Conceptual Design of a Blended-Wing-Body for a Short/Medium Range Mission Enhanced by High-Fidelity Aerodynamics

Benjamin Fröhler[1], Michael Iwanizki[2], Thomas Zill[1]

ABSTRACT

The ambitious goals of Flightpath 2050 [1] for a sustainable air transport are being pursued by several projects. In the European Clean Sky 2 project NACOR (New innovative Aircraft Configurations and Related issues), ONERA and DLR collaboratively investigate the potential of innovative unconventional aircraft architectures to reduce fuel consumption for two specific design missions, i.e. short-medium range and business jet. A down-selection process is defined, which aims at gradually reducing the number of different aircraft architectures, while increasing the fidelity of the employed analysis methods. Previous findings of the analysed configurations for both missions were presented by M. Iwanizki et al. [2]. Therein, the activities of the conceptual aircraft design phase, including initial high-fidelity (HiFi) studies, are described in detail.

This paper summarizes the work and results related to the blended-wing-body (BWB) configuration. During the course of NACOR, this configuration was identified to be most promising to achieve the goals of reduced environmental impact of air transportation in the future at short and medium range missions. For the overall aircraft design (OAD), a multidisciplinary optimization (MDO) process has been set up. Additionally, the process is enhanced by HiFi aerodynamic data. The HiFi aerodynamic studies comprised the optimization of the wing twist distribution and the airfoil shape of the BWB configuration. The corresponding performance data has been applied to the OAD process for the calibration of the aerodynamic methods of lower fidelity, which are typically employed at the conceptual design stage. The results are compared to a A320 - Baseline configuration (with assumed incremental technological improvement in the year 2035) and show an overall block fuel reduction by up to 10.3 %. The paper will describe the design methodology and the results obtained from the calibration of LoFi and HiFi aerodynamic results as well as the overall results of the BWB sizing process.

KEYWORDS

Conceptual aircraft design, multidisciplinary design and analysis, Blended Wing Body, RCE, CPACS, Clean Sky 2

1 INTRODUCTION

The potential of unconventional air vehicle configurations to reduce Jet A1 consumption and hence, the carbon footprint of future aircraft has been investigated in Clean Sky 2 within the ITD Airframe project NACOR (New Innovative Aircraft Configurations and Related Issues). In the frame of the project, the design of air vehicles for two missions - short/medium range mission based on the requirements of an Airbus A320, and a business jet mission has been conducted collaboratively by ONERA and DLR.
Both have investigated a plethora of unconventional aircraft configurations that could reduce the environmental impact of air transportation in future. To conduct such large design space exploration more efficiently, NACOR applied a stepwise analysis and downselection methodology.

Starting with various feasible aircraft concepts and evaluating them with fast analysis capabilities, the teams improved the accuracy of their design process after each design assessment and the subsequent configuration downselection. In this process both teams identified the Blended Wing Body (BWB) configuration as the most promising concept for the given mission requirements and the selected technology scenario, surpassing concepts such as box-wing or strut-braced wing aircraft in its performance. Figure 1 depicts a simplified overview of the downselection process in NACOR.

[1] DLR, Hein-Sass-Weg 22, 21129 Hamburg (Germany)
[2] DLR, Lilienthalplatz 7, 38108 Braunschweig (Germany)

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doi: 10.25967/550015

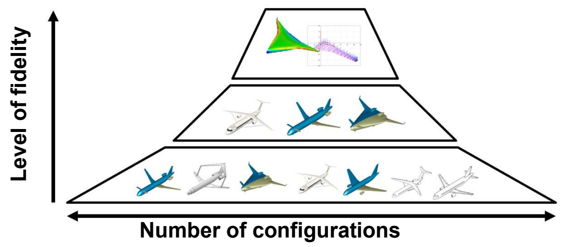

Figure 1 Downselection process in NACOR [2].

In this paper the key findings of the DLR activities in NACOR on the BWB are presented. Previous findings of the analysed configurations for both missions were presented by M. Iwanizki et al. [2]. Therein, the activities of the conceptual aircraft design phase, including initial high-fidelity (HiFi) studies, are described in detail.

2 OVERALL AIRCRAFT DESIGN ENVIRONMENT

An overall aircraft design process within the remote component environment RCE [3] was created for the design and evaluation of the BWB and is shown as a flowchart in Figure 2. The RCE environment enables the combination of software components into a combined workflow that communicate using the common language CPACS [4]. The process is initialized by an input file containing top level aircraft requirements (TLARS) and specific design parameters. Subsequently, the input file is interpreted by means of the level 0 conceptual aircraft design tool openAD [5], resulting in a CPACS output file. OpenAD is developed for conventional tube- and- wing aircraft configurations, however, for the purpose of this project, it has been adapted for the evaluation of unconventional BWB configurations. The software core remained unchanged, but the geometry generation and mass estimation methods of the vehicle components were significantly changed.

To extend the design space with refined level 1 methods, disciplinary tools are integrated throughout the aircraft design process. Refinements include methods for estimating the aircraft's engine design, aerodynamics, and mission performance. In an preceding step, the engine was designed using DLR's in-house tool GTlab (Gas Turbine Laboratory) [6]. As part of the aircraft design process, the engine design is imported from GTlab and additionally adapted for the Boundary Layer Ingestion (BLI) effect. The estimation of BLI is done by using the power saving coefficient (PSC) and the actuator disc theory. For this purpose, the boundary layer height is calculated based on the generated drag of the fuselage surface in front of the propulsor. Due to BLI, the fan experiences a deterioration in efficiency, which is also considered in this stage. In parallel, the aerodynamic coefficients are estimated in the design space of the flight envelope using the LIFTING_LINE tool, which is based on a potential theory method [7]. The aerodynamic coefficients are calibrated to the results of a previous high fidelity CFD simulation. Subsequently, the engine and aerodynamic performances are used for the aircraft mission performance analyses of the aircraft with DLR's in-house tool AMC [8]. In the final step, openAD is used to interpret and synthesize the level 1 results.

This process is iterated until convergence and a consistent aircraft design is reached. In a post-processing step, further disciplinary tools can be deployed. For this study, the payload range characteristics are calculated using the AMC tool mentioned above.

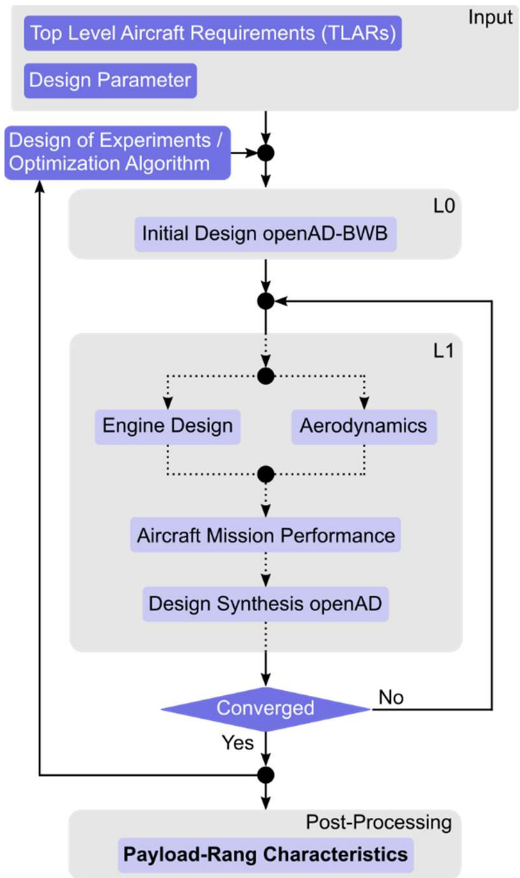

Figure 2 Flowchart of the overall aircraft design workflow [5].

3 REFERENCE CONFIGURATION

For the short and medium range (SMR) mission, an Airbus A320-200 similar aircraft was used as reference. The reference aircraft was based on the

CeRAS CSR-01 open configuration developed by RWTH Aachen [9]. To account for incremental technological improvements, a baseline configuration is assumed with entry into service (EIS) in 2035 and improvements in aircraft and engine technology as proposed by SGUEGLIA et al. [10]. The key aircraft characteristics of the baseline configuration are listed in Table 1 and will be referred to as the "A320 Baseline" in this paper.

Table 1 Key aircraft characteristics of the A320 Baseline aircraft [9] with EIS in 2035 and technology improvements after SGUEGLIA et al. [10].

Aircraft	Unit	A320 Baseline
Entry into Service	[-]	2035
Engine Type	[-]	Turbofan
No. of Engines	[-]	2
MTOM	[t]	66.1
OEM	[t]	38.1
Design Payload	[t]	17.0
Cruise Mach No.	[-]	0.78
Design Range	[NM]	2500
Initial Cruise Altitude	[ft]	33000
Design Block Fuel	[t]	8.9

4 BLENDED WING BODY RESULTS

For the SMR mission, several unconventional aircraft configurations are analysed in terms of their fuel consumption. IWANIZKI et al. [2] showed that a BWB configuration is the most promising for reducing fuel consumption. This chapter describes the latest findings of the BWB that utilize the synergies of the BWB configuration with BLI and high-fidelity (HiFi) aerodynamic optimizations to improve the design.

4.1 Overall Description of the BWB

The BWB is designed as a single-deck configuration, with the cabin and cargo compartment located in the centre wing body to provide sufficient space. The overall dimensions of the BWB are shown in Figure 3. The left and right sides of the cabin accommodate the cargo compartment. The sweep of the outer wing was optimized with regard to mission fuel and MTOM. The results showed an optimal leading-edge sweep angle of $\varphi_{LE} = 42.5°$. A combination of reflected airfoils on the center body and supercritical airfoils on the outer wing is assumed. The engines are located at the rear end and are embedded on the top of the center body to allow for BLI. Additionally, the engines are located close to the center of the BWB to reduce yaw motion in the event of an engine failure.

In general, BWB's are inherently unstable, requiring an elaborated movable layout with a flight control system due to the absence of an empennage [11]. To counteract aerodynamic forces and ensure stability, it is recommended to use a combination of flaps, slats and winglet rudders. Figure 4 shows a preliminary layout of the control system. The flight control system supported by the control surfaces are necessary to ensure a safe take-off, landing and flight condition. The inboard flaps are installed for pitch control, while the outboard flaps and ailerons generate roll and yaw moment. Rudders are integrated into the winglet to provide yaw control. [12]

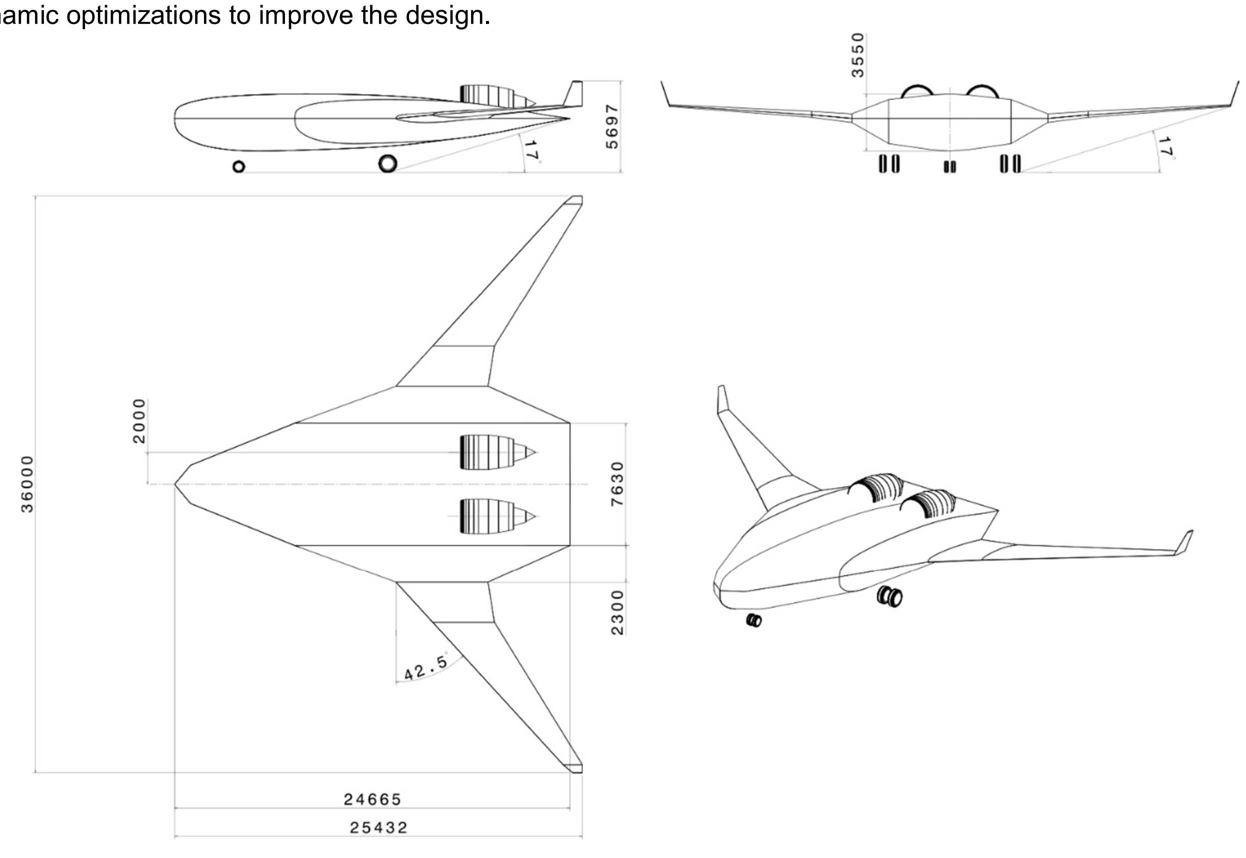

Figure 3 Three view of the BWB configuration (dimensions in mm).

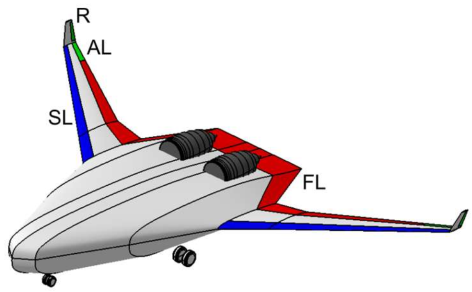

Figure 4 BWB preliminary movable layout; R: Rudder, AL: Aileron, SL: Slats, FL: Flaps.

The cabin and cargo compartments of the BWB were designed according to the A320-200 reference aircraft. Figure 5 shows the location cabin (displayed in grey) and cargo compartment (displayed in orange) of the BWB. The cabin has an area of 102 m², which is marginally larger than the A320-200's 101.2 m². The volume of the cargo compartment is 40 m³, thus 6.9 % larger compared to the reference (A320-200: Volume = 37.42 m³), but was not designed to accommodate standard containers.

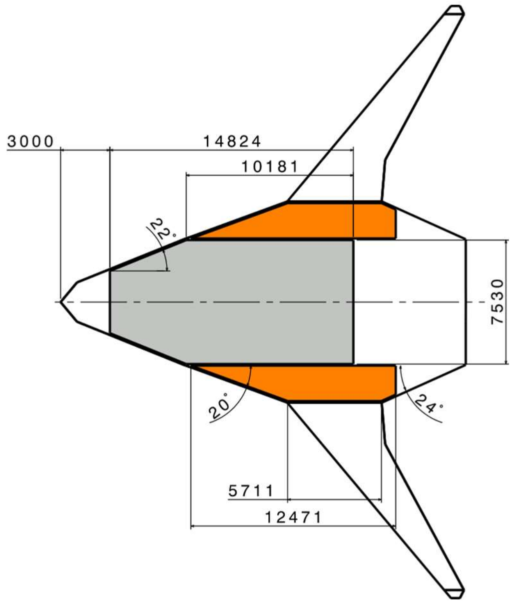

Figure 5 BWB cabin (grey) and cargo (orange) compartment layout.

4.2 HiFi Aerodynamic Investigation

The purpose of the HiFi analyses is the evaluation of the aerodynamic performance of the proposed BWB configuration. The work includes the following topics: the preparation of the geometry suitable for HiFi-CFD calculations, the manual adaption of the wing twist distribution for maximum L/D-ratio in trimmed cruise conditions, an automated optimization of the wing twist distribution and the airfoil optimization of the outer wing, the calculation of reference polars for the calibration of the OAD process. The HiFi analyses are limited to the glider configuration without consideration of the nacelles and engines.

For the geometry definition, the CPACS format and the CAD software "CATIA" have been used. The meshes for CFD calculations were generated by the grid generator "CENTAUR". The CFD computations (RANS) have been carried out with the DLR's TAU code [13,14] version 2019.

First, based on the CPACS geometry provided by the OAD, a parametric CATIA-model suitable for HiFi-CFD analyses was created. It has been built using DLR's in-house tools in a semi-automated process (see Figure 6). Compared to the OAD-CPACS-geometry, the CAD model has been smoothed in order to avoid flow separations. Additional degrees of freedom for the shape optimization have been introduced by further subdividing the outer wing segment.

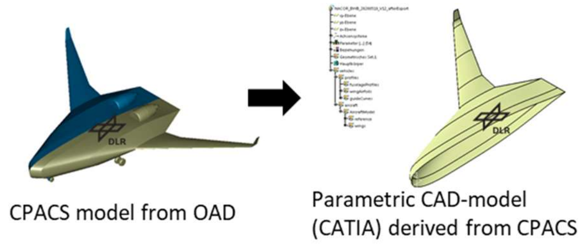

Figure 6 Process for the generation of the parametric CAD model.

At this stage of the project, comparably coarse meshes (about 3e6 nodes) have been used in order to reduce the computational effort. Regarding the resolution of the prismatic layers in the boundary layer, in-house knowledge has been applied in order to ensure a sufficient quality of the results. A fully turbulent flow has been assumed applying the Spalart-Allmaras turbulence model. An exemplary mesh is shown in Figure 7.

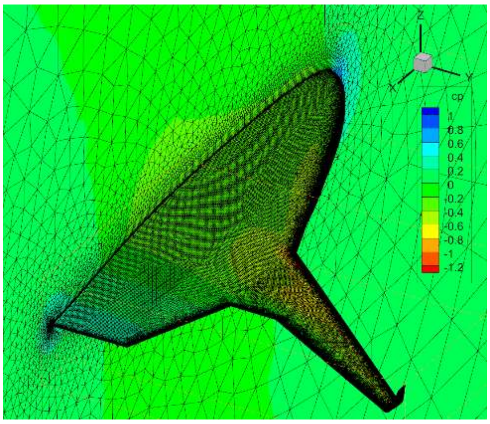

Figure 7 Exemplary CFD-Mesh of the BWB.

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The first HiFi-evaluation of the geometry based on the inputs from OAD revealed an inferior aerodynamic performance. The reason was the twist distribution obtained by LoFi methods that was not well suited for the transonic flight regime. Hence, the shape had to be adapted utilizing HiFi-CFD methods in order to account for the driving physical phenomena. The first step was a manual wing twist optimization, meaning that the twist angles of the wing were adapted systematically by manual inputs. This approach achieved a L/D-ratio of 21.6 for the glider in trimmed cruise flight. A comparison of the pressure distribution of the initial and the final twist distribution is shown in Figure 8.

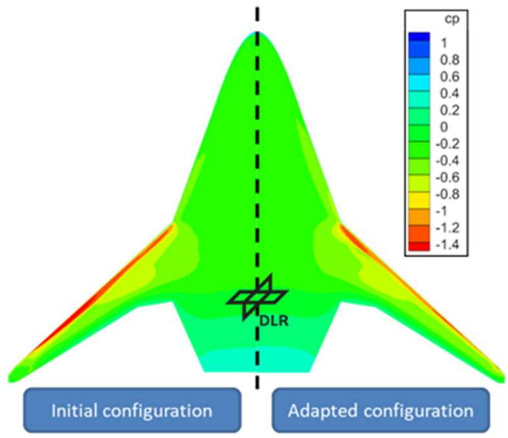

Figure 8 Pressure distribution of the initial and the optimized configuration.

In the next step, a fully automated optimization of the twist distribution and the outer wing airfoils has been conducted. A process in RCE has been set up for this purpose, utilizing the aforementioned tools for HiFi-aerodynamic calculations and the RCE-own optimization capabilities. The workflow architecture is shown in Figure 9. The initializer, the optimizer, the pre-processing, and the evaluation are executed on a local workstation because of the low computational resources required. The meshing, the calculation of the flow solution and the post-processing are carried out on DLR's own cluster.

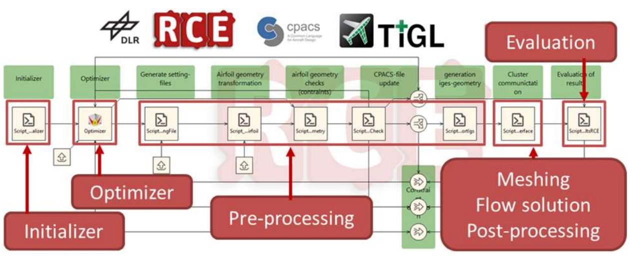

Figure 9 Overview of the automated HiFi aerodynamic optimization workflow

For the automated optimization, the parametric CATIA model has been converted to a refined CPACS geometry. The reasons are that the CPACS format enables a fast modification of the twist angles and the airfoil shapes based on the CST-parametrization [15], and it does not require proprietary licenses. As consequence, a minor deviation from the CAD-shape had to be accepted (Figure 10).

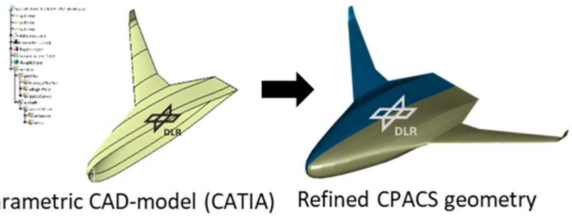

Figure 10 Parametric CATIA model and the derived CPACS geometry for automated optimization.

The automated twist optimization confirmed the results of the manual process described previously. The airfoil shape optimization could not provide further notable benefits compared to the initial geometry. This indicates a reasonable choice of airfoils in the scope of the OAD. Finally, the calculation of data for the calibration of the OAD-process has been carried out. The corresponding polars are shown in Figure 11.

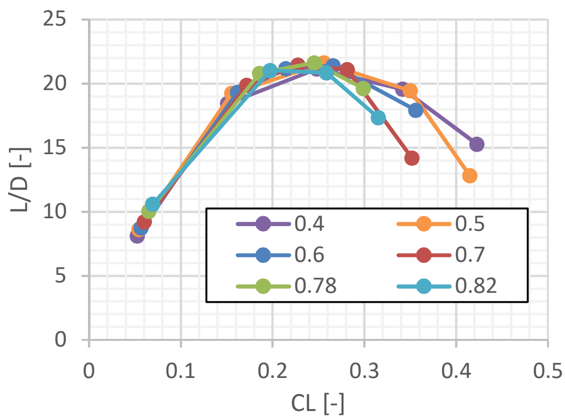

Figure 11 L/D-polars at different Mach numbers for the glider configuration.

4.3 BWB – BLI Configuration

After the HiFi aerodynamic analysis, the aerodynamics and wing twist distribution are applied to the low fidelity (LoFi) BWB aircraft design process. To fit HiFi aerodynamic results to the LoFi aircraft design process, the aerodynamics are calibrated in terms of zero lift drag and lift dependent pressure drag. Figure 12 shows the aerodynamic polar of the HiFi glider configuration which is matched to the LoFi glider configuration. In addition, the full configuration with the full nacelle drag is displayed. In general, the BWB-glider has a maximum lift-to-drag ration (L/D) of 21.6 and mainly due to the nacelle drag, the aerodynamic efficiency is reduced by 5.1 %.

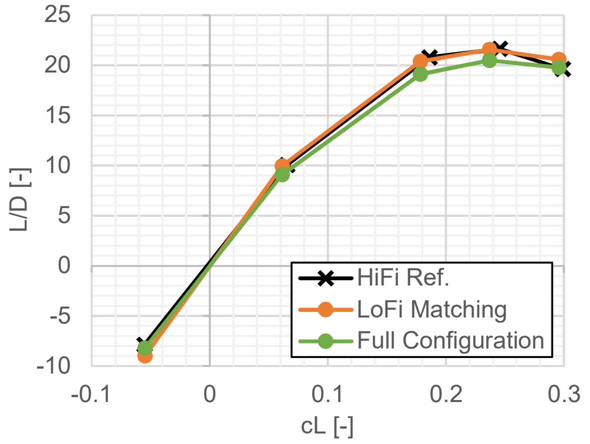

Figure 12 Matching of high-fidelity aerodynamic polar to the low fidelity BWB design process at mid cruise. (M = 0.78, Altitude = 12000 m)

To account for BLI, the effects on engine performance and overall aircraft aerodynamics are included. BLI has two main effects on engine performance. First, the efficiency of the engine is enhanced due to the decreased intake momentum caused by the reduction in flow velocity through the boundary layer. Thus, at constant thrust and mass flow, the efficiency of the engine is improved by reducing the exhaust gas velocity. Second, the efficiency of the fan deteriorates due to an non-uniform inflow at the inlet of the engine [16], [17]. For this study, the positive BLI effect and the negative effect of fan efficiency cancel each other out. To accommodate the engine into the wing body and to reinforce the engine structure, the mass of the power units will increase, but the effect of structural mass is neglected in this study. The attachment of the power units to wing body is represented by the pylon.

The overall aerodynamics of the aircraft are improved by reducing the wetted area of the BWB. The wetted area is reduced by embedding the nacelle into the wing body and thus removing surfaces from the free flow, i.e. lower half of the nacelle, pylon (attachment of engine to wing structure) and engine section from the wing body. Interference drag is increased, however, this effect is neglected within this study to avoid complex HiFi aerodynamic computations. Figure 13 shows the influence of the aerodynamic improvements due to BLI and the reduction of the wetted area compared to the HiFi glider configuration and the LoFi full configuration. The results show an improved L/D ratio for the BLI configuration by 3.9 % compared to the full configuration.

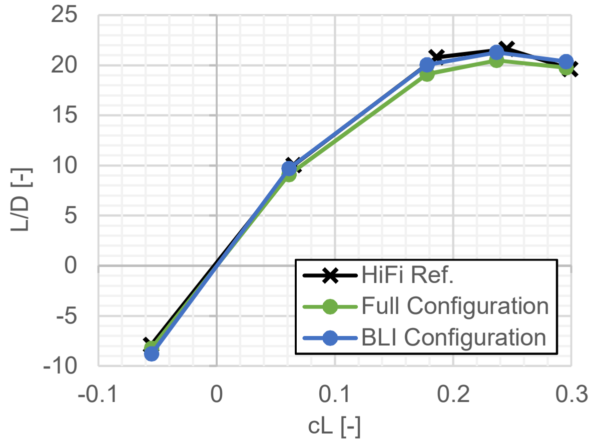

Figure 13 Aerodynamic polar of the BLI configuration compared to the HiFi glider configuration and matched Full configuration. (M = 0.78, Altitude = 12000 m)

A comparison of block fuel consumption between the A320 Baseline and the BWB configuration is shown in Figure 14. By changing from a conventional tube and wing configuration to a BWB configuration, a ~7 % reduction in block fuel can be expected using the results of HiFi aerodynamics computation.

For the next step, the BLI concept was added and first the effect of BLI on the engine was investigated. By calculating the momentum deficit caused by the boundary layer of the body in front of the propulsor, a power saving coefficient (PSC) of about 1 % was obtained. However, from previous projects, a fan efficiency loss of 1 % was assumed, indicating that the BLI effect on the engine does not lead to a meaningful reduction in block fuel. The main benefit of the BLI concept was observed to be the reduction in the wetted area of the nacelle and pylon as they are embedded in the BWB body. The wetted area effect shows an additional 3.4 % block fuel reduction and adds up to a total block fuel reduction of 10.3 % compared to the A320 baseline. A more detailed description of the BWB - BLI configuration is presented subsequently.

For the mass estimation, a combination of methods provided from the VELA [18] project and additionally handbook methods implemented in the conceptual aircraft design tool openAD [5] were used. The VELA methods are based on area-dependent masses and are used for the inner wing, i.e. the structure and furniture of the cabin and cargo compartment.

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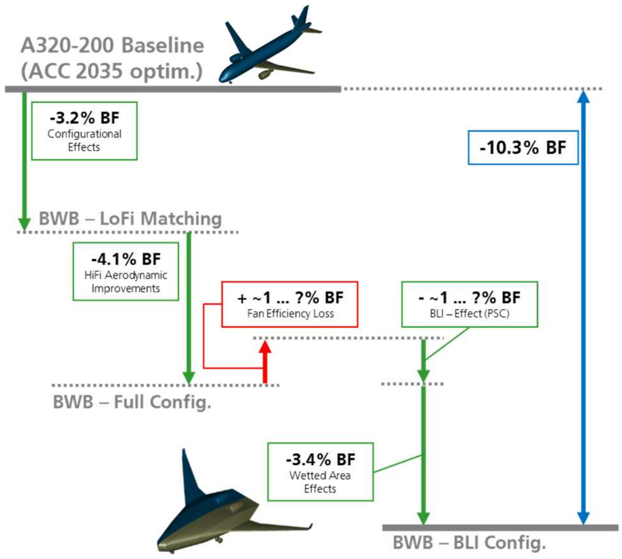

Figure 14 Ladder chart of BWB compared to A320 Baseline.

This is where the greatest uncertainty of the conceptual design lies, since experience with flying BWB designs is not yet available. It is also assumed that the systems, furnishing and operators items will be equivalent to the A320 baseline. A detailed mass breakdown is provided in Figure 15. A maximum take-off mass of MTOM = 63.24 t is divided into 27 % payload, 16 % fuel mass and 57 % in operating empty mass. The highest proportion is accounted for by the component masses of the inner and outer wing with 16 % and 12 %, respectively. The pylon mass corresponds to the internal attachment from the engine to the BWB structure and is estimated to be 1 % of maximum take-off mass.

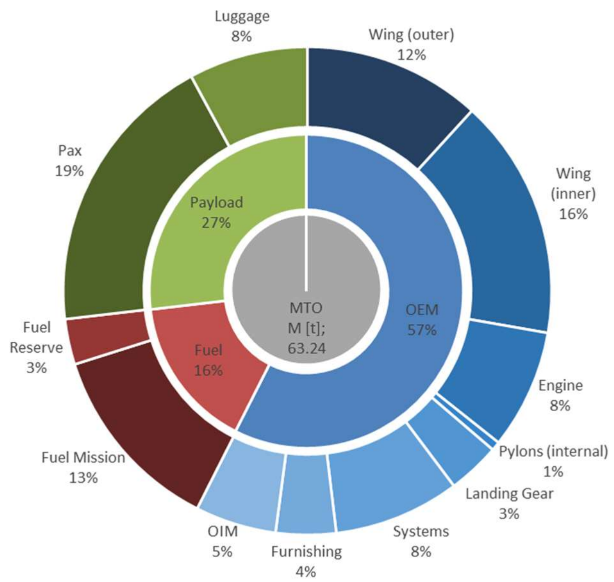

Figure 15 Mass Breakdown of the BWB – BLI configuration.

The trajectory of the BWB are shown in Figure 16. The flight path shows level flight with no cruise steps. Due to the low wing-loading, the BWB has a high initial cruise altitude of FL370 and continues level flight as the engine deck is limited to this flight level. A mid cruise point, defined as the point at which half the fuel is consumed, is indicated at a distance of 1050 NM.

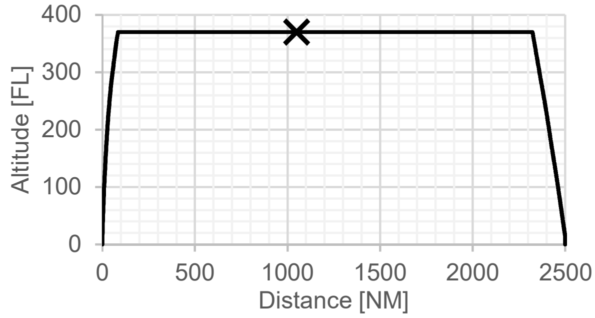

Figure 16 Trajectory of the BWB – BLI configuration.

The aerodynamic performance for the design mission is shown in Figure 17. The initial L/D ratio is approximately 21.44 for the BWB and is continuously reduced to a L/D of 21.08 as the aircraft fuel mass is consumed. The mid cruise condition shows a lift coefficient of $c_L = 0.22$ and a drag coefficient of $c_D = 0.0103$. Since the engine deck is limited to a flight level of FL370, additional aerodynamic improvement for higher cruise flight may be possible. To analyze the full potential of the BWB, future work should analyze the mission performance with an engine deck designed for a higher flight level.

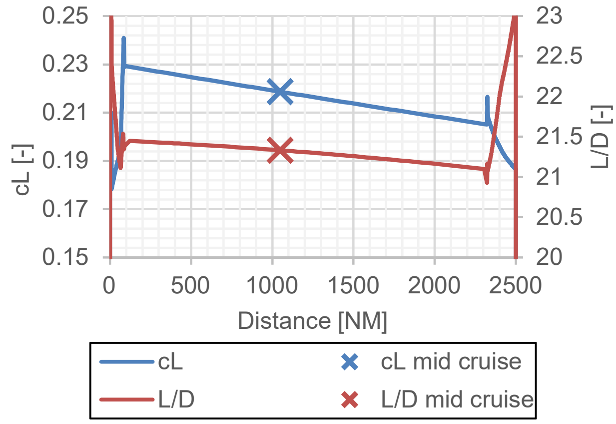

Figure 17 Aerodynamic performance of the BWB – BLI configuration.

A detailed drag breakdown at mid cruise is shown in Figure 18. The total drag is divided into zero lift drag generated by the aircraft components and the lift-dependent drag, such as wave drag, induced drag and lift dependent pressure drag. The highest component is the zero lift drag of the combined inner and outer wing. The engine nacelles have only a minor influence of 2.32 % on the drag distribution because they are embedded in the wing body. Pylons are not exposed to the free flow and have no aerodynamic effect.

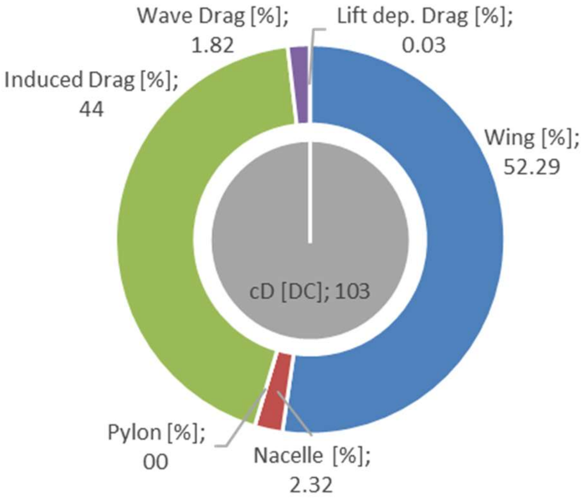

Figure 18 Drag breakdown of the BWB – BLI configuration at mid cruise.

4.4 Comparison to Baseline Aircraft

For the final assessment, the BWB – BLI configuration is compared in terms of relative deviations with the A320 Baseline in Figure 19. In addition to the BWB - BLI configuration, a variant with a mass penalty of 20 % is provided for the inner wing structure, given that the mass estimate for the non-circular cross-section of the cabin and cargo compartment is subject to high uncertainties. The results show a 4.5 % reduction in operating empty mass and an 8.1 % improvement in aerodynamic efficiency, resulting in a 10.3 % reduction in block fuel consumption. Considering the uncertainty of the cabin mass, which leads to an increased operating empty mass and a comparable aerodynamic efficiency improvement, a block fuel reduction of 7.2 % is still possible.

Figure 19 Relative difference of the BWB – BLI configuration to the A320 Baseline.

5 CONCLUSION

The presented paper outlines the recent activities of the European Clean Sky 2 project NACOR (New innovative Aircraft Configurations and Related issues). Previous studies by IWANIZKI et al [2] showed that a BWB configuration is potentially the most promising to reduce fuel consumption for a short and medium range mission. The scope of the work was to provide a detailed overview of the studied BWB and to present an evaluation of the improved performance compared to the reference.

To assess the BWB, a conceptual aircraft design process was created and partially enhanced with results from HiFi methods. The BWB is a single-deck configuration with cargo compartment adjacent to the cabin. A combination of reflexed airfoils at the center body and supercritical airfoils at the outer wing are assumed. Furthermore, the planform was optimized with respect to block fuel. To utilize the synergies between a BWB configuration and the engine design, the engines were embedded in the wing body to benefit from the BLI effect. Compared to the A320 Baseline, a block fuel reduction of 10.3 % is expected. The results indicate that the main benefit for the reduction in fuel burn is the aerodynamic improvement due to the change in vehicle architecture from a conventional tube and wing configuration to a BWB configuration and in addition, the reduction of wetted area due to the embedded engines improve the aerodynamics efficiency. Further aerodynamic improvements appear to be possible by expanding the design space with a more matched engine that allows a higher flight altitude. Challenges arise due to the high uncertainties in mass estimation, especially of the wing body, as there are no operational BWB configurations available yet. To show a trend and effect of higher operating empty mass, the structural mass of the cabin was increased by 20 %. The results show that a 7.2 % reduction in fuel consumption remains possible.
Next steps include additional HiFi studies to further improve the current aircraft design and reduce uncertainties of the mass estimation.

6 ACKNOWLEDGEMENTS

The project leading to this application 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-2018-2019-01. The authors would like to

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thank the project partners from Dassault Aviation (Jean Le Gall, Michel Ravachol) and AIRBUS (Lars Joergensen) for their interest in this topic and their guidance.

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