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IMPACT OF THE NUMBER OF WING STATIONS ON THE TWIST DISTRIBUTION OF A BWB CONCEPTUAL AIRCRAFT DESIGN IN A MDAO ENVIRONMENT TO MATCH TARGET LIFT DISTRIBUTION

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Abstract

The design of a blended wing body (BWB) has been the subject of numerous research projects worldwide, as it offers significant advantages over a conventional tube-and-wing configuration. The European Clean Sky 2 project NACOR investigated the potential of innovative unconventional aircraft architectures. A BWB configuration was identified to reducing fuel consumption by 10% compared to a relevant reference aircraft with entry into service 2035 and prevailed against box-wing or strut-braced wing aircraft. For this reason, the need to be capable of designing and evaluating BWB configurations was recognized.

Especially for the design of BWBs, an optimized wing twist is important to achieve high aerodynamic performance, but on conceptual design level the number of wing stations is often limited to reduce complexity which impedes this optimization. Computationally expensive calculations such as Reynolds-averaged Navier-Stokes (RANS) or Euler method are required to optimize wing twist, but this reduces the number of possible designs examined in a given time. Therefore, this paper presents the feasibility of flexible number of wing stations to achieve an aerodynamically optimized wing twist for BWB architectures on conceptual aircraft design level with embedded low fidelity multi-lifting line approach.

The aim of the flexible wing modelling combined with a multi-disciplinary design analysis and optimization (MDAO) aircraft design environment is to exploit the benefits of low computational costs and high flexibility with respect to the vehicle architecture to be analyzed with an adequate level of fidelity. The resulting fast analysis capability enables a wide range of possible sensitivity studies and optimizations to ensure a more robust aircraft design space exploration.

The target lift distribution is determined by high fidelity RANS calculations and used as an objective function for the twist optimization. In addition, typical lift distributions, i.e. elliptical and triangular lift distributions, are used to benchmark the results. The final results show the influence of the number of wing stations on the resulting twist distribution, induced drag as well as the CPU cost, and provide a proposal for an appropriate number of wing stations to be used.

Keywords: Blended-Wing-Body, Twist Optimization, Flexible Number of Wing stations, Multi-Disciplinary Design Analysis and Optimization (MDAO), Conceptual Aircraft design

1. Introduction

A wide range of unconventional commercial aircraft configurations, i.e., a strutted swept-wing aircraft, a tailless aircraft, a box wing aircraft, and a blended wing body (BWB) were investigated by IWANIZKI et al. [1] within the European Clean Sky 2 project NACOR (New innovative Aircraft Configurations and Related issues). The study indicated that a BWB is the most promising configuration to enhance the aircraft's performance for short- and medium-haul operations. Unconventional aircraft configurations therefore have the potential to significantly reduce fuel consumption. The potential is realized by expanding the design space of possible configurations and optimizing them to reduce fuel consumption while at the same time reducing climate impact, or by exploiting synergies between energy carriers and aircraft configuration, for example.

In addition, LIEBBECK et al. [2] revealed for a BWB design with 800 passengers and a range of $7000NM$ that a 27% reduction in fuel consumption is possible with a lower operating empty mass and take-off mass of 12% and 15%, respectively, and 20% improved aerodynamics compared to an appropriate reference aircraft. In Europe, several contributions have been made to the development of BWB configurations through the "Multidisciplinary Optimization of a Blended Wing Body" (MOB) [3], "Silent Aircraft eXperimental Design" (SAX-40) [4], "Very Efficient Large Aircraft" (VELA) [5, 6], "New Aircraft Concept Research" (NACRE) [7] and "Active Flight Control for Flexible Aircraft" (ACFA) [8] projects [9]. These projects have demonstrated the potential of BWB configurations where a possible fuel benefit ranges from 1.2% [5] to 25% with additional synergies for noise reduction [4]. However, the BWB configuration has not yet gained acceptance as a passenger aircraft due to the many unanswered questions regarding the BWB's structural definition and handling characteristics. A model-based collaborative MDO framework to design BWBs is presented by PRAKASHA et at. [10] as part of the AGILE project. The framework showed a reduction in time for the setup of complex design problems involving a large multinational team. The ONERA CICAV project has developed an MDAO process for the design of BWBs that incorporates a broad range of expert knowledge [11]. The process was demonstrated on an A350-1000 as a reference aircraft and resulted in a 26.4% reduction in block fuel for an optimized BWB.

Within NACOR, FRÖHLER et al. [12] analyzed a BWB configuration on conceptual aircraft design level and was partially enhanced with results from high fidelity (HiFi) methods. The single-deck configuration with the cargo compartment adjacent to the cabin included embedded engines to make use of the boundary layer ingestion (BLI) effect. A comparison of the A320-Baseline aircraft with incremental technology improvement for the year of entry into service 2035 showed that a 10.3% reduction of block fuel seemed possible.

This paper introduces a methodology capable of analyzing BWB configurations to enable for a wide range of sensitivity studies, optimizations and design space explorations at low computational cost. Numerous detailed assessments and optimizations are required during the conceptual design phase of aircraft to enable the most accurate prediction of the potential for new aircraft designs and to further identify configurational design drivers. It is well established that BWB architectures are aerodynamically efficient and reduce interference drag due to the blending of the fuselage and the wing. However, BWBs have a low aspect ratio due to their large wing area, which consequently leads to an increase in induced drag coefficient. To maintain high aerodynamic efficiency, an optimized wing twist is essential to obtain desired lift distributions and aerodynamic performance. On conceptual design level the number of wing stations is often fixed to reduce complexity, however, this impedes this optimization and the aerodynamic potential cannot be thoroughly identified. Therefore, a conceptual aircraft design tool is being further enhanced and matured suitable for the design of BWBs with the ability to prescribe a flexible number of wing stations. The resulting conceptual aircraft design capability provides consistent estimates of the geometry, mass & center of gravity, propulsion system, aerodynamics and aircraft performance for BWBs. The design is enriched with the results of higher-fidelity disciplinary methods including: an engine model, an estimation of aerodynamic forces for the whole flight envelope and estimation of aircraft performance as well as an evaluation of longitudinal flight stability and supporting a flexible number of wing stations throughout the whole process.

Therefore, the current work will provide a detailed overview of the developed variable fidelity MDAO aircraft design environment with an additional twist optimization and will describe the used and developed methods. Subsequently, based on the presented methods, the process of identifying the number of wing stations for a desired lift distribution and optimal computational performance is shown.

2. Aircraft Design Environment

The aircraft design environment is integrated into the RCE (Remote Component Environment) platform [13]. RCE is a workflow-driven integration platform to combine several software components of different disciplines and variable fidelity to allow for a collaborative and distributed work between different DLR institutes and external partners. The software components can be integrated from local or remote locations and communicate with a common language through their inputs and outputs. The "Common Parametric Aircraft Configuration Schema" (CPACS) [14, 15] supports the exchange

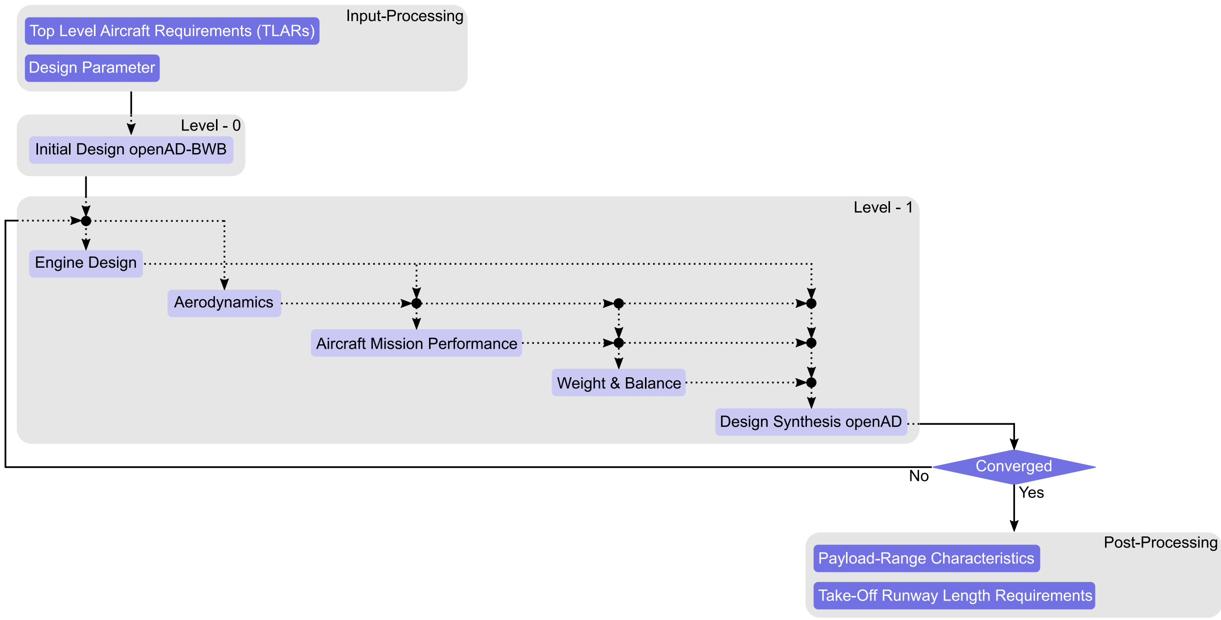


Figure 1 – Variable fidelity MDAO conceptual aircraft design environment

information and stores data of the aircraft's shape and performance as well as information on its operations.

The flowchart in Figure 1 represents the design process originally developed for the design of conventional tube-and-wing configurations, but now extended for the design of BWBs. The process is divided into an input process, the Level-0 and Level-1 simulation modules, and a post-processing step. Due to its modular approach and a common language to communicate between each module, the capabilities of the design environment are versatile with respect to a wide variety of possible vehicle architectures. Utilizing the design environment provides an estimate of the geometry, weight & balance, propulsion system, aerodynamics and aircraft performance. OpenAD is a conceptual aircraft design tool which initiates the design process and provides the required complete description of the aircraft. Higher-fidelity disciplinary tools are allocated in the level-1 domain which refine the preliminary results of openAD. The engine performance module incorporates the results of virtual engine platform GTlab (Gas Turbine Laboratory) [16] which describes the engine performance. The aerodynamic module estimates the aerodynamic forces for the whole flight envelope including the high-speed aerodynamics, low-speed aerodynamics with a deflection of control surfaces and a twist optimization to obtain the desired lift distribution. To assess the aircraft performance, two tools are deployed which use the engine design in conjunction with the aerodynamics. The low-speed performance tool [17] estimates the take-off and landing performances. The high-speed performance tool [18, 19] calculates the mission performance for an optimized initial cruise altitude at maximum specific range, and combines a constant altitude and a stepwise climb for the cruise flight. Flight stability is particularly important for BWB configurations. A sophisticated flight control system along with a movable layout is assumed to ensure artificial stability. The longitudinal flight stability is evaluated for the design mission within the weight & balance module. To obtain a consistent aircraft design, the process is iterated until the major aircraft parameters converge, followed by post-processing of the results. As DLR's tool landscape is constantly evolving, the design environment can easily be extended to answer future scientific questions.

2.1 Conceptual Aircraft Design Module

An integral part of the aircraft design environment is the conceptual aircraft design tool openAD with its capabilities to initialize the design process and to synthesize higher fidelity results. WÖHLER et al. [19] presented openAD as part of a MDAO design environment dedicated to conventional tube-and-wing aircraft architecture valid for a design space ranging from 19 passengers (Dornier 228 size) up to 800 passengers (Airbus A380 size) as illustrated in Figure 2.

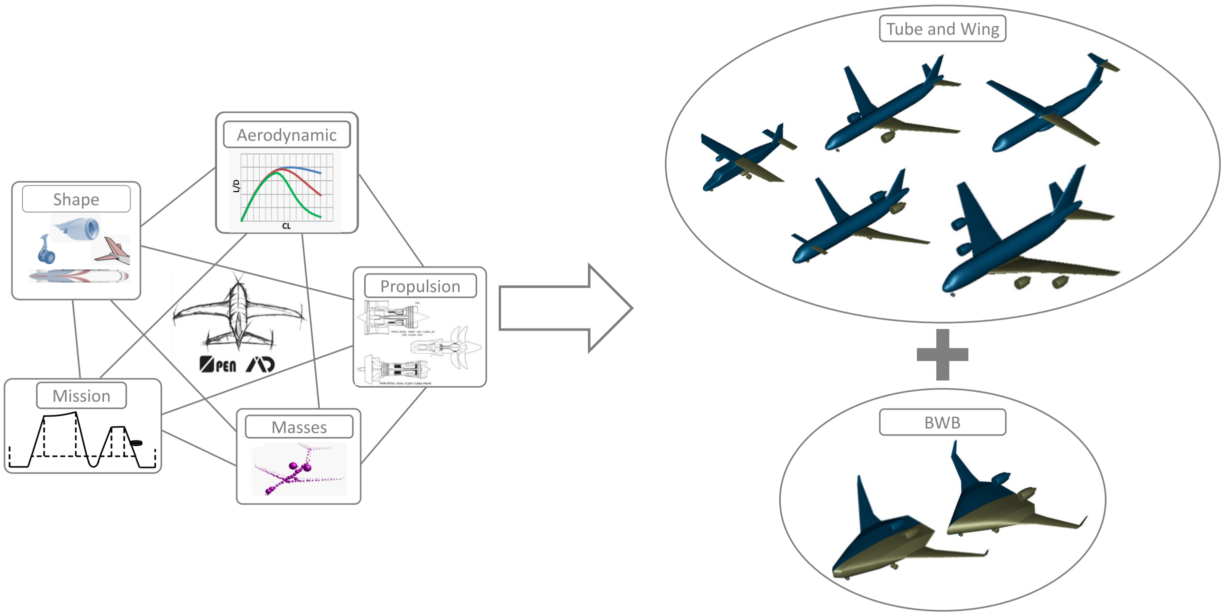
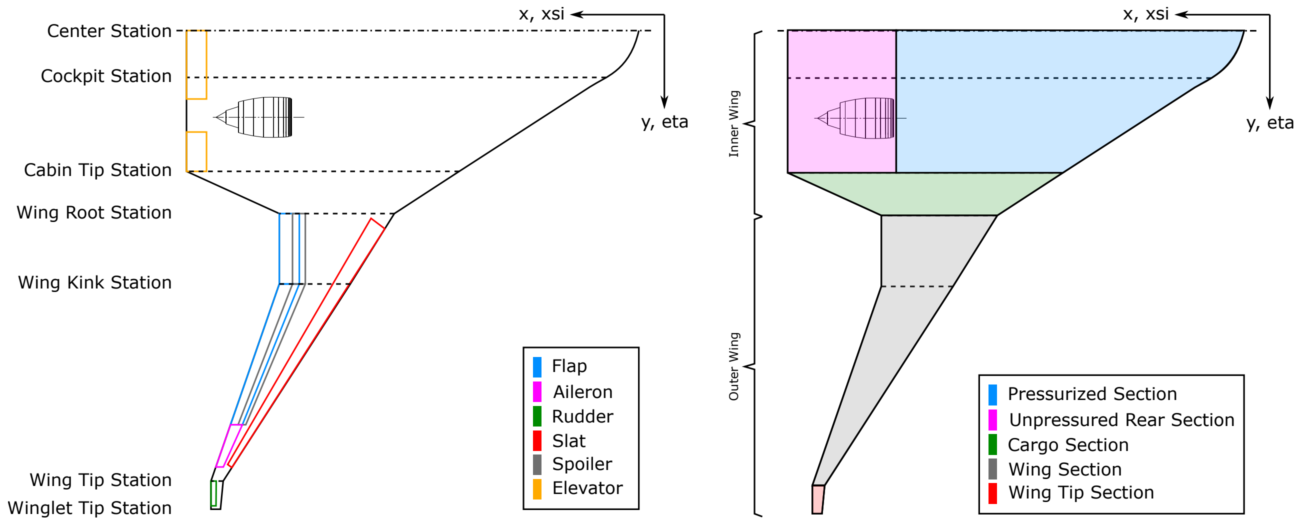


Figure 2 – Conceptual aircraft design tool openAD extended for BWB architectures

In addition to the capabilities to design conventional tube-and-wing configurations, openAD was extended in the course of this work to design BWBs. This included the implementation of appropriate mass methods, an approximation of the cabin area, and the possibility to consider a flexible number of wing stations to provide more starting points for the optimization of the planform or the lift distribution. The default setting of openAD is for the design of conventional tube-and-wing aircraft and interprets the fuselage, empennage, landing gears, propulsion unit and a wing with five stations and four segments. Due to the radical change in the geometry of a BWB configuration, the geometry definition was revised to meet the requirements of BWBs with a flexible number of wing stations and the removal of unnecessary components. The general philosophy remained the same as for conventional aircraft, where the wing is designed starting from the trailing edge and overall parameters, i.e., dihedral angle, sweep angle, and predefined dependencies, are implemented to obtain a wing planform geometry with a minimum set of input parameters. Local parameters for each station and segment, i.e. profile thickness, angle of incidence for twist distribution, sweep angle for the leading and trailing edge, and dihedral angle, can be set to produce the desired geometry. It is necessary to predefine certain stations to define the positions of the different sections for the cockpit, cabin, cargo, wing root, wing kink and wing tip (see Figure 3). A variable number of additional stations can be inserted between these predefined stations, which can either be interpolated to match the planform or customized to give a more individual shape. In this way, a fully parameterized wing is implemented, opening the design space for future planform optimizations. Furthermore, an initial movable layout is defined as shown in Figure 3(a), including elevators in the center wing and rudder on the winglet for yaw control, as well as a typical movable layout consisting of slats, flaps, ailerons, and spoilers on the outer wing. The BWB is principally divided into five sections (see Figure 3(b)), with the pressurized section comprising the cockpit and cabin compartment, which is sized according to a PAX density equivalent for a reference aircraft with a typical cabin layout.
For the mass estimation, a combination of methods for conventional tube-and-wing configurations and new methods for BWBs that were developed as part of the VELA project were used [5, 20]. The mass methods for the power unit, the pylon, the landing gears, systems and furnishings are the standard openAD methods which are based on empirical and semi-empirical methods [21–24] and were selected based on a trade-off between accuracy and sensitivity. The methods obtained from the VELA project are based on area-dependent masses and are used to calculate the BWB structure for inner and outer wing. The position of the center of gravity (CG) is estimated separately for each component and has been derived from statistical data. The other disciplines, i.e., aerodynamics, propulsion unit, and mission performance, remained similar to the conventional calculation, but were



(a) Initial Movabel Layout (b) Section Definition

Figure 3 – Overview of BWB planform definitions on openAD

adjusted for the design of BWBs. However, the design of BWB configurations remains challenging due to the lack of validated methods for estimating the governing physical effects, leading to large uncertainties in the design.

2.2 Propulsion Unit Module

The virtual engine framework GTlab (Gas Turbine Laboratory) [25–27] enables the multi-fidelity multidisciplinary design of aero engines and is developed at the DLR. The framework combines a central data model with several tools and modeling capabilities e.g. the performance code DLRp2 or conceptual design methods to predict engine geometry and mass [28]. In the context of this paper, GTlab is used to design a geared unmixed turbofan engine specifically suited for the BWB application. Therefore, the flight conditions, off-take demands and thrust requirements of the BWB aircraft are accounted for at all relevant sizing operating points. The engine model has a low-pressure turbine with 3 stages which drives the fan in front of a gearbox and the booster. The high-pressure system consists of a compressor with 9 stages and a double-staged turbine. The predicted engine geometry is depicted in Figure 4. The engine features an overall pressure ratio of 55 at top of climb with a combustor outlet temperature of 1732 K and has a thrust specific fuel consumption of 13.8 kg/kN/s at cruise conditions. An engine deck is calculated to provide the performance of the propulsion unit for the entire flight envelope.

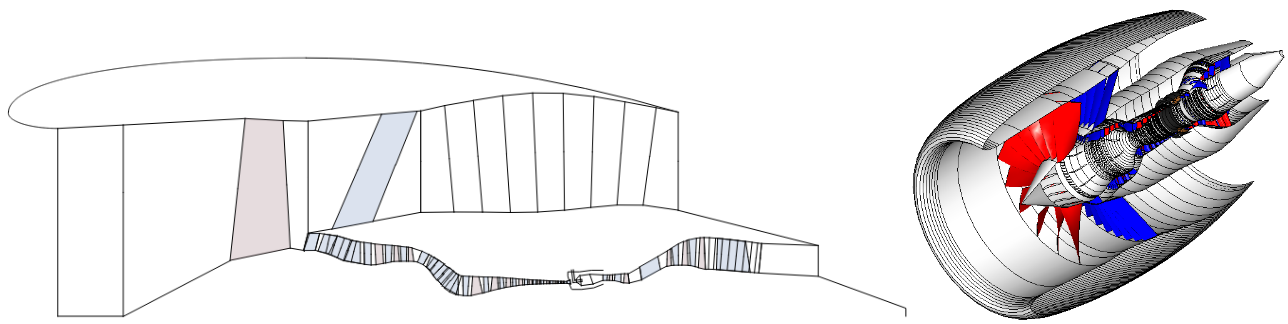


Figure 4 – Illustration of the engine geometry

2.3 Aerodynamic Module

The aerodynamic module estimates the aerodynamic forces and moments for the whole flight envelope. Two DLR-own tools, i.e. Lifting-Line (LiLi) and HandbookAero (HB) and a python-script are utilized for this purpose.

2.3.1 High-Speed Aerodynamics

LiLi [29, 30] is a multi-lifting-line method and used to calculate the aerodynamic parameters of non-planar wings. It is based on the potential flow theory, assuming an inviscid, irrotational and steady flow around a wing following the theory of the thin airfoil. Furthermore, it is extended by a compressibility correction for subsonic flows. In the scope of this work it is mainly used to estimate the lift, the induced drag and the pitching moment within the whole flight envelope. LiLi also calculates the impact of simple control and high lift devices. HB is used to calculate the viscous drag contributions that are not covered by LiLi. It utilizes established semi-empirical handbook methods [21, 23] and methods developed by DLR [31]. User-defined equations can be used for additional flexibility. Both tools are CPACS-compatible and perform their calculations based on the actual geometry defined in the dataset. Finally, the lift dependent pressure drag and the wave drag are calculated in a post-processing step with an external python script [21, 22]. The tools have been already thoroughly tested in different projects and the subject of many previous and ongoing studies.

2.3.2 Low-Speed Aerodynamics

For aircraft configurations with simple high lift systems, low-speed polars are also generated utilizing LiLi and HB. Since none of the tools is capable of estimating the maximum lift coefficient, this parameter is calculated by external tools based on handbook methods or is provided by HiFi analyses. It is then used to limit the polars calculated by the aforementioned tools.

2.3.3 Neutral Point

LiLi is applied for the calculation of the configuration's location of the neutral point (x_{np}). For this purpose, the static margin $-\frac{C_{m\alpha}}{C_{L\alpha}}$ is calculated based on the aerodynamic parameters at two angles of attack. Using the geometric information in CPACS that includes the location of the CoG (x_{cg}) and the mean aerodynamic chord (c), the location of the neutral point is calculated as described in [21] using the equation 1.

$$-\frac{C_{m_\alpha}}{C_{L_\alpha}} = \frac{x_{np} - x_{cg}}{c} \tag{1}$$

2.3.4 Twist Distribution

Using LiLi, the wing twist is tailored to target lift distribution assuming a trimmed mid-cruise flight condition without any control-surface deflection. A load case at mid-cruise condition for a target lift coefficient is prescribed and LiLi estimates the lift distribution in spanwise direction. The principle of the twist fitting is illustrated in Figure 5 and is based on an approach presented by EFFING et al. [32]. Based on the lift $(c_l \cdot c)$, the target lift distribution and the resulting lift distribution is compared and at each wing station (n_i), the difference in lift is calculated and the angle of incidence adapted accordingly by

$$\alpha_{i_{n_{new}}} = \alpha_{i_{n_{old}}} + \frac{\Delta(c_l \cdot c)_n}{c_{l\alpha} \cdot c_{n_{old}}} + AoA \tag{2}$$

where α_i is the incident angle, $\Delta(c_l \cdot c)$ is the delta lift which descibes the difference of the resulting lift disribution to the target lift disribution, $c_{l\alpha}$ is the lift coefficient gradient and assumed to be $c_{l\alpha} = 2\pi$, c is the chord length and AoA the angle of attack. In order to obtain a constant planform, the chord length must also be adjusted with

$$c_{n_{new}} = \frac{\cos(\alpha_{i_{n_{old}}}) \cdot c_{n_{old}}}{\cos(\alpha_{i_{n_{new}}})} \tag{3}$$

and in additon, the z-position at the trailing edge is kept constant by

$$z_{new} = z_{old} + \tan(\alpha_{i_{n_{new}}}) \cdot c_{n_{new}} - \tan(\alpha_{i_{n_{old}}}) \cdot c_{n_{old}} \tag{4}$$

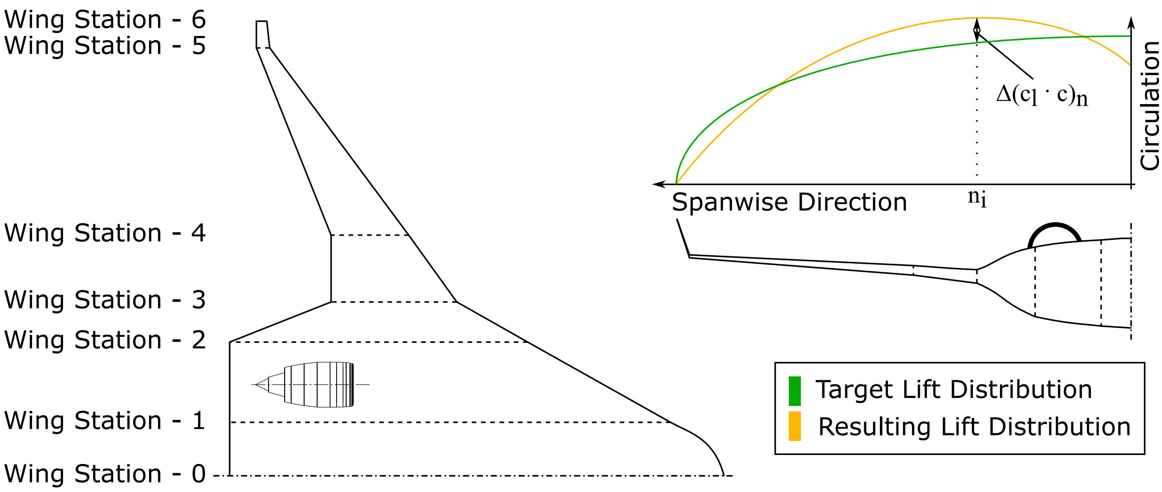


Figure 5 – Illustration of lift distribution in spanwise direction

As suggested by EFFING et al. [32], a residuum based on the root-mean-square error is calculated and was set to a convergence rate of $\varepsilon = 0.02$.

2.4 Weight & Balance Module

As the aircraft consumes fuel throughout the mission, the center of gravity (CoG) of the aircraft shifts and therefore the static margin with it. This shift in static margin is determined by a simple weight & balance tool. The aircraft CoGs are extracted from the output of openAD and it is assumed that the fuel tank CoG are unaffected by their filling levels. Figure 6 illustrates a typical shift in static margin for a conventional tube-and-wing configuration. The tool analyzes the fueling and de-fueling sequence of a given combination of fuel tanks and thus provides a basic longitudinal stability check.

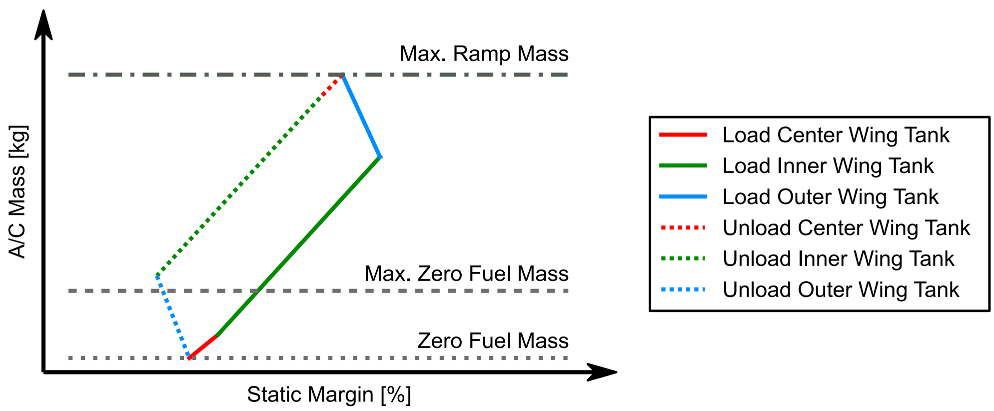


Figure 6 – Illustration of the change in aircraft static margin during flight due to fuel consumption

2.5 Aircraft Mission Performance Module

The aircraft mission performance is essential for the assessment of a given aircraft configuration. Within this aircraft design environment, two tools are used to estimate low and high speed performance that have been well proven in many previous and ongoing studies.

The low-speed performance tool [17] computes the take-off and landing trajectories by stepwise solving the 2D equation of motion incorporating the low speed aerodynamic polar with deflected control surfaces and the engine with a maximum take-off rating (MTO). During the level-1 segment, an all engines operating (AEO) case for a standardized take-off and landing trajectory [33] is used which provides the fuel consumption and transmits it to the high-speed performance calculator.

To calculate the high-speed performance and the energy consumption of payload-range combinations, the aircraft mission calculator (AMC) is applied [18, 19]. It combines the high-speed aerodynamic and propulsion performance as well as mass properties of the aircraft by reading performance

decks in CPACS format. For high flexibility, the tool allows arbitrary sequences of predefined segments. A specific aerodynamic and engine performance deck can be defined for each segment. Furthermore, the optimum flight altitude is calculated for minimum energy consumption, considering several constraints. Multiple segments can be clustered to segment blocks, each with a specific end condition such as range, fuel consumed or electric energy consumed.
Finally, in a post-processing step, the payload-range and balanced-field-length characteristics are estimated using the aforementioned tools to provide a more detailed assessment of aircraft performance.

3. HiFi - Aerodynamics

In the scope of the project NACOR, HiFi-CFD (Reynolds-averaged Navier-Stokes (RANS)) computations have been carried out for a short-and-medium range BWB-configuration [12]. This configuration has been delivered in the CPACS-format by the overall aircraft design (OAD) and has been converted to a parametric CAD-model in CATIA suitable for RANS calculations. The geometry has been reduced to the glider configuration. For mesh generation, the commercial tool CENTAUR has been used. A representative mesh is shown in Figure 7.

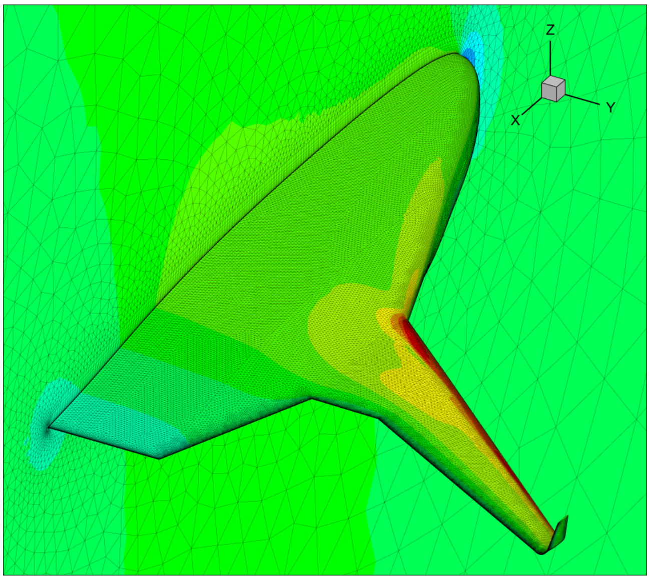


Figure 7 – CFD-Mesh of the BWB with $3 \cdot 10^6$ nodes

For flow calculations, the DLR TAU code [34, 35] has been applied. A fully turbulent flow has been assumed and the Spalart-Allmaras turbulence model has been utilized. A wing-twist optimization of the outer wing has been carried out in order to maximize the L/D-ratio at cruise conditions, considering the requirement for trimmed flight. Finally, polars at different operating conditions and the spanwise lift distribution in cruise for the optimized configuration have been provided for the calibration of the LoFi-methods.

4. Baseline BWB Configuration

As part of the European Clean Sky 2 project NACOR, a BWB was designed for a short and medium range mission in combination with embedded engines using the BLI effect. Earlier work was presented by Fröhler et al. [12] who provided a detailed description of the BWB including the results of the aerodynamic HiFi calculations. The top-level aircraft requirements (TLARs) are extracted from the CeRAS CSR-01 open configuration developed by RWTH Aachen [36] which are based on an Airbus A320-200. Table 1 shows the relevant key aircraft parameters of the analyzed BWB.

Table 1 – Relevant key aircraft parameters of the NACOR - BWB

Parameter	**Unit**	**Value**
Entry into Service	-	2035
Design Range	NM	2500
Design Payload	t	17.0
Number of Passengers	-	150
Cruise Mach Number	-	0.78
Span Limit ICAO Code C	m	36

A three-view of the analyzed BWB configuration with its overall dimensions is depicted in Figure 8. The planform was optimized with respect to passenger and cargo accommodation of the inner wing to match the requirements of the reference A320 configuration as well as the sweep of the outer wing to reduce fuel consumption. The profiles were obtained from the VELA project [5, 6], which assigned the reflected airfoils to the inner wing, while the outer wing was assigned supercritical airfoils. An elaborated flight control system is assumed to ensure artificial flight stability.

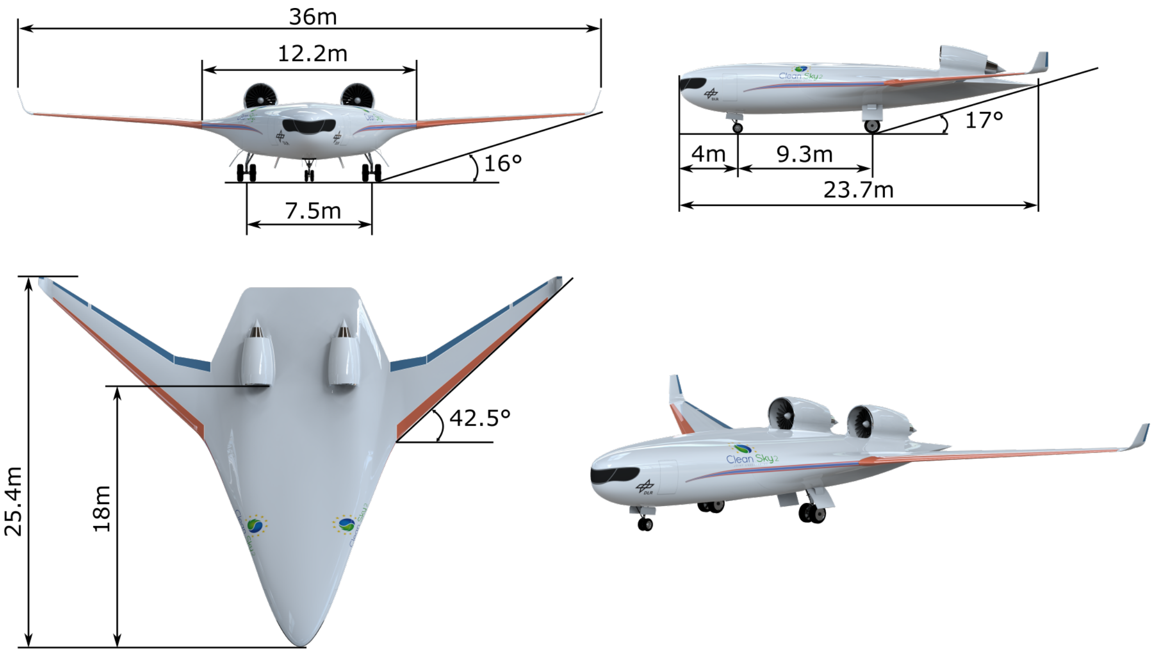


Figure 8 – Three-view of the NACOR - BWB configuration with BLI

The BWB was evaluated by comparing the maximum take-off mass (MTOM), operating empty mass (OEM), lift-over-drag ratio (L/D), and block fuel (BF) to the A320 reference with technology improvements for the year 2035. Figure 9 shows a bar chart analyzing the BWB with and without BLI. It can be seen that for both configurations, the MTOM and OEM are reduced by approximately 4%, while the L/D is improved by 8.3% for the BLI configuration and 4.3% for the configuration without BLI. The difference in L/D resulted from the fact that the BLI configuration had embedded engines at the rear of the inner wing, which reduced the wetted area and thus viscous drag. The integration of BLI technology also affects the engine, but in this study the advantage of the power saving coefficient is compensated by the disadvantage of the fan pressure losses, and therefore no significant increase in engine efficiency is anticipated. This yielded a BF reduction of 10% for the BLI configuration which came exclusively from the reduction in wetted area, while a reduction of 6.7% is still feasible without BLI.

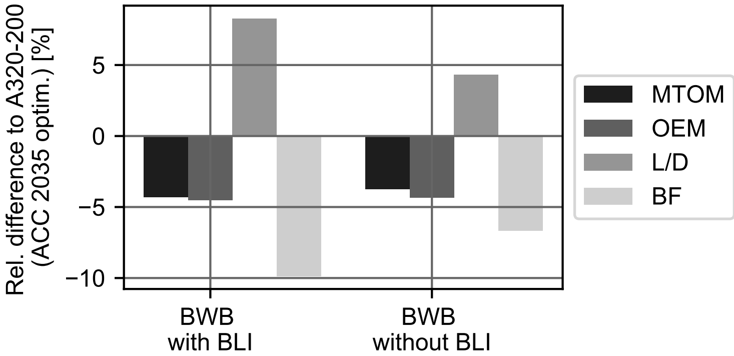


Figure 9 – Comparison between the NACOR - BWB configuration to Reference

Figure 10 displays the lift and twist distribution of the HiFi and LoFi results for a wing with eight stations. The twist optimization was performed at constant flight conditions with a constant angle of attack of 5°, a flight altitude of $12000m$ and a Mach number of 0.78. For the HiFi twist optimization, the same stations were used to adjust the twist distribution as defined by the OAD. However, a spline was defined between each sample point, which deviates from the linear relationship of the LoFi OAD. It can be observed that although the twist distribution at the prescribed station agrees well, the lift differs and a large calibration effort was necessary for further studies, as shown by FRÖHLER et al. [12]. The research question arose as to whether the number of stations used to adjust the twist was sufficient to represent the targeted lift distribution. In other words, is it possible to increase the number of stations to reduce the calibration effort and improve the accuracy to achieve the targeted lift distribution?

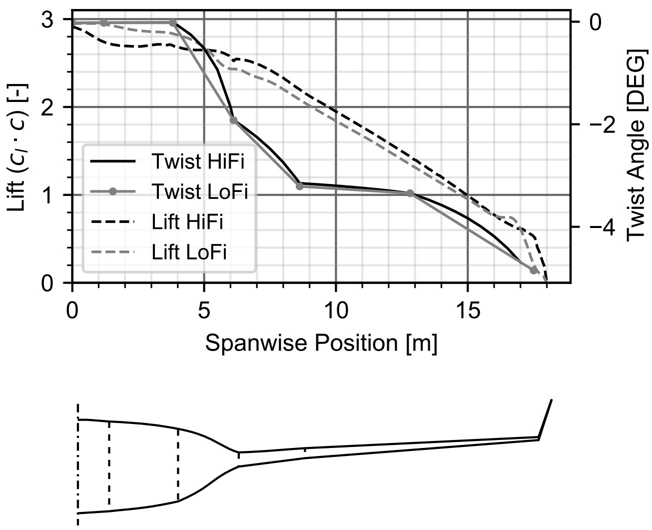
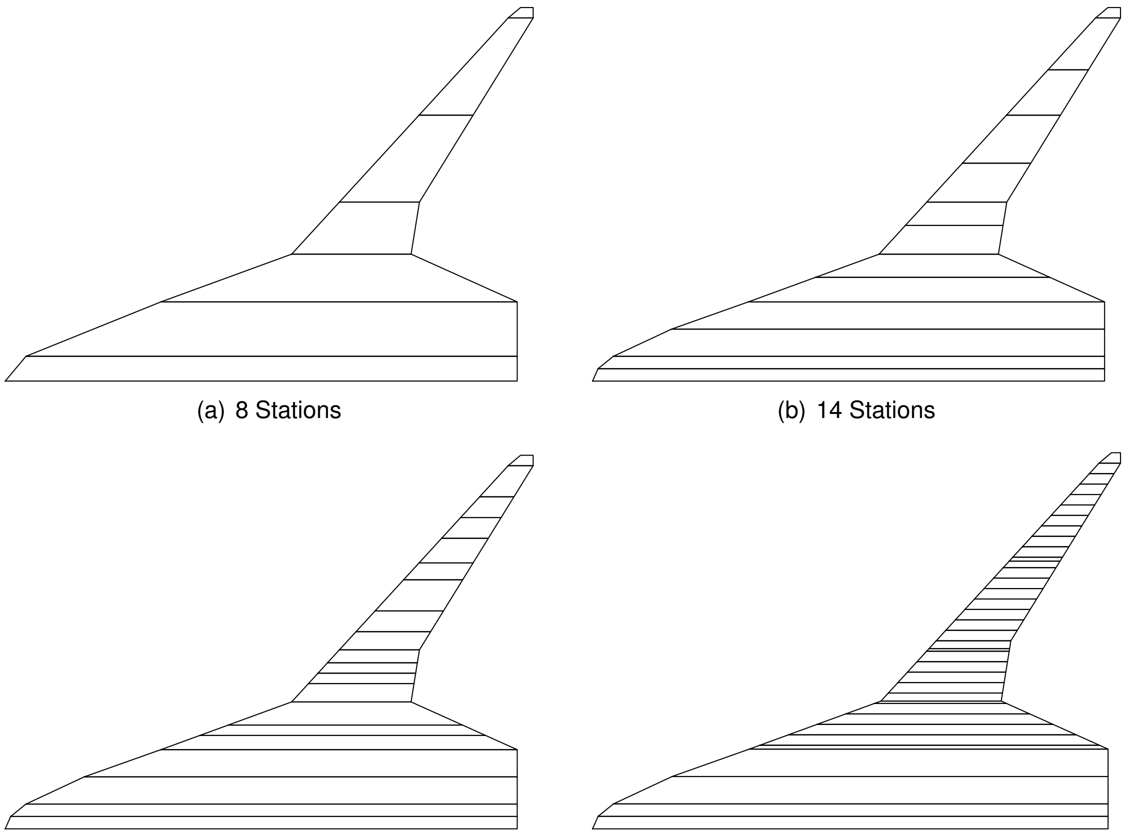


Figure 10 – Spanwise twist and lift distribution of the NACOR - BWB configuration

5. Results

To determine an appropriate number of wing stations, the lift and twist distribution of the HiFi CFD results are compared with the low-fidelity results from the aircraft design environment. Starting from the initial wing geometry with 8 stations and 7 segments, the number of stations is increased successively. Figure 11 shows the four different patterns with 8, 14, 21 and 37 stations. A particular attention was given to the transition between the inner and outer wing as well as to the outer wing itself.

First, the results of the effects of the number of wing stations on the twist distribution were analyzed for an elliptical, triangular, and an intermediate between elliptical and triangular lift distribution, which were used as the reference case. Subsequently, the lift distribution of the HiFi CFD simulation was



(a) 8 Stations (b) 14 Stations

(c) 21 Stations (d) 37 Stations

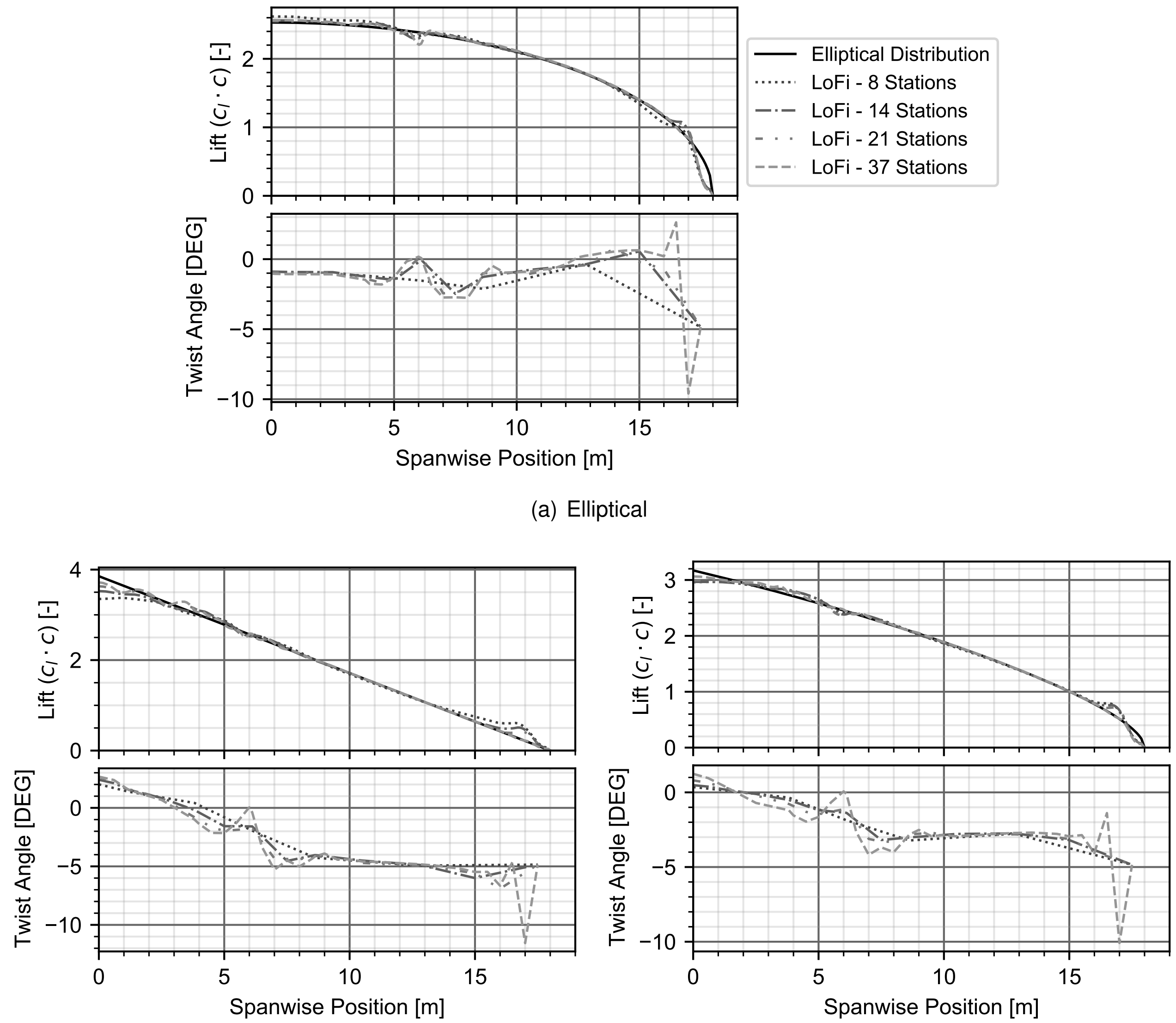
Figure 11 – Comparison of the BWB planform with different number of stations

compared to the LoFi model. It is investigated how the number of wing stations affects the aerodynamics and performance of the aircraft and how this affects the computational cost.

5.1 Typical Target Lift Distributions

The lifting line theory suggests that an elliptical lift distribution should be targeted to minimize the induced drag. However, structural effects as well as the positioning of secondary wing structures, such as control surfaces, must be taken into account, leading to a deviation from such an elliptical lift distribution. Especially for BWBs, the optimization of the lift distribution becomes increasingly challenging since BWBs are highly multidisciplinary and it is inevitable to consider the blended wing as a holistic system. But in conceptual aircraft design, a target lift distribution is often not available and benchmark lift distributions must be relied upon. Therefore, three lift distributions are proposed by QIN at al. [37], namely an elliptical distribution, a triangular distribution, and an intermediate between elliptical and triangular distribution, which are studied subsequently.

Figure 12(a) shows the result of fitting to an elliptical target lift distribution and the resulting twist distribution. The general shape of the elliptical lift distribution is well matched, but variations in lift are observed at a spanwise position of 6 m, the transition between the inner and outer wings. These variations are due to the rapid change in chord length and profile thickness, which was intended to be compensated by the twist leading to fluctuations in the twist distribution. Furthermore, larger deviations of the lift distribution can be seen at the wing tip. This deviation is due to the interaction between the outer wing and the winglet, which changes the local lift and does not achieve a clean elliptical distribution. This deviation was also to be compensated for by the twist, which resulted in a twist distribution that was not reasonable, since it would not be feasible to manufacture. Similar to the elliptical lift distribution, the triangular distribution and an intermediate shape between the elliptical and triangular distributions in Figure 12(b) and Figure 12(c), respectively, show good agreement with the target lift distribution. Fluctuations at the inner wing section and at the wing tip are also observed. The fitting to the three benchmark lift distributions was successfully performed and resulted in an



(a) Elliptical

(b) Triangular

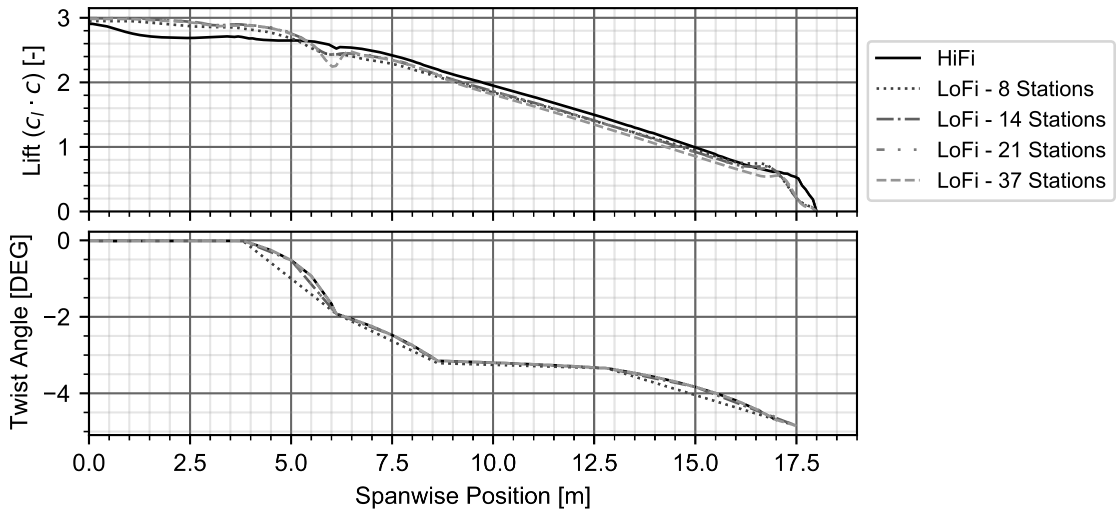
(c) Intermediate Ellip./Trian.

Figure 12 – Benchmark lift distribution and twist distribution

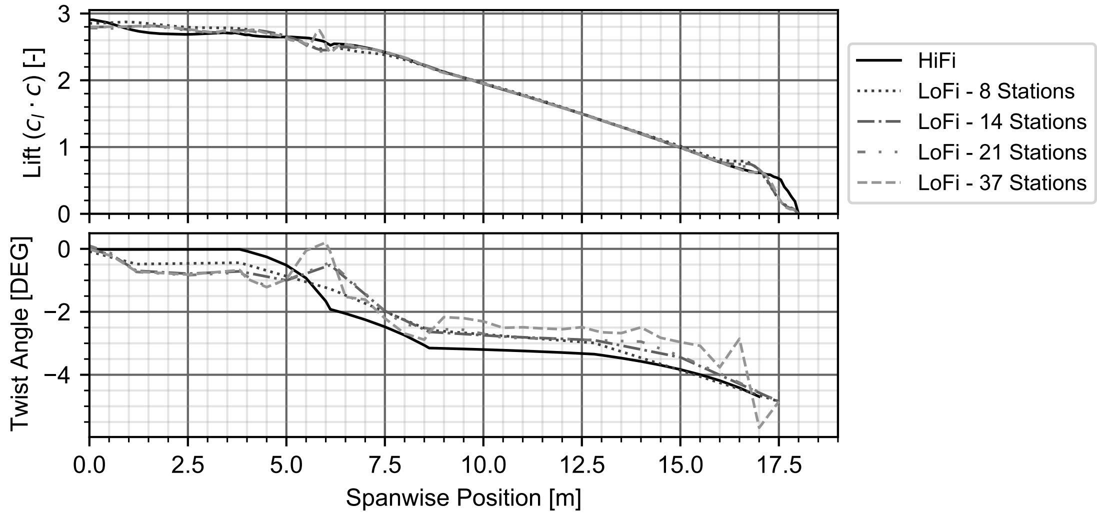
overall good match. Only with 8 wing stations some deviations from the target lift distribution were observed. As the number of wing stations increases, the agreement with the target lift distribution improves, while the twist distribution starts to fluctuate more, leading to deterioration and thus to an unsuitable twist distribution for manufacturing.

5.2 HiFi Lift Distributions

Since it is important with BWBs to consider the design as a holistic system, it is not advisable to rely solely on minimum induced drag optimization. It is desirable to reduce the loading on the outer wing by shifting the loading inwards. This reduces bending moment and benefits structural considerations while reducing the strength of shocks and wave drag on the outer wing. [38]. Figure 13 shows the lift and twist distribution obtained from the preceding HiFi design procedure (see chapter 3.). First, the twist distribution of the HiFi procedure is applied to the four samples with different numbers of wing stations (see Figure 13(a)). It is investigated how increasing the number of wing stations to more closely match the desired twist distribution changes the lift distribution. It can be observed that despite good agreement of the twist distribution, the lift distribution shows a deviation from the target lift distribution. As originally anticipated, increasing the number of stations to improve coincidence with the HiFi lift distribution was not present.



(a) Fitting Twist



(b) Fitting Lift

Figure 13 – HiFi lift distribution and twist distribution

In a next step, the lift distribution of the HiFi procedure is targeted by adjusting the twist. Figure 13(b) shows an overall good agreement between the target and the resulting lift distribution. However, similar to the benchmark lift distributions, an increase in the number of stations resulted in improvement, while twist fluctuation increased. In particular, 37 wing stations did not give a reasonable twist distribution with a large delta in twist angle between wing stations.

5.3 Proposed Number of Wing Stations

It has been previously shown that increasing the number of wing stations leads to a better match between the lift distribution and the HiFi target lift distribution, but conversely deteriorates the twist distribution due to large fluctuations. In this section, an advantageous number of wing stations is proposed depending on the desired planform and CPU cost. Figure 14 shows the relative CPU costs as a function of the number of wing stations. It can be clearly seen that the CPU costs increase with an increasing number of wing stations. While CPU costs remained within an acceptable range for up to 21 wing stations, costs increased significantly for 37 wing stations. In addition to the number of wing stations, it is proposed to change the twist fitting process by setting the inner wing stations to a constant twist angle and adjusting only the outer wing stations. This step is performed because the planform and twist distribution of the inner wing depends not only on aerodynamic performance, but also on passenger and cargo accommodation. Furthermore, the flow field at the inner wing is distorted by the interference from the engine at the rear of the inner wing, which is not considered in the LoFi aerodynamic analysis. Therefore, starting from the planform definition with 37 wing stations, the number of wing stations is reduced until the twist distribution is of acceptable quality and the CPU costs are within a reasonable range.

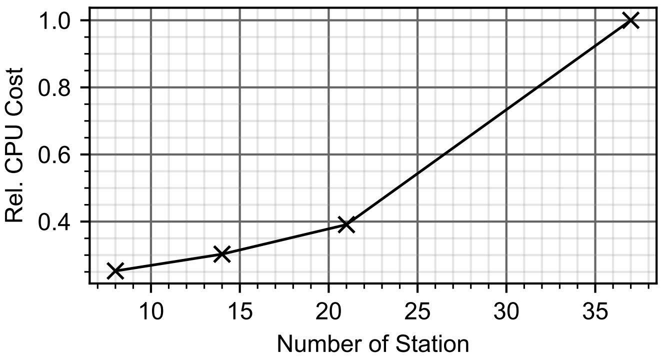


Figure 14 – CPU cost for different number of wing stations

The execution of this approach resulted in a planform design with 16 wing stations. For the inner wing, only four stations are defined that sufficiently capture the desired planform, and a higher definition with 12 wing stations are used for the outer wing. The results of the fitted lift distribution and its twist distribution are shown in Figure 15. As the inner wing was kept with a constant twist, larger deviations between the target and the resulting lift distribution can be observed. While on the one hand the outer wing agrees well with the desired lift distribution, on the other hand the twist distribution has the general shape of the HiFi result, but an offset is visible. This indicates that the LoFi methods are able to estimate the lift distribution well, but for the twist distribution, methods with higher fidelity are needed for a more detailed and precise design.

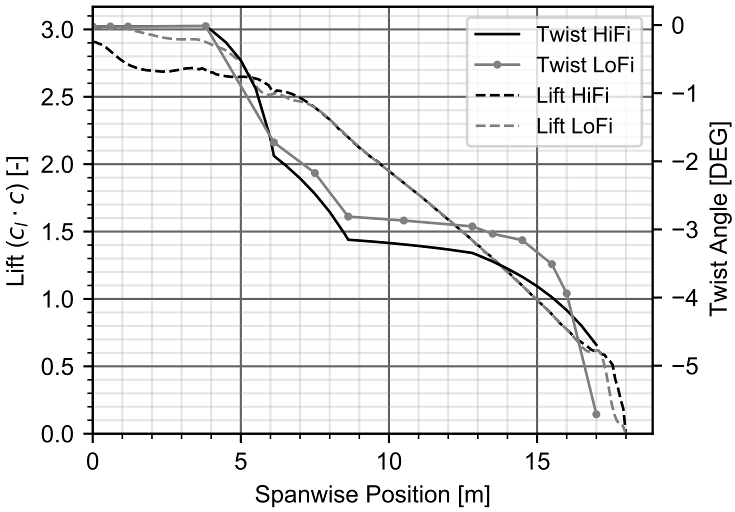


Figure 15 – Spanwise twist and lift distribution with an optimal number of wing stations

5.4 Performance Comparison

To enable a fair and robust comparison between two or more aircraft configurations, aircraft performance parameters, i.e. maximum take-off mass (MTOM), operating empty mass (OEM), lift over drag ratio (L/D), block fuel (BF) and in addition the induced drag (c_{D_i}), are used. Figure 16 shows a comparison between the configurations with a different number of wing stations, the three benchmark lift distributions, and the HiFi target lift distribution for the aforementioned aircraft performance parameter. For comparison, each configuration is represented as a relative change from the baseline configuration that was introduced in Chapter 4. The induced drag is compared at a flight altitude

of 12000 m, a Mach number of 0.78 and a lift coefficient of 0.25. Furthermore, the L/D ratio is an average value over the entire design flight mission.
As expected, the results confirm that the elliptical distribution gives the lowest induced drag among the different target lift distributions. Together with the low induced drag, the L/D ratio improves compared to the baseline, leading to a reduction in fuel consumption and thus a reduction in MTOM and OEM. However, since the mass estimations for the wing structure are based on the planform area and do not account for different lift distributions, the uncertainties for the OEM are high. The triangular lift distribution shows the highest induced drag with an increase of approximately 20%. This also affects the other performance parameters and leads to an inefficient aerodynamic design. The intermediate lift distribution of elliptical/triangular and the HiFi lift distribution show very similar results with only a small deviation to the baseline. It is noticeable that the OEM, especially for a planform design with 37 wing stations, shows a large deviation. This can be explained by the method employed, which is area dependent, and by changing the angle of twist, the area also changes, resulting in a different structural mass. Comparing the planform design with a different number of wing stations, it can be observed that the induced drag clearly depends on the number of wing stations. However, the design not only requires a minimum of induced drag, but must also be balanced with the other disciplines. It is necessary to determine a twist distribution that not only matches the desired lift distribution, but also considers the feasibility of the design.

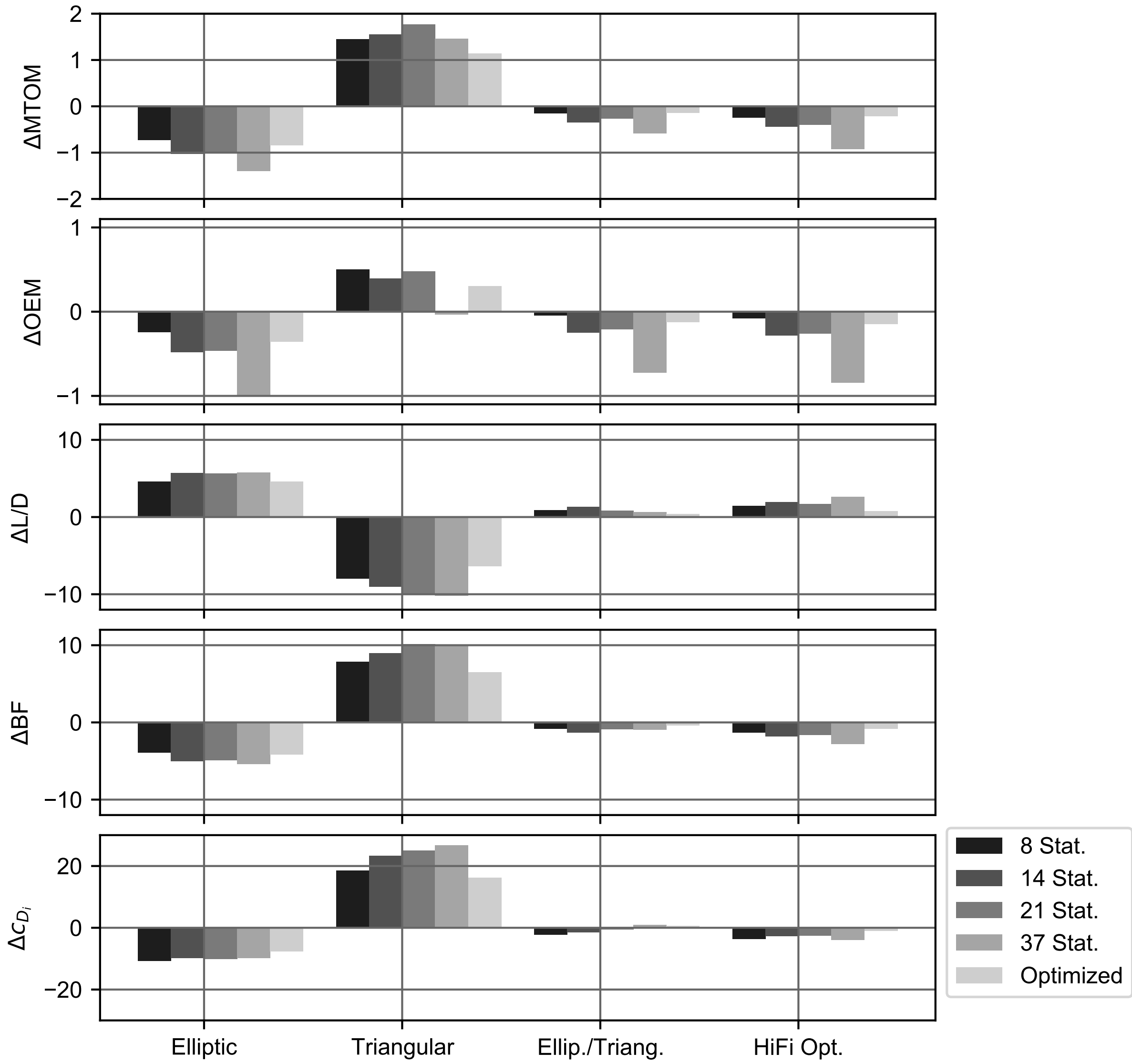


Figure 16 – Aircraft performance comparison for different lift distributions and for different numbers of wing stations

6. Conclusion

This research has shown the role of the number of wing stations and how it affects the lift distribution of BWBs. The developed MDAO variable fidelity aircraft design environment provided the means for the overall BWB design, which successfully designed a BWB aircraft with the same TLARs as the A320 reference configuration. Various tools and disciplines were combined to provide a holistic overview of the designed BWB. Since high aerodynamic efficiency is the objective for BWB configurations, optimized wing twist is required to achieve the desired lift distribution in the spanwise direction. Three benchmark lift distributions and a target lift distribution from a HiFi aerodynamics optimization were used to analyze the effects of the number of wing stations.

It was identified that the number of wing stations could lead to an improvement in estimating the lift distribution and a better representation of the desired BWB planform. However, with an increase in the number of wing stations, the distance between each wing station was reduced leading to fluctuations in the twist distribution and high CPU cost. A planform design with 16 wing stations was proposed and a new strategy for adjusting the lift distribution was applied. When adjusting the lift distribution, the inner wing stations were disregarded considering that other disciplines have to be considered here, and only the outer wing was used to obtain the desired lift distribution. The resulting lift distribution matched well with the target lift distribution, but although the twist gave the same shape as the HiFi result, an offset was found. It can be concluded that the LoFi aerodynamic methods can accurately estimate the desired lift distribution while providing a good initial twist distribution for subsequent investigations with higher fidelity. Furthermore, a target lift distribution from aerodynamic HiFi calculations is not always available, so benchmark lift distributions must be relied upon. The intermediate between the elliptical and triangular lift distribution provided similar aircraft performance compared to the HiFi results. This benchmark lift distribution balances wing bending for low structural mass with aerodynamic efficiency, providing a good starting point for future BWB designs and allowing a fair comparison between different designs.

A large number of different disciplines influence the performance of the aircraft and determine the feasibility of each design. Therefore, it is important to consider the multidisciplinary nature of aircraft development and BWB configurations in particular. Future work should further improve the aircraft design environment by incorporating various disciplines such as an economic perspective. The economic feasibility of an aircraft design can enable or prevent radical new developments, since the aviation industry is strongly cost-oriented. Further sensitivity studies and optimizations or incorporation of existing uncertainties of the applied methods would ensure a more robust design.

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8. Copyright Statement

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