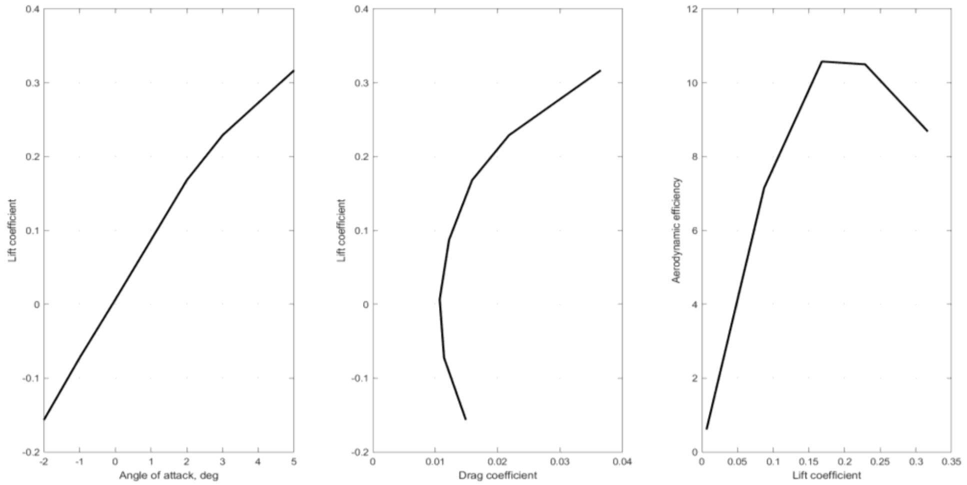
Among the BWB TLAR, the 0.85 cruise Mach number and the 150 kts approach calibrated airspeed, with a max take-off mass (MTOM) of over 435 tons, lead to a cruise lift coefficient C_L between 0.35 and 0.40 and a maximum lift coefficient $C_{L\max}$ of 1.55, as reported in Table 2. The aerodynamic efficiency, evaluated with the lift-to-drag ratio, is expected to be between 21 and 24 for a BWB [7]. The tailless configuration also poses severe limitations to the wing pitching moment, unless artificial stability augmentation is adopted, if it is acceptable to fly with a naturally unstable aircraft. To allow for payload allocation and passengers comfort, the thickness ratio of the inner sections should be about 17% and the cabin deck angle should be within 3°. Thus, the aircraft configuration, its MTOM, and the high-speed cruise require a careful selection of the airfoil and wing planform parameters such as thickness ratio distribution, twist angle distribution, and sweep angle. The assigned approach speed also requires a high lift system that must not deteriorate stability, control, and cruise performance.

Aerodynamic data of the baseline geometry were calculated with both Lo-Fi (NASA Blackwell method [8], implemented in the JPAD software developed at UniNa [9] [10] [11] [12]) and Hi-Fi tools (CFD Eulerian and RANS simulations). The software STAR-CCM+ has been used to perform CFD analyses. RANS simulations have been run with steady, compressible, fully-turbulent flow. The applied turbulence model is the Spalart-Allmaras one-equation model [13]. The mesh is made up of more than 5 million polyhedral cells with 20 layers of prismatic cells extruded from the wing walls to account for the boundary layer. Prism layer distribution and thickness are such to achieve a unit value of the characteristic distance y^+ at the Reynolds number (referred to the mac) Re = 1.67×10^8. Numerical, high-fidelity, aerodynamic design, analysis, and optimization for a variety of aircraft categories have been performed in recent years by the DAF research group (www.daf.unina.it) [14 15 16 17 18 19 20 21 22], giving confidence in CFD RANS results that often have been verified in wind tunnel tests and integrated in aircraft preliminary design methods and software [23 24 25].

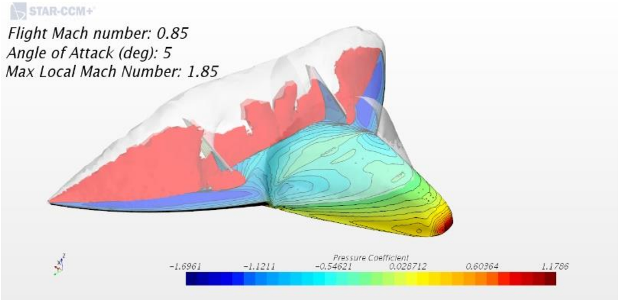
Preliminary Eulerian analyses on the BWB baseline showed a low aerodynamic efficiency in cruise conditions (M = 0.85, C_L = 0.30), mainly due to a shock wave. This was confirmed by RANS simulations (Figure 8). The aerodynamic coefficients are referred to the planform area of 900 m^2. The wing zero-lift coefficient is very close to the zero angle of attack because of the low cambered wing profiles and twist distribution. Such combination of airfoil shape and twist requires more than 5° angle of attack to provide the desired cruise lift coefficient. In this attitude, adverse pressure gradients determine a rapid compression of the flow and the generation of a strong shock wave, causing flow separation and the loss of the aerodynamic efficiency, as visible in the pressure and skin friction coefficients contours of Figure 9. The main cause of the shock wave is the airfoil shape, with a max thickness ratio $t/c \approx 17\%$ at wing root, shown in Figure 10, which is not suitable for the required high-speed cruise. A further analysis at M = 0.78 also highlighted the interference effect of the vertical tail, which was hidden by the shock wave at M = 0.85. By removing the vertical tail, the aerodynamic efficiency increased by more than 10%. It was clear that the provided baseline geometry was simply unfit for the mission.

Table 2: Top level aircraft requirements related to aerodynamics.

Parameter	***Symbol***	***Value***	***Unit / Note***
Max take-off mass	MTOM	435617	Kg
Max take-off weight	W	4273403	N
Mach number	M	0.85	
Reynolds number	Re (mac)	1.67×10^8	
Cruise altitude	h	43000	ft
Wing area	S	900	m^2
Cruise lift coefficient	C_L	0.35	90% W
Calibrated approach speed	V_a (CAS)	150	kts
Max lift coefficient	$C_{L\max}$	1.55	trimmed
Note: The MTOM assumed for aero analysis was evaluated using predesign method and updated later.			



a) Lift curve. *b) Drag polar.* *c) Aerodynamic efficiency.*



d) Pressure coefficient contour and shock wave visualization.

Figure 8. Preliminary CFD RANS results on BWB baseline, M = 0.85, Re = 1.67 × 10^8.

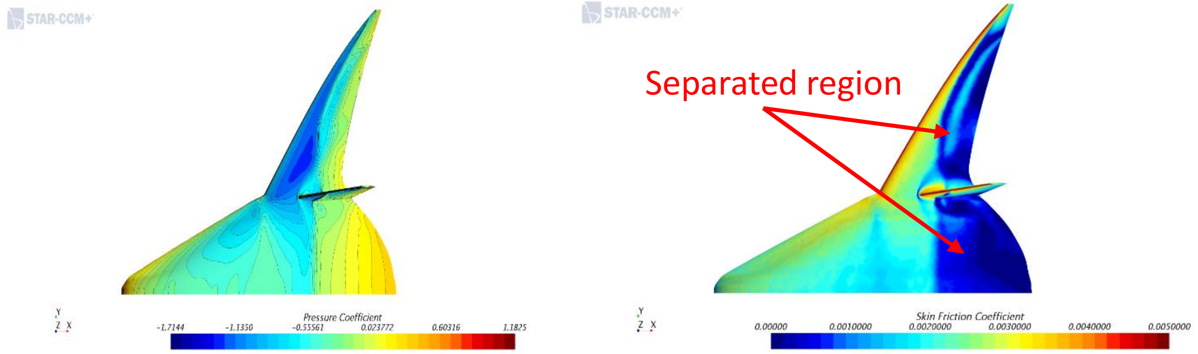


Figure 9. Pressure coefficients and skin friction coefficients contours in cruise condition at AoA = 5°, M = 0.85, Re = 1.67 × 10^8.

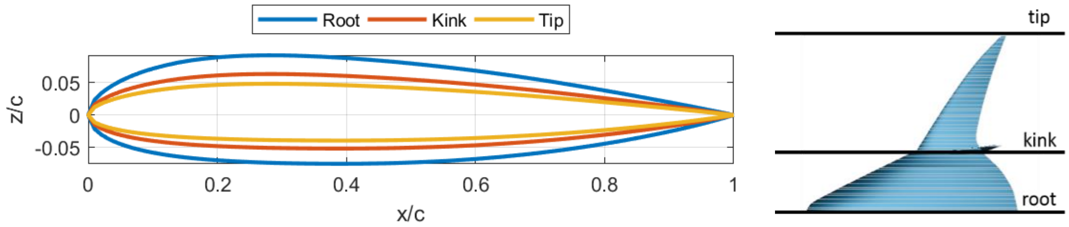
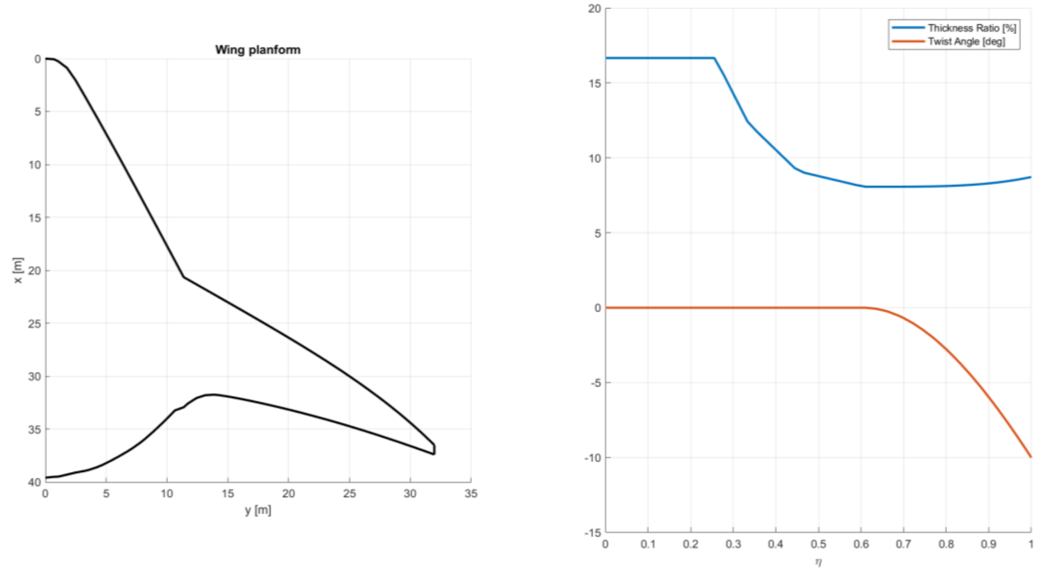
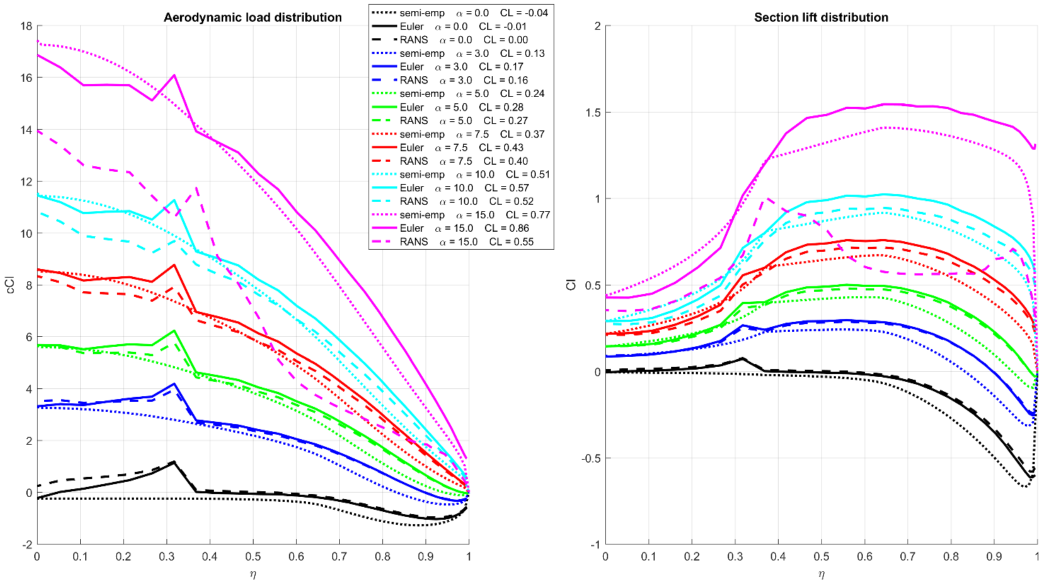


Figure 10. The baseline characteristic airfoils.

Thus, it was decided to provide a new baseline before attempting any MDO process on the BWB. The main target was to get a max aerodynamic efficiency $E_{\max} > 20$, whereas longitudinal and lateral-directional stability will be dealt at a later stage. To get reliable data in a short amount of time, the UNINA WingAnalysis package of the JPAD software has been called in a MATLAB program to provide a design tool that later was integrated with movable surfaces analysis for high lift, longitudinal stability, and control, a simplified planform generator, and a Design of Experiments (DoE) environment. Airfoil data is taken from an experimental database written in hierarchical data format (HDF) files to get reliable results, especially in stall condition, and to ease the work of the designer when only the airfoil family and its thickness ratio are of interest. The program is fully compatible with the CPACS standard. The aerodynamic executable is a Lo-Fi tool based on the paper of Blackwell [2], which has shown to agree with CFD RANS results in attached flow conditions. Figure 11 shows the wing load and lift coefficient distribution on the original baseline planform. Discrepancies at a station close to the 30% wing span are due to the aerodynamic interference of the vertical tail, which is not present in the Lo-Fi code. The close agreement between results of Lo-Fi and Hi-Fi tools gave confidence in using the former to provide indications in the selection of a new baseline planform.



a) Baseline planform. *b) Thickness ratio and twist angle distribution.*



c) Wing load distribution. *d) Lift coefficient distribution.*

Figure 11. Comparison between Lo-Fi and Hi-Fi aerodynamic tools. Low speed condition (M = 0.20).

The selection of the new BWB baseline has been divided in two steps. The first step consisted in the selection of a suitable airfoil class and its application on the original baseline planform. Supercritical airfoils have been chosen for the scope. The new profiles have been obtained by scaling the NASA SC(2)-0414 airfoil, shown in Figure 12. The second step is related to the variation of the planform parameters such as thickness and twist angle distributions. Since the baseline planform is made up of 55 profiles, to easily manage airfoil and planform modification, an initial simplified geometry has been generated with 4 supercritical airfoils, with small variations in their thickness ratio and twist angle distribution (Figure 13). Results of the WingAnalysis aerodynamic code are reported in Figure 14, where the 2D airfoil low-speed input data were provided with Xfoil, except for the $C_{l\max}$, which was taken from the HDF experimental database. The combination of airfoil shape and planform parameters resulted in the achievement of the desired wing cruise lift coefficient at a very low angle of attack and a high aerodynamic efficiency due to the strong reduction of the wave drag.

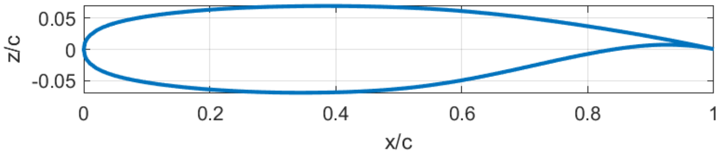


Figure 12. The NASA SC(2)-0414 airfoil used as reference wing section for the new wing profiles.

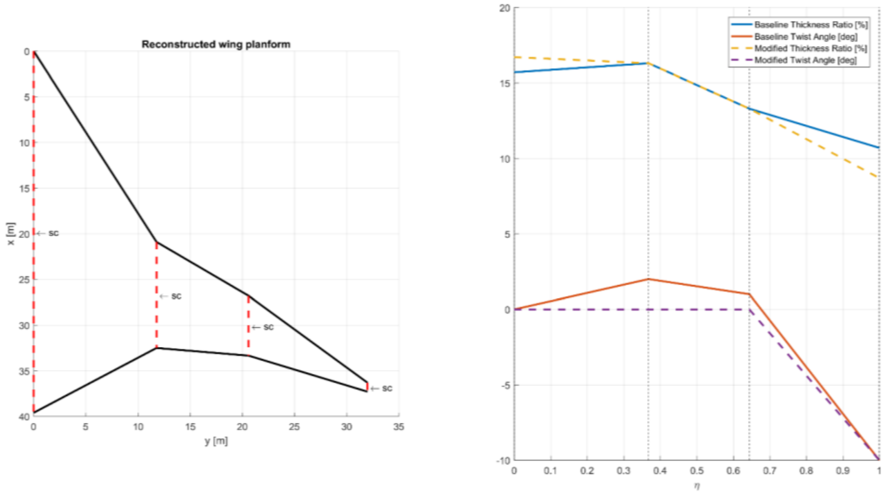
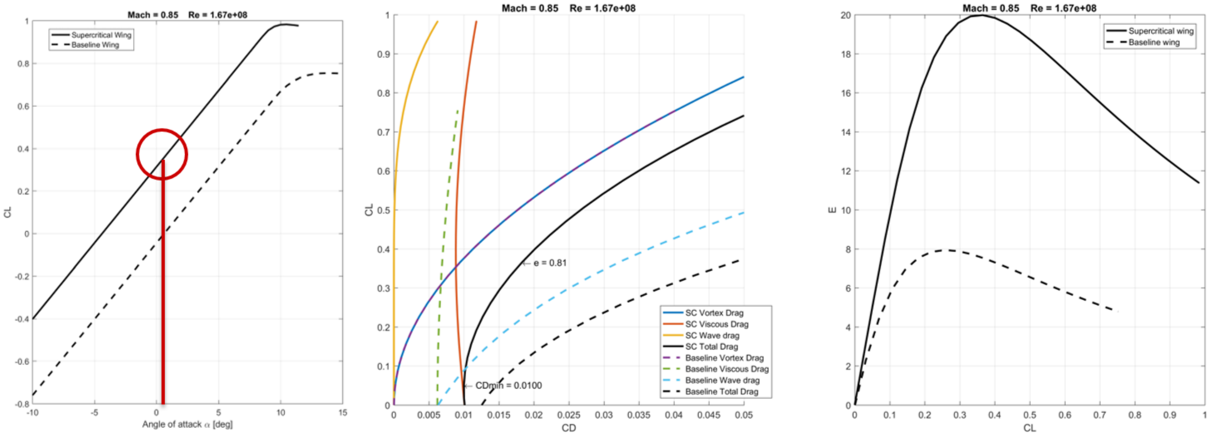


Figure 13. A simplified BWB planform with a comparison of the thickness ratio and twist angle distribution between versions.



a) Lift curves. *b) Drag polars.* *c) Aerodynamic efficiency.*

Figure 14. Comparison of the aerodynamic curves between the original and modified planform. Results of the WingAnalysis Java program based on the method of Ref. [2].

Once demonstrated the capabilities of our aerodynamic tools, it was decided to perform a DoE to investigate numerous planforms and choose the new baseline with more confidence. The objective of the DoE is to provide the best combination of aerodynamic efficiency, untrimmed $C_{L\max}$, and an inner wing stall to avoid the pitch-up phenomenon typical of aft swept wings. The design space includes variations of planform area, wing span, outer wing sweep angle, twist angle, and thickness ratio, whereas the profiles have been fixed. The DoE matrix is shown in Table 3 and it provides 576 combinations. At the end of the process, 10 geometries, representative of DoE points of interest, have been transformed in CAD files for high fidelity analyses and passed to the other aerodynamics partners to perform CFD RANS simulations. The best of these 10 Hi-Fi geometries is taken as a new baseline for all the partners.

Table 3. DoE matrix.

	Area	***Span***	***Sweep angle (outer wing)***	***Combinations***
	Baseline, +15%	Baseline, 80m	−10% baseline +10%	2 × 2 × 3
	Twist angle	***t/c***	**Airfoil**	
Root	0° +2°	16%	Supercritical	2 × 1
Kink	0° +2°	8% 10% 12%	Supercritical	2 × 3
Tip	−5° −3°	8% 10%	Supercritical	2 × 2
Combinations				576

A full-factorial DoE has been performed in a MATLAB program, which includes the cores of the previously described tools (WingAnalysis and planform generator), on a simplified baseline made up of 3 characteristic airfoils (root, kink, and tip) distributed over 5 sections to get a starting point very similar to the original baseline made up of 55 profiles. The vertical tails have been removed. The simplification of the geometry is shown in Figure 15. For each of the 576 configurations, 2 low fidelity aerodynamic analyses have been performed: one in low speed condition ($M = 0.20$, sea level), to calculate $C_{L\max}$ and the incipient stall station on the wing span (evaluated with the stall path approach), and one in high speed condition ($M = 0.85$, 43000 ft altitude), to get max aerodynamic efficiency in cruise. At the end of the DoE process, BWB configurations are sorted according to each DoE target ($E_{\max}$, $C_{L\max}$, incipient stall station) and their combination. Response surfaces can be plotted to highlight the effect of design variables on the output variables, as shown Figure 16. To describe all the effects in a single chart, a scatter plot with variable markers color and size has been provided. Figure 17 shows this plot for the maximum aerodynamic efficiency. The most important design variable is the outer wing sweep angle, reported on the abscissa, whereas variations of the twist angle and thickness distribution among the wing sections are represented by change in markers color and size, respectively. The leap between groups of markers represent a variation of aspect ratio, due to the combination of wing area and span.

Some configurations have been annotated on the plot. They are not the best 10 configurations in terms of aerodynamic efficiency, but points of interest chosen to expand the DoE results with RANS CFD simulations. They are indicated in Figure 17 and Table 4. It is here noted that the initial DoE configuration has an increased wing tip chord to get an outer taper ratio (tip-to-kink chords ratio) equal to 0.23 to prevent wing tip stall avoiding excessive wing twist. Finally, all but one of the configurations of Table 4 have a further increase in wing area, obtained by increasing the inner wing chords, to allocate longitudinal control surfaces and engines, as shown in Figure 18.

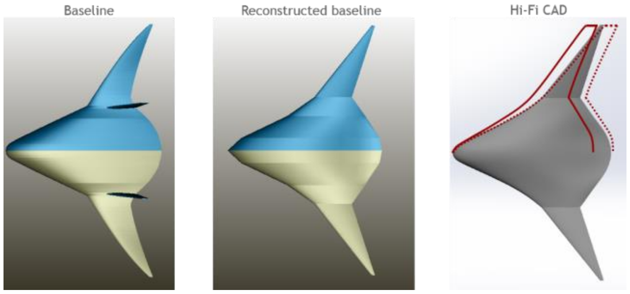
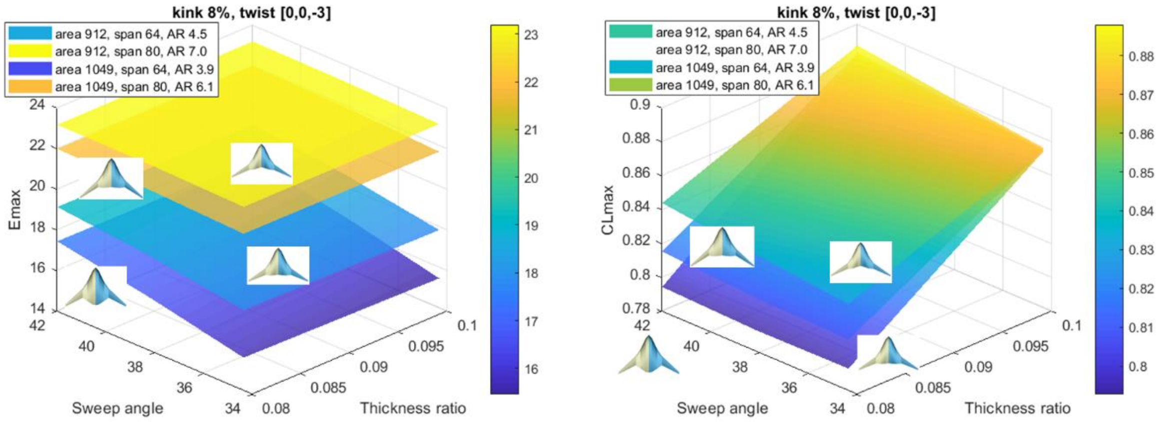


Figure 15. Simplification of the original baseline geometry.



a) Max aerodynamic efficiency. *b) Max lift coefficient.*

Figure 16. Example of DoE response surfaces with sweep angle and thickness ratio as independent variables.

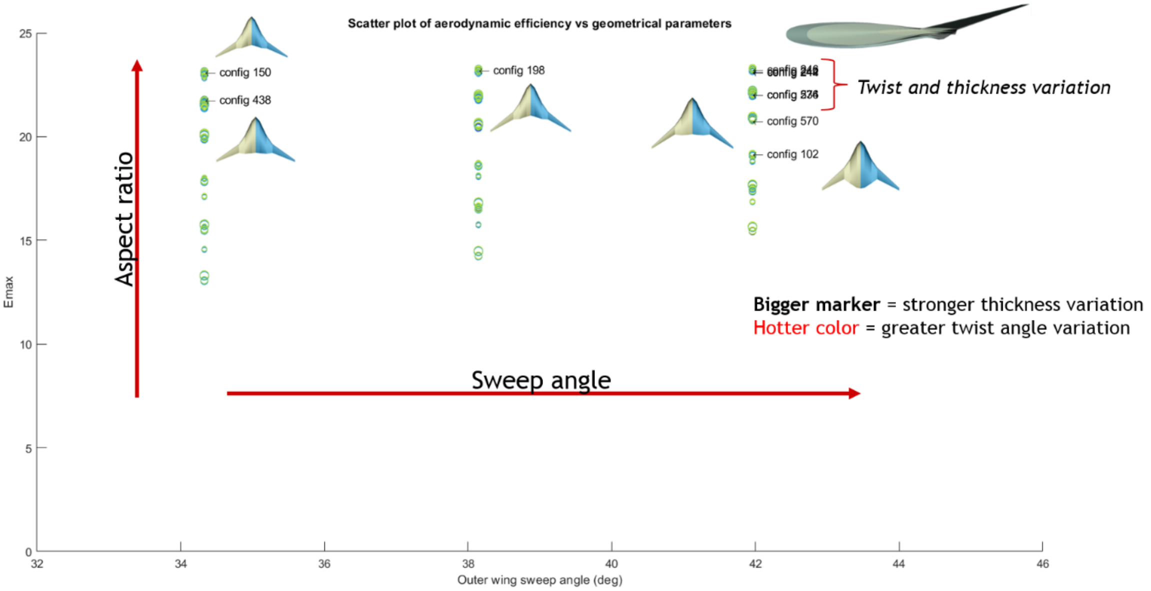


Figure 17. Scatter plot of the max aerodynamic efficiency, representing all the DoE combinations. The annotated configurations have been passed to other aerodynamic partners as Hi-Fi CAD files for CFD RANS analyses.

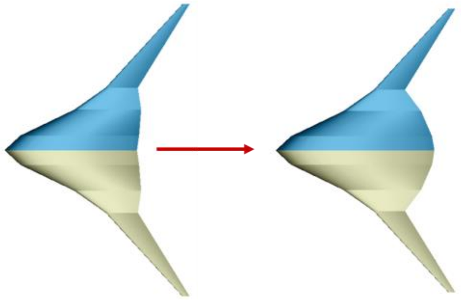


Figure 18. Example of the final modification of an output DoE geometry: the inner chords length of DoE output geometry has been increased to allocate movable surfaces and engines at a later stage. This has increased the wing planform area by 16%.

Table 4. Reduced DoE input matrix for Hi-Fi analyses.

ID	*S (m2)*	*b (m)*	*AR*	*Sweep (°)*	*t/c (%)*	*Twist (°)*	*Config.*	*Ref. length (m)*	*Ref. point (m)*	*Partner*
1	1174	80	5.45	42	[16, 8, 8]	[0, 0, -3]	242	32.88	18.41	AIRINNOVA
2	1174	80	5.45	42	[16, 8, 8]	[2, 0, -3]	246	32.88	18.41	
3	1174	80	5.45	42	[16, 8, 8]	[0, 2, -3]	244	32.88	18.41	
4	1174	80	5.45	38	[16, 8, 8]	[2, 0, -3]	198	32.88	18.41	CFSE
5	1174	80	5.45	34	[16, 8, 8]	[2, 0, -3]	150	32.88	18.41	
6	1174	80	5.45	42	[16, 12, 8]	[2, 0, -3]	276	32.88	18.41	
7	912	64	4.49	42	[16, 8, 8]	[2, 0, -3]	102	24.80	17.80	TSAGI
8	1213	80	5.28	34	[16, 8, 8]	[2, 0, -3]	438	30.67	19.67	
9	1213	80	5.28	42	[16, 8, 8]	[2, 0, -3]	534	30.67	19.67	
10	1213	80	5.28	42	[16, 12, 10]	[0, 0, -3]	570	30.67	19.67	

2. Aerodynamics: Narrowed Down Design Space Exploration : High Fi Analysis

The 10 DoEs proposed by UNINA are distributed and analyzed by 3 partners, Airinnova, CFSE and TsAGI, using their own meshing tools and CFD tools respectively. Then all the solutions are gathered and compared, and a "best" configuration is selected according to the aerodynamic aspects. There are two design conditions are considered, (1) the cruise condition (high-speed M=0.85) with low angles of attack, and (2) the taking off (low-speed M=0.2) with large range of angles of attack.

Table 5 shows the meshing properties and CFD tools used to analyze the 10 selected DoEs. All the DoEs are analyzed by CFD tools at L3 level, namely, the RANS solver. Note that, since the 10 configurations are meshed in different tools with different meshing algorithms, the different turbulence models are chosen in different CFD tools, one may argue that it is not straightforward to select the "best" configuration among the 10 analyses. However, those analyses, show the trends of the aerodynamic coefficients in a good manner, furthermore, with the resolution of the meshes increased, we expect that all the solutions from different CFD tools would converge.

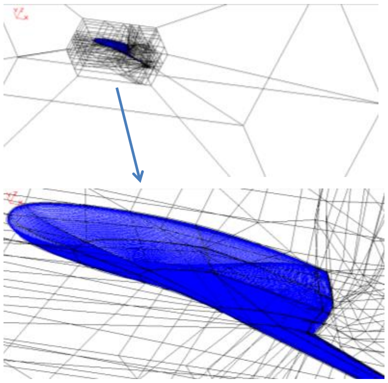
Table 5: Tools and mesh properties used for HiFi analysis.

config.	*Meshing tool*	*Mesh type*	*Mesh size [million]*	*CFD*	*Turb. model*
198	ICEM CFD	multi-blocks, structured	12	NSMB	k-ω SST
150	ICEM CFD	multi-blocks, structured	12	NSMB	k-ω SST
276	ICEM CFD	multi-blocks, structured	12	NSMB	k-ω SST
102	TsAGI code	-	45	TsAGI	-
438	TsAGI code	-	45	TsAGI	-
534	TsAGI code	-	45	TsAGI	-
570	TsAGI code	-	45	TsAGI	-
242	Pointwise	hybrid, unstructured	20	Edge	S-A
244	Pointwise	hybrid, unstructured	20	Edge	S-A
246	Pointwise	hybrid, unstructured	20	Edge	S-A

Edge is the Swedish national CFD code for external steady and unsteady compressible flows used by Airinnova. Developed by the Swedish Defense Research Agency (FOI), it uses unstructured grids with arbitrary elements and an edge-based formulation with a node-centered finite-volume technique to solve the governing equations. Edge supports a number of turbulence models, as well as LES and DES simulations.

The solver NSMB (Navier-Stokes Multi-Block) used by CFSE is a CFD solver using the cell-centered finite volume method on multi-block structured grids. The ANSYS® ICEM CFDTM pre-processer tool was used to generate the structured grid for the 3D BWB aircraft. One grid was generated and adapted for the different configurations selected. The NSMB high-fidelity computations were performed using a central space discretization scheme and the LU-SGS time integration scheme. Local time stepping was employed to accelerate the convergence to steady state. A fully turbulent flow was assumed, and the turbulence was modelled using the $k - \omega$ Menter Shear Stress model.

The characteristics of the grid for TsAGI computation are shown in the tables in Figure 19



Total cells	45 258 752 cells
Cells near conf.	42 113 024 cells
Near wall cell height	3-e7 m
Wing foil approximation	576 cells
Wing span approximation	116 cells
Bl approximation	~60 cells

Fine grid	45 258 752 cells
Medium grid	5 639 128 cells
Coarse grid	704 891 cells

Figure 19: TsAGI Mesh Feature

Rebuilding of computed grids for each layout was carried out manually, that is, without the use of automatic reconfiguration of design grids. For each model, the convergence in the grids on the flight mode of the aircraft with Mach number of the oncoming stream of 0.85 and an attack angle of 2.5° was investigated. The results of the convergence study for grids are shown in Figure 1.2. On the graphs shown in Figure 1.2, the abscissa represents the value of the inverse of the number of cells in a three-dimensional mesh calculated to a power of 2/3. A second-order computational scheme for spatial approximation must linearly approach the result corresponding to an infinitely large number of cells in the computational grid. The analysis of the results allows us to make a conclusion about the sufficiency of the grid with the number of cells greater than 45 million for predicting the results with an accuracy of 0.0001 for the value of the drag coefficient and 0.001 for the magnitude of the lift coefficient. Decoding of markers is presented on each chart.

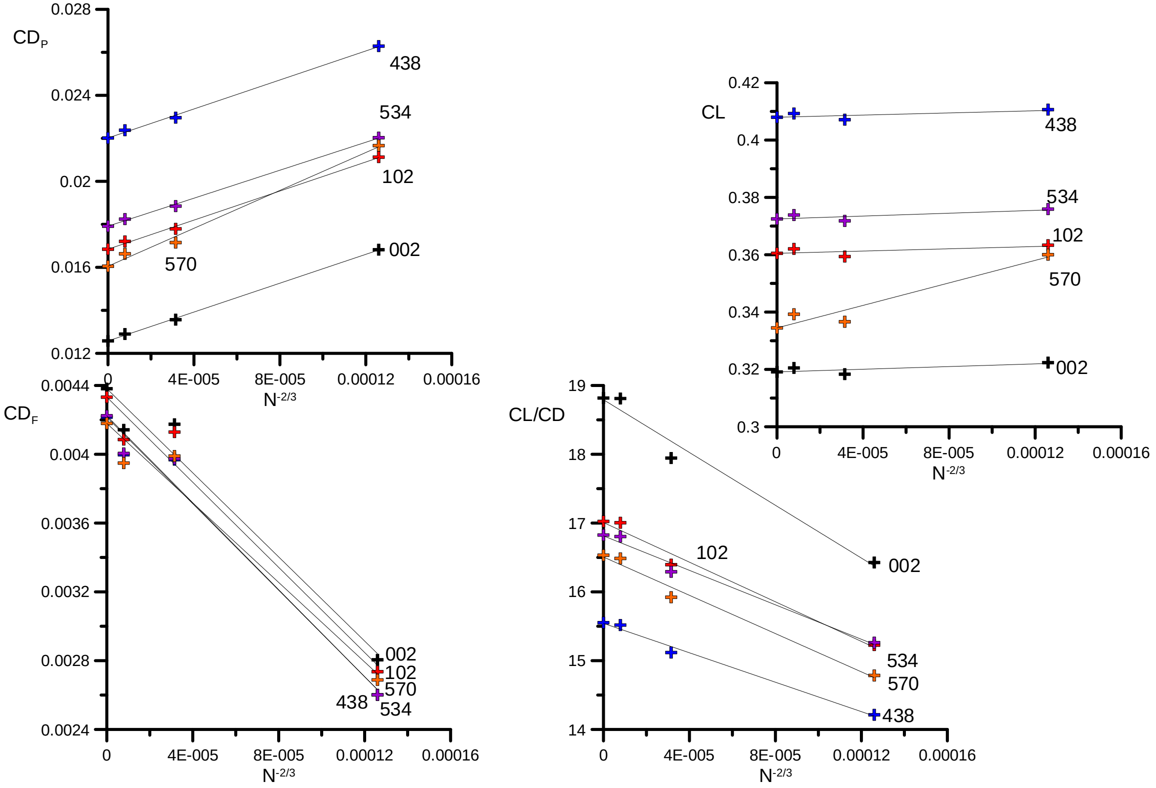


Figure 20: Grid cell number effects on aerodynamic results by TsAGI for BWB

Figures 19 and 20 show the L/D of different DoEs for two flight conditions. For the low-speed, DoE 570 shows the best L/D properties and for the high-speed conditions, DoE 102 shows the best L/D properties.

The most interesting quality for the stability and control is the pitching moment. The CFD results in Figure 21 show that there are breaks for most of the configurations in the pitch moment curve at Mach = 0.2. The first break occurs at about $\alpha = 8\circ$ for DoEs 276, 198, 102, 438 and 534 and occurs at about $\alpha = 13\circ$ for DoE 570, it results in an increased slope of the curves. DoEs 102 and 438 show a mild slope increase after about $\alpha = 8\circ$. The second break occurs at about $\alpha = 10\circ$ for DoEs 276 and 198, where the pitch moment suddenly drops and continues with about the same slope. DoEs 242, 244 and 246 show almost linear slopes without breaks.

For the high-speed analyses, Figure 22 shows that all the CFD results ensure a stable aircraft with negative slope of the pitching moment. DoEs 276 and 244 are almost neutral stable at about $\alpha = 3 - 4\circ$.

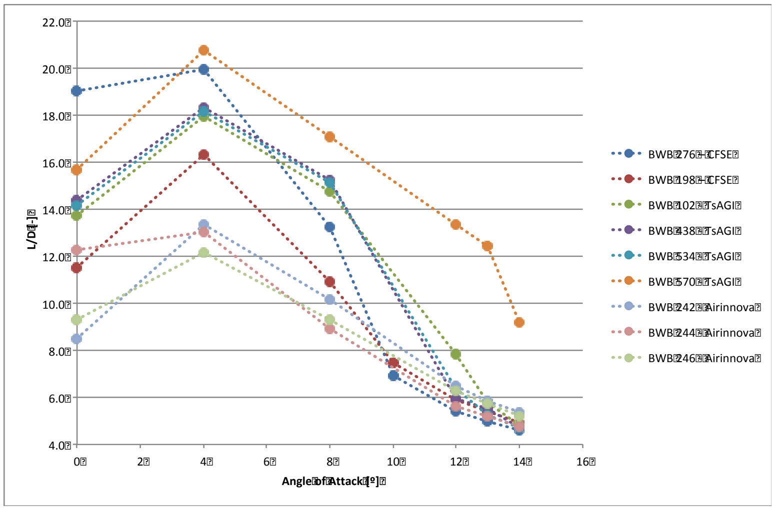


Figure 21: L/D comparison of the DoEs computed by L3 solvers (RANS) at take-off conditions, Mach=0.2, altitude=0m.

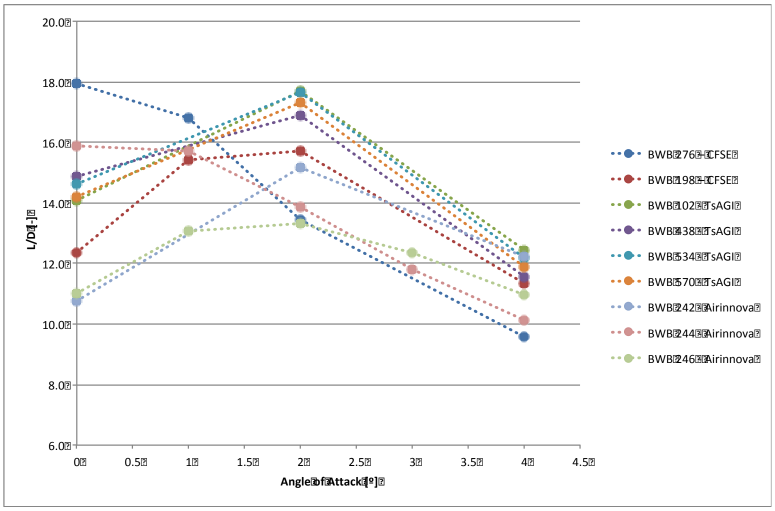


Figure 22: L/D comparison of the DoEs computed by L3 solvers (RANS) at cruise conditions, Mach=0.85, altitude 13200m

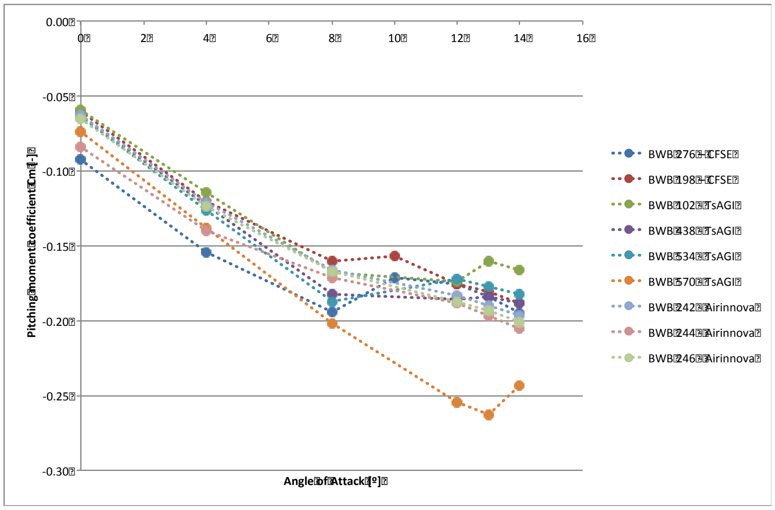


Figure 23: Pitching moment comparison of the DoEs computed by L3 solvers (RANS) at take-off conditions, Mach=0.2, altitude=0m.

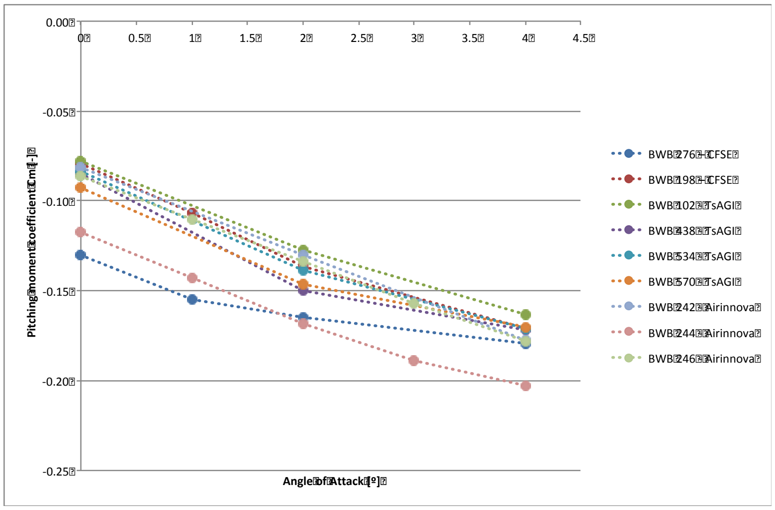


Figure 24: Pitching moment comparison of the DoEs computed by L3 solvers (RANS) at cruise conditions, Mach=0.85, altitude 13200m

3. *Final configuration selection and Aerodynamics performance map*

A final configuration for the BWB activity is selected to be DOE 102, which is has best L/D performance as well as least structural weight from structural analysis estimations at DLR. This DoE case has been also selected for cross-checking between partners, in order to avoid grids and/or numerical tool effects on the aerodynamic performances obtained. Finally, CFSE and TsAGI partners have shown confident results on this selected case, as reported in Figures 23 and 24. Some discrepencies appears at high angles of attack for low speed configuration, but can be attributed to the grid refinement (40M for TsAGI against 12M for CFSE), more sensitive to the recirculation that occurs on the body at high angles of attack.

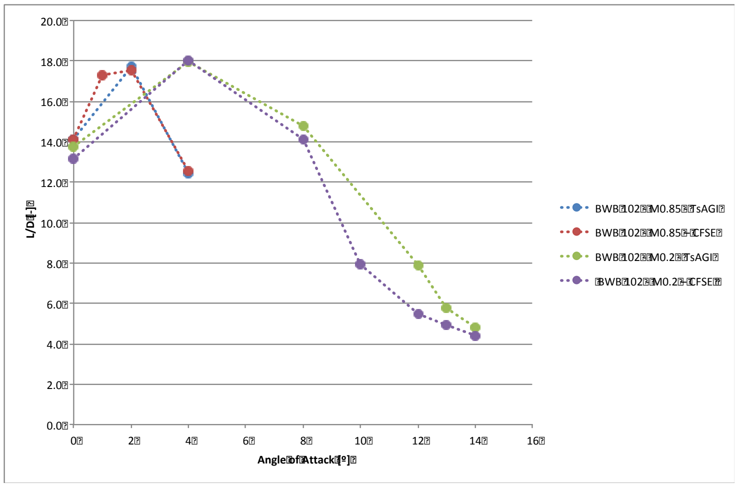


Figure 25: L/D comparison of the DoE case 102 computed by CFSE and TsAGI at cruise and take-off conditions (M=0.85 and M=0.2)

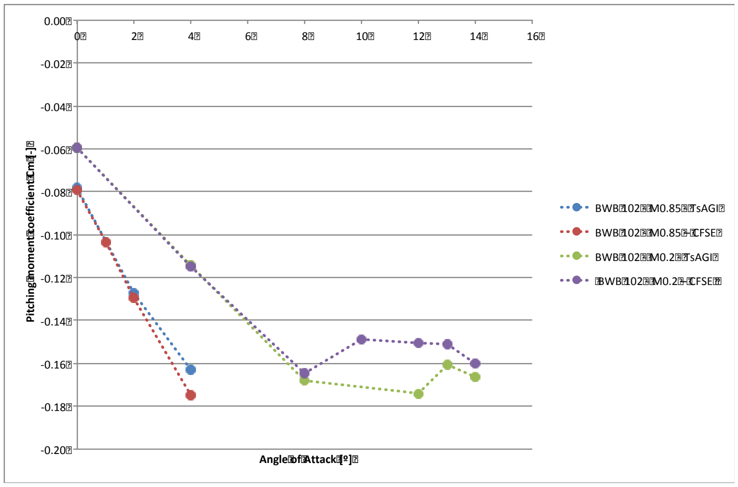


Figure 26: Pitching moment comparison of the DoE case 102 computed by CFSE and TsAGI at cruise and take-off conditions (M=0.85 and M=0.2)

The performance map was collaboratively provided be the aerodynamic partners. In future exercises a data fusion tool will be used to fill the flow matrix (Mach, Altitude , Clean / Takeoff – Langing config) and populate the aeroperformance map collaboratively.

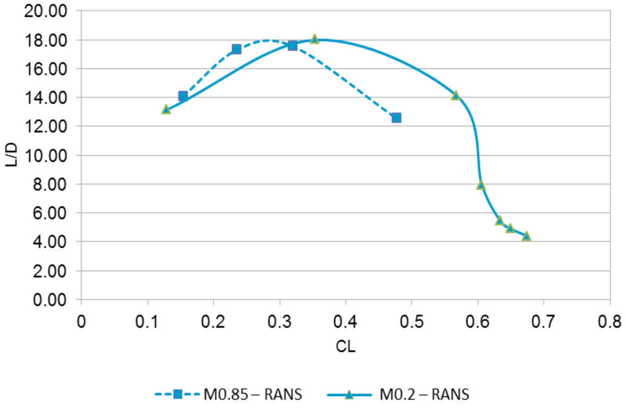


Figure 27 : L/D vs CL for selected BWB configuration

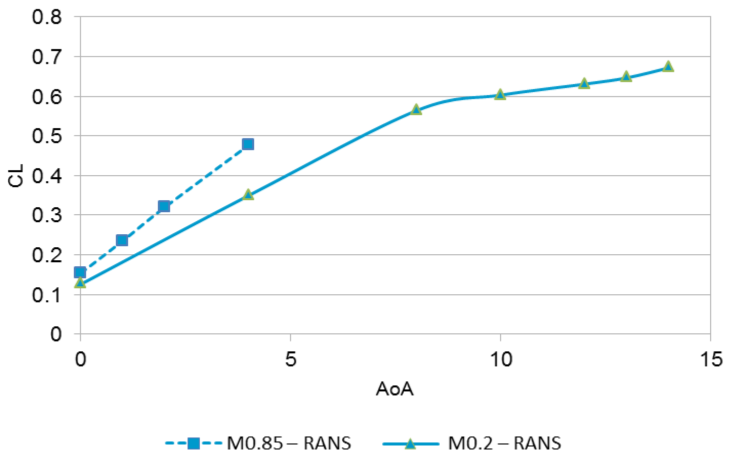


Figure 28: Lift Coefffecient vs Angle of Attack plot for selected configuration

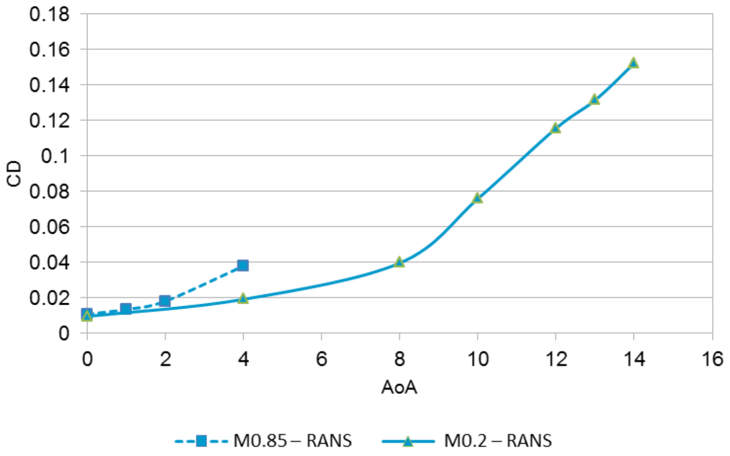


Figure 29: Drag Coeffecient Charecteristics of selected configuration

This above aerodynamic characteristics was recorded in central data schema as aeroperformance map, It was used to evaluate mission simulation also some of the aerodynamic analysis results were also used for Stability and control evaluation as described in G

A. Aircraft On Board Systems Design (Politechnica Di Torino)

The On-Board Systems (OBS) of the Blended Wing Body (BWB), proposed as use case of the AGILE Project, have been designed using the tool ASTRID [26]. The tool is based on semi-empirical and physic-based models. Each model is individually developed for one main equipment. All the main OBS can be designed considering conventional and innovative configurations (i.e. More and All Electric). The main results are in terms of OBS masses and volumes at both equipment and system levels. Additionally, the power offtakes of each OBS and for each mission segment are calculated. Focusing on the BWB implementation, the architecture selected is the All Electric Aircraft (AEA) presented in Figure 30 and based on the previous results described in [27], [28]. The AEA architecture is able to combine the reduction of OBS mass removing the hydraulic system and the reduction of the power required avoiding the need of engine bleed air [29], [30]. Moreover, the AEA configuration has been selected considering the safety increment due to the removing of the ECS hot pipes and the hazardous hydraulic oil [31].

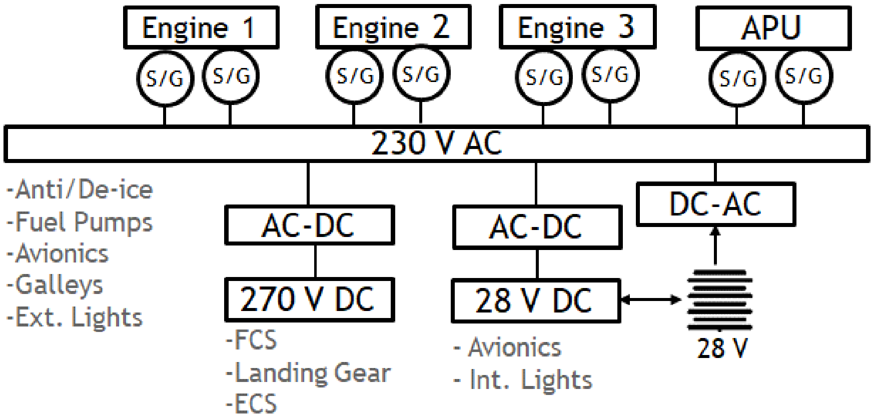


Figure 30: All Electric architecture for OBS of BWB aircraft.

As shown in Figure 30, the three engines and the Auxiliary Power Unit (APU) are all provided with two electric starter generators enabling the electric engine starting function and removing the pneumatic starting system [32]. The Electric Power Generation and Distribution System (EPGDS) provide high voltage power in alternate current to reduce cables mass and distribution losses. Therefore, the Ice Protection System (IPS), galleys and other power demanding systems are directly connected to 230 V AC bus. The full electric Environmental Control System (ECS) is provided with dedicated compressors and it represents one of the most power demanding system. Consequently, the ECS is connected to the high voltage 270 V DC bus. Similarly, the same bus supplies the actuators of the Flight Control System and Landing Gear. Some avionic equipment and the internal lights are connected to the low voltage bus.

The masses of the OBS are listed in Table 6. As usual, the main mass items are the landing gear and furnishing comprehensive of In-Flight Entrainment (IFE), lights, seats, galleys and the other internals. The EPGDS mass is considerable as it is the only system demanded to power generation and distribution. The power required by OBS is depicted in Figure 31 for each flight segment. The ECS is the system that requires more power during both ground and flight operations. The electric actuators of the FCS and the electro-thermal IPS are the second more power demanding users. However, the IPS is only operated in climb and descent segments. Finally, considering the maximum power required and the power needed during the emergency condition (i.e. One Engine Inoperative), the starter generator should produce at least 230 KVA nominally.

Table 6. Mass breakdown of the OBS for BWB aircraft

System Masses [kg]	AEA
Avionics	617
FCS	784
Landing gear	9268
ECS and anti-ice	2339
Fuel System	409
Aux Power System	772
Furnishing System	16622
Hydraulic	0
Electric	3978
Total Systems Mass	39364

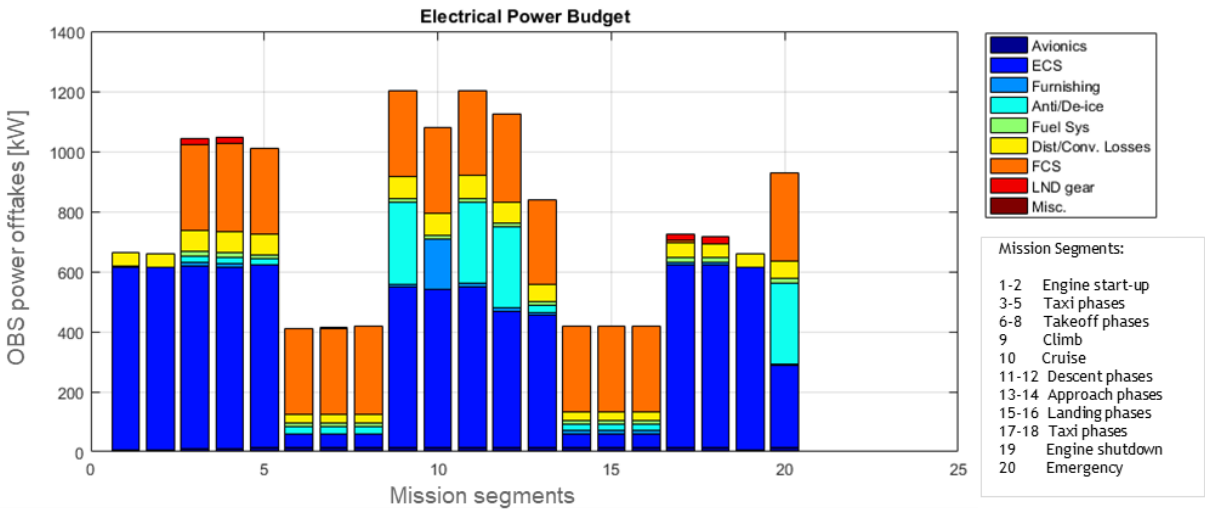


Figure 31. OBS power offtakes calculated for each segment of the mission profile.

B. Engine Design and Engine Airframe Matching (CIAM, Russia)

General Electric GE90-115B (Figure 1) high-bypass ratio unmixed turbofan was used as initial prototype of baseline engine for Propulsion System of BWB configuration because of total required takeoff thrust for 3 engines was around 1500kN.

Figure 1. General Electric GE90-115B high-bypass ratio unmixed turbofan.

Commercial software GasTurb v12 were used for engine modeling. A steady state engine performance is represented by an Engine Deck (ED).

Cruise conditions at flight level of 13100 m and flight Mach Number of 0.85 are considered as design conditions.

The ED provides the engine performance for the engine operating envelope. Operating envelope included several flight segments and engine rating (Automatic Power Reserve APR, Normal TakeOff NTO, Climb, Cruise, Descent, Approach, Landing, Maximum Continuous for mission simulation, static See Level uninstalled performance for Landing/TakeOff cycle NOx emission simulation, etc.). Real engine components maps were used to provide acceptable level of the compressors stability at all operating conditions.

Each of flight segments and engine ratings were characterized by different level of power offtakes, set of engine constraints, intake pressure recovery, etc. Main requirements defining required engine size was required takeoff engine thrust at design atmospheric conditions (ISA temperature deviation of 15 C) and APR of 468.3 kN.

Required offtakes for different flight segments are presented in the Table 7.

Table 7: Required offtakes for different flight segments

Flight Segments	*Power Offtake per Engine, W*
Normal Takeoff (NTO)	175098
Climb	501173
Cruise	449560
Descent	501320
Approach	349967
Landing	174637

As are shown in the table maximum required power offtake are required on the Maximum Continuous flight conditions when one engine is inoperative.Engine installed performance for typical flight conditions on different flight segments are presented on the Figure 32 and Figure 33.

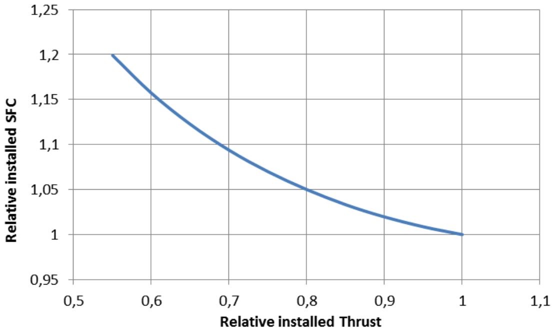


Figure 32 : Cruise throttle performance at flight level 13100 m and flight Mach Number 0.85.

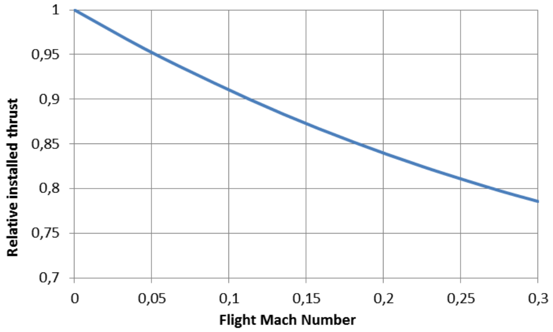


Figure 33 : Change of relative installed thrust at Normal Takeoff.

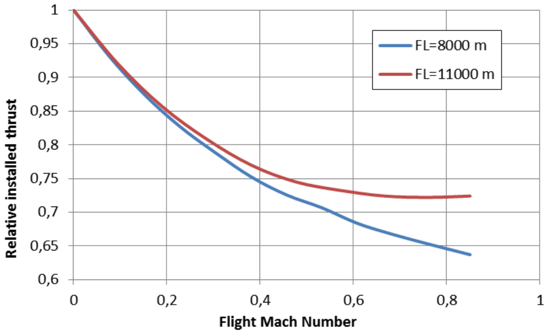
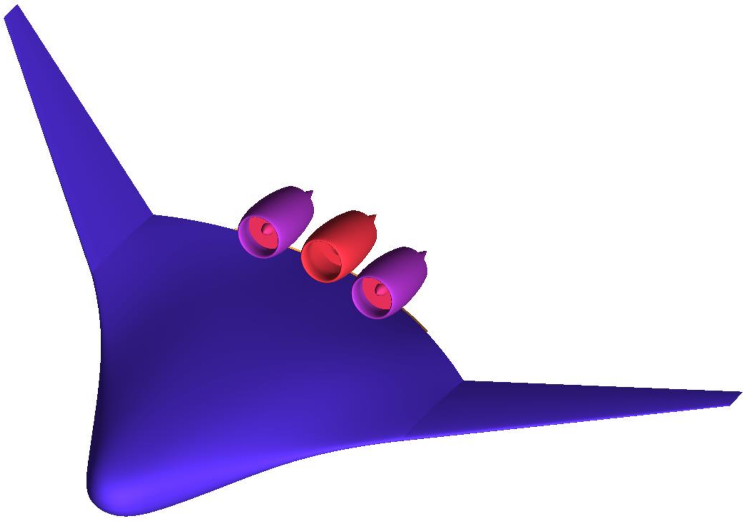


Figure 34 : Change of relative thrust based on Mach and Altitude for Climb Mode

C. Nacelle integration and results (TsAGI)



The Propulsion system includes nacelle and engines. The Engine information are shared between CIAM and TsAGI. TsAGI designed Nacelle and integrated the propulsion system onto the aircraft. The optimization involing location of the Engine and spacing is being carried out by TsAGI. At the time of the paper submission, the final optimum result is still being evaluated. Thus presented in the conference and updated.

D. Flight Stabilty & Control Assesment (CFSE - TU Delft)

The Performance, Handling Qualities and Loads Analysis Toolbox (PHALANX) is used to analyse the stability and controllability characteristics of the Blended Wing Body configuration. This is a nonlinear flight mechanics model that serves as a virtual flight test vehicle. The main modelling features of PHALANX used in the present research study are described in the next paragraph. This is followed by a paragraph with example results.

The BWB numerical flow simulation has been perfomend using medium-fidelity tool (L2) resolving Euler equations with the open-source code SU2 [33]. It has been developed by the Stanford University to solve fluid dynamics incompressible/compressible and inviscid/viscous flows. In this paper the SU2 is used as an Euler equation solver for solving the inviscid compressible flows.

The mesh used for these calculations is a 6,46M tetrahedra unstructured mesh create with SUMO [34]. In order to compute the elevator deflections, the SU2 built-in mesh deformation function “SU2_DEF” is used to deform the mesh around the elevator locations on the horizontal tail. A Free-form deformation (FFD) [35] box is defined at the elevator locations. With the hinge line location specified, the mesh in the FFD box can be deformed around the hinge line within a certain angle. To avoid high aspect ratio cells (or even negative volume) usually small deflection angle is preferred.

1. *Model Description:*

The equations of motion are represented using a multibody dynamics simulation. For the current test-case, the model consists of two rigid bodies with constant mass and inertia and one rigid body with time-varying mass and inertia. The first body represents the mass and inertia of the empty aircraft. A second body represents the mass and inertia of the payload. The third body represents the fuel mass and inertia which can vary dynamically during flight. The bodies are interconnected with prismatic joints. Using this approach, any aircraft configuration (weight, c.g. position) can easily be defined. External forces such as the aerodynamics and the propulsive force are applied on a fixed reference point on the rigid body that represents the empty aircraft.

The aerodynamic coefficients required for the flight dynamics simulations are stored in multi-dimensional look-up tables [36] . These tables are calculated offline by means of computational fluid dynamics. The six force and moment coefficients are calculated according to the following equation.

$$C = C_{static}(\alpha,\beta,M,Re)+\frac{\partial C}{\partial p}(\alpha,\beta,M,Re)+\frac{\partial C}{\partial q}(\alpha,\beta,M,Re)+\frac{\partial C}{\partial r}(\alpha,\beta,M,Re)+\sum_{i=1}\Delta C_{control}(\alpha,\beta,M,Re,\delta_i)$$

Where C indicates either a force or moment coefficient. In the present case study, all coefficients are computed at 4 angles of attack and 3 sideslip angles. A single flight altitude (13300 m) and Mach number (0.85) is evaluated. The aircraft has 10 control (symetric two by two) surfaces which are all evaluated at a small positive and a small negative deflection (+- 2 degrees).

The engine performance is modelled in a similar fashion as the aerodynamics. Multi-dimensional look-up tables are used which provide Thrust and fuel consumption as a function of throttle setting, flight altitude and Mach number.

The flight control system includes models for the actuator dynamics, saturation limits and rate limits. The aircraft is over-actuated, since it has 10 redundant flight control surfaces. Therefore, pitch, roll and yaw commands must be translated in 10 control deflections. As starting point in the evaluations, a daisy chain approach is used to distribute the commands. In future evaluations, the impact of more advanced control allocation techniques on the design will be explored [37] [38] .

The flight mechanics model can be trimmed in any desired flight condition (including unsteady conditions) using a Jacobian approach [39] . After trimming the aircraft, nonlinear time domain simulations can be conducted to evaluate stability and controllability characteristics. In addition, the model can be linearized by means of numerical perturbation, for control law design and further stability evaluations. Finally, the flight mechanics model can be constructed automatically without any user in the loop using the techniques presented in [40] and [41]. This is particularly suitable in case the model is used within an MDO framework.

D. Results

From the different cases calculated with SU2, force coefficients (Figure 35) and moment coefficient (Figure 3) have been plotted vs the angle of attack for different angle of sideslip. All the three graphs show a very small influence of the angle of sideslip on force and moment coefficients. Pitching moment derivaive have aslo been plotted versus the angle of attack. On Figure 4 we can see that pitching damping derivative is slightly increase when the angle of sideslip angle become higher. First analysis of control derivaive has shown a bad controllability of the aircraft. As the design is still under development, this issue will be one important point to fix during the next design iteration loop.

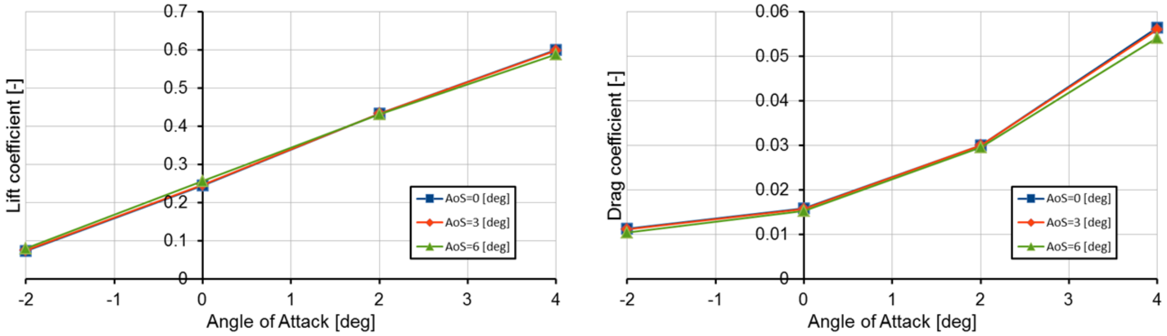


Figure 35 : SU2 Force Coeffecients

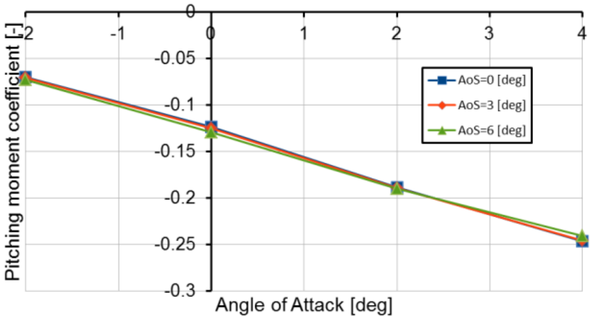


Figure 36 : SU2 Pitch Coeffecient

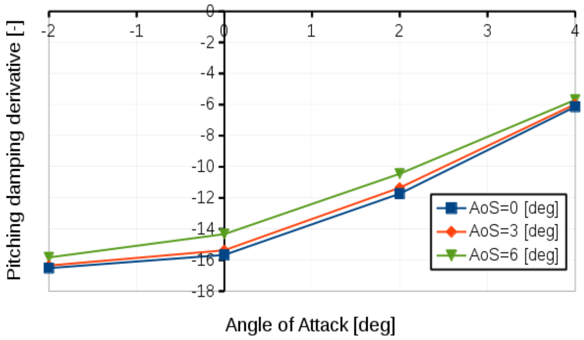


Figure 37 : SU2 Pitch Damping Coeffecient

The flight mechanics model is trimmed in the cruise condition for both the maximum take-off mass and the maximum zero fuel mass. These are extreme conditions and cruise conditions will always be within those two extremes. At both conditions, the Phugoid and short period characteristics are evaluated. Results are summarized in the table below.

Table 8: Longitudinal stability characteristics in cruise flight

Configuration	Mass [kg]	c.g. [m]	α_{trim} [deg]	$\square_{ph}$ [rad/s]	$\square_{ph}$ [-]	$\square_{sp}$ [rad/s]	$\square_{sp}$ [-]
MTOM (Initial)	435618	23.0	4.7	0.0564	0.0646	2.75	0.13
		22.0	4.7	0.0561	0.0645	3.23	0.34
		21.0	4.6	0.0559	0.0642	3.63	0.51
		20.0	4.6	0.0558	0.0641	4.01	0.65
MZFM (Initial)	292996	23.6	2.6	0.0546	0.0385	3.26	0.99
		23.1	2.6	0.0547	0.0393	5.87	1.00

Note: The weights are initial preliminary design estimation, the updated weight after mission simulation is again fed back and S&C analysis will be re iterated along with aero improvements.

The phugoid mode handling qualities are in the level 1 and 2 region for the various weight and c.g. locations analysed. This can be expected for this aircraft configuration with a high lift over drag ratio. The short period frequency and damping are quite sensitive to the total aircraft weight, inertia and its cg position. In terms of frequency, the handling qualities are level 1. For the MTOM with the c.g. furthest aft, the damping is considered too low. These simulation results are a first preliminary evaluation. Results will be used as constraints within the MDO framework to ensure acceptable handling qualities.

E. Mass Budget Data

In this section all the Masses evaluated or sourced from different models are provided. Some were estimated in the disciplinary analysis models and some were from other internal projects.

Table 9 : BWB Mass Budget Data

Mass Component			***Mass in Kg***	***Source***
	Sub component	***Mass in Kg***		
BWB wing and fuselage Mass			127644	Internal Project
Total Propulsion system mass			26620.5	Internal Project
System Mass				
	Avionics	617		
	FCS	784		
	Landing gear	9268		
	ECS and anti-ice	2339		
	Fuel System	409		
	Aux Power System	772		
	Furnishing System	16622		
	Hydraulic	0		
	Electric	3978		
Total Systems Mass			39364	POLITO Estimation - Section V.D of this paper
Furnishings			20214.7	Internal Project
Mass of other equipments			20828.2	Internal Project
Total Operating Empty Mass			234671.7	Summation of above masses
Payload Mass	Pax		45000	450 Pax @ 100kg/pax
	Cargo		5000	cargo requirement
Total Payload Mass			50000	
Total Zero Fuel Mass			284671.7	
Fuel mass			142621.5	Estimation from Mission simulation for 12000 Km range and allowable MTOM – Section F of this paper.. (Next section)
Total Max Takeoff Mass			427293	Section F of this paper.. (Next section)

Note: The weight models are constantly being updated, the values are updated through further analysis. Focus of the reader should be on the methodology of integration of several disciplines using model based approach. The weight values are being updated at the time of manuscript submission.

F. Mission suimulation and overall results

Mission simulation model uses

- Aeroperforamce maps (as per above HiFi aerodynamic section)
- Massdata [Table 9]
- Engine performance maps data, and
- Additional Nacelle and pilon drag (methodology covers onon optimum engine aircraft integration drag, optimum location is still being evaluated and presented in conference and updated).

The Seven engine perforamce maps such as Take off, Climb, Cruise, Decent, Approach, Landing and Max Continious were used for mission simulations as shown in Engine design modelling section above, Also, it should be noted that the engine already considers the onboard system offtake estimated from POLITO onboard system model as explained in above 'Aircraft Onboard system design' section.

Mission Simulation Results:

The final mission simulation results are shown in Figure 38 & Figure 39. The BWB aircraft could not fly for 8500 NM or 15742 kms as per TLAR but for only 12000 kms with full 50000 kg payload. This maybe non optimum profile parameters such as climbs,cruise and descent profile and speed of these mentioned mission segments. Also the Onboard system offtake effect may have affected the sfc of the engine. A detailed comparison of BWB aircraft with offtake assumptions and without offtake is ongoing and presented in the conferene and also the profile parameter optimization. The aerodynamics is also needs to be improved to iprove the range of the aircraft to the required 15742 km range.

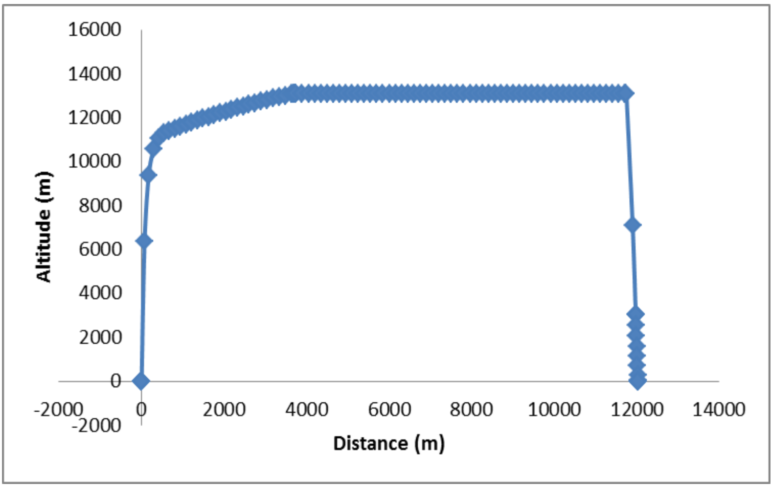


Figure 38: Altitude and Distance lot of Mission Profile

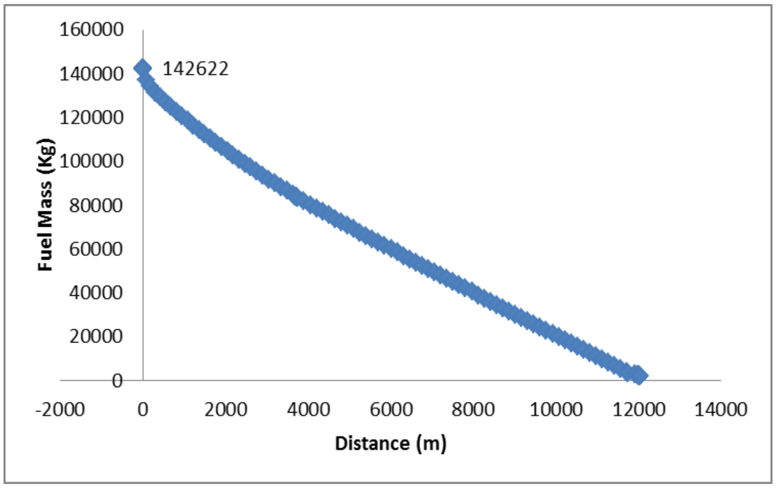


Figure 39: Fuel Mass (kg) and Mission Distance Plot

V. Conclusion and Future works

The model based design approach using AGILE paradigm was successfully tested for Novel configuration. Certain model data exchanges for hifi CFD analysis through a central data format is still a challenge. Neverthless this method provides good opportunity to easily integrate distributed multiple disciplinary models through a single framework. Some of the sections of this paper containes intermediate results. And at the stage of manuscript deadline this was the only feasible results but good enough to demonstrate the Model based design approach for BWB. The results are to be updated before the conference and more updated papers can be found at https://www.agile-project.eu/ and open source packages will eb released for public use through the website and upadated reports or papers.

Acknowledgements

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