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Assessment of Structurally-Constrained Spanloads for Span-Extended Wing Design

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High aspect ratio wings are receiving increased attention as a promising solution in pursuit of reducing aviation's environmental impact. To address the challenging trade-off between induced drag and weight, this paper presents an overview of the evaluation of the synthesis of wing aerodynamic and structural requirements for the design of high aspect ratio wings. This is done as a means to improve overall vehicle performance and enlighten the relevant complexities of the design process. A physics-based framework for the conceptual design stage has been composed to produce a set-based design space for the analysis of aircraft with high aspect ratio wings under prescribed aero-structural requirements, integrating state-of-the-art computational models and in-house developed methodologies to create a multi-disciplinary and multi-fidelity design environment. This enables to conduct comparative performance analyses of the proposed concepts relative to a conventional airliner. The impact of such a design approach is assessed at a mission performance level, yielding up to a 30% reduction in structural weight growth with span extension and increasing range-to-weight capabilities by 2%.

I. Introduction

The study of wing design has been consolidated through the engineering excellence reflected in the safety standards of aviation. However, the current socio-economic prospect has fuelled the prevailing need for a technological future that is in closer harmony with the environment, yet accommodating to our ever-growing demands. The consequential strive for more efficient flight has led many to challenge a diversity of conventionalities in civil aircraft design. These range from the venture into novel aircraft configurations to the redefinition of the design methods employed.

A. Current Trends in the Conceptual Design Stage

The established desire to develop unprecedented civil aircraft is becoming more conceivable and is present in the vision for the near future generations of aircraft[1–3]. Aircraft configuration is regarded as a critical factor that will redefine the way in which the current technological challenges are addressed. So far, airliners have been restricted to the conventional cantilever tube-and-wing configuration due to several limitations on structural and operational aspects, amongst others, which have hindered revolutionary changes in aviation. This increased interest in alternative configurations to increase efficiency follows the ever-growing concern for the stagnating levels of improvement given by conventional aircraft.

The novel concepts being pursued present many challenges to legacy methods traditionally employed at the conceptual design stage, where the fundamental assumptions that provided simplicity and speed now become limiting factors. Conceptual design tools still make extensive use of semi-empirical approaches, which consist of analytically-based equations derived from a theoretical foundation that is then adjusted using statistical correlations from historical and experimental data. Nevertheless, such approaches significantly increase the uncertainty on the prediction of novel configurations and technologies. It is widely accepted that novel aircraft concepts being proposed deviate significantly enough from the empirical databases for these methods to become unreliable. With this, trade-offs being assessed nowadays are heavily linked to the level of model fidelity required at this stage against the time and computational cost of the models[4–16].

Conceptual wing design is already a multidisciplinary task, where multiple disciplines come together on a top level to initiate the process with a reasonably constrained design space. Moreover, most of the life cost of a design is

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incurred during the decisions made in the conceptual design phase, because an appropriate early configuration will avoid costly re-design and corrections at later stages[17, 18]. Still, new concepts are becoming increasingly coupled across multiple disciplines, and with this, the need to address the multi-disciplinary nature of the conceptual design process has been exacerbated, in which traditional methods are becoming less reliable for the modelling of the envisioned novel configurations and technologies. Consequently, the conceptual design stage is under transformation, shifting from the use of analytical methods to predict the key parameters in each discipline to evolve into a vast design space where the interaction between variables can be evaluated via multidisciplinary design optimisation (MDO) and through sensitivity and uncertainty analyses, for which thousands of design points can be explored.

A significant number of aircraft concepts that have been recently proposed for future airliners revolve around the idea of induced drag reduction. These aircraft are predominantly characterised by having high aspect ratio wings (HARWs) [19, 20, 20–23], and their link to increased efficiency is found at the core of aerodynamic theory[24], in which induced drag reduces proportionally to the increase in aspect ratio. This alone could result in tremendous increases in aerodynamic efficiency.

Nevertheless, the distinctive features of HARWs develop into a challenging task for the analysis of such wing designs. There is still considerable uncertainty directly related to aero-structural, aeroelastic and flying qualities trade-offs that prevent the assertion of the feasibility of HARW concepts. Many of these challenges have not been thoroughly addressed, but have proven to initiate a large number of snowballing effects that call for concessions on the expected improvements by adding design sacrifices. Larger bending moments, high susceptibility to non-linear aeroelastic instabilities and the need for additional control surfaces all characterise HARWs, and culminate in multidisciplinary penalties that may overtake the anticipated gains in aerodynamic efficiency. Accurate predictions of static and dynamic behaviours through the conventional linear modelling approaches become unreliable. Here, it is critical to capture the non-linear geometric effects on aerodynamic lift to compute the resulting shear forces and moments and accurately estimate the flight mechanics and aircraft performance[25, 26]. Furthermore, the multi-disciplinary properties of these configurations have not been subjected to sufficient flight tests, which has not allowed the establishment of useful correlations with wind tunnel or computational fluid dynamics models. Hence, there is a knowledge gap that cannot be covered with existing empirical databases and cannot be suitably modelled with traditional design tools at the conceptual design stage.

B. An Alternative Approach

To address some of the prevailing challenges in the design of HARWs, an elegant analytical approach promising improvements in the trade-off between wing induced drag and structural weight has gained the interest of researchers around the world. This design approach proposes to remove the fixed-span constraint and instead prescribe structural requirements[27, 28]. This solution expands the design space by yielding a set of equivalent span-extended wings with lift distributions characterised by an inboard-shifted centre of lift, commonly known as bell-shaped or non-elliptic lift distributions (NELDs). With this, the optimal combination of spanload and span extension is provided such that the theoretical ideal balance between the wing's aerodynamic efficiency and structural weight requirement is achieved, which is here referred to as aero-structural efficiency. An example of such spanload solution is depicted in Figure 1, along with a diagram of the aerodynamic forces generated shown in Figure 2.

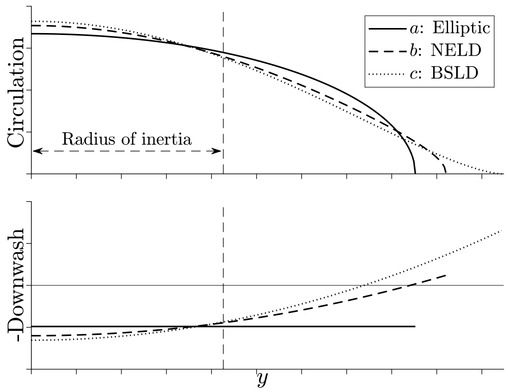

Fig. 1 Reproduction of Prandtl's 1933 solutions for circulation and downwash distributions[27].

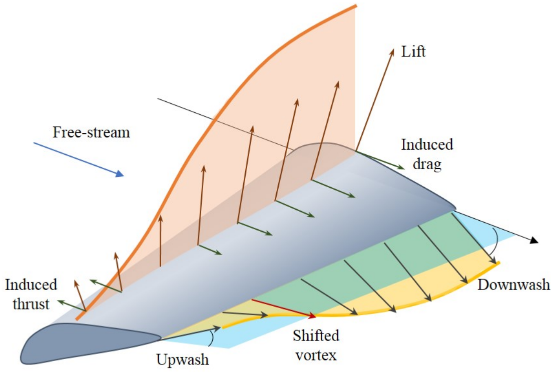

Fig. 2 Representation of the aerodynamic forces on a wing with non-elliptic lift distribution. Reproduced from Reference [29].

Numerous extensions and alternative derivations of this theoretical approach have emerged since Prandtl's initial proposal. Many of these approaches aim to overcome the limitations posed by the early theories, while other work have revisited its fundamental hypothesis. Early theories prescribed different wing structural parameters to characterise structural weight[30–34]. Other studies have taken on the integration of critical load cases and contributors to structural weight into the analysis[35–37]. Additional efforts have focused on addressing further design and mission requirements by incorporating the impact of additional wing planform and airframe geometric properties within different regions of the flight envelope, along with considering diverse forms of drag [38–44]. A notable body of work has delved into the analysis of aeroelastic characteristics and their associated limitations[45–52] in the early stages of the design. Approaches to this problem include closed-form solutions, semi-analytical methods as well as numerical optimisation. Essentially, the literature emphasises that the optimum wing lift distribution is a conditional problem, the solution of which is not unique, but attached to the assumptions and requirements demanded by the design criteria adopted.

The work carried out in this field opens a wide range of research opportunities that can bring beneficial contributions to the requirements for the design of efficient HARWs, in which penalties may be reduced and improvements achieved without major increases in design complexity. This wing design approach presents an opportunity to address the current socio-economic demands. However, conclusions on the actual benefits and practical implications of the application of this theory remain unsettled. The available research has mainly focused on the analytic extension of the theory, or the independent impact on various disciplines involved in the conceptual design stage, and mainly considering low-speed flight conditions. Consequently, it is still necessary to assess the impact of such an approach at an overall aircraft level and identify the propagated contributors of such wing designs.

With this, some of the research questions derived from this approach are addressed here within the context of the conceptual design of high aspect ratio wings. Out of the many hindrances that arise from these configurations to increase aerodynamic efficiency, the study presented in this paper revolves around the compromises generated against structural weight, since the optimisation of one is usually detrimental to the other. To do so, the synthesis of wing aerodynamic and structural requirements under a single design theory is assessed at a mission level. For this purpose, a design and analysis environment has been composed for the analysis of aircraft with high aspect ratio wings designed under prescribed aero-structural requirements and enables a state-of-the-art approach to conceptual design whilst minimising the use of statistical and historical data. Comparative studies of the performance of the produced configurations relative to a conventional airliner are conducted, allowing to establish aero-structural trends and metrics. This is done as a means to improve overall vehicle performance and enlighten the relevant complexities of a multidisciplinary design process in order to in order enhance decision-making in the design process.

II. Methodological Approach

The present study explores the correlation between increasing aerodynamic efficiency and reducing structural weight by simultaneously manipulating the lift distribution and wingspan. Therefore, the study adopts the principles of wings designed with structurally constrained spanloads as a premise for efficient aero-structural design of HARWs, as opposed to conventional design methods which require compromising aerodynamic and structural efficiency independently. The attainment of such goals has been facilitated through the development of a multi-fidelity and interdisciplinary design framework tailored for the analysis of civil aircraft with NELD wings at the conceptual design stage. The framework integrates physics-based methods for more accurate modelling and synthesis of several aircraft design disciplines, providing comprehensive analyses of overall aircraft performance at a mission level, and offering a more holistic evaluation of the related compromises. The framework loosely follows a set-based design approach, where requirements and design options are kept flexible throughout the development process. While the analysis begins with a single-point baseline solution, the exploration focuses on revising its wing design across multiple simultaneous options. This approach creates a design space that allows the designer to eliminate less favourable choices over time.

The purpose of this research is not to provide an optimal HARW design, but to evaluate the impact of modifying wing lift distribution to efficiently increase the aspect ratio. Consequently, the methodology establishes a systematic method for the study of the correlations between key input variables as well as the interdependence of the resulting output parameters. The comparative assessment of the generated database and evaluation of the behaviour of the design space enhances comprehension of the evolution of key parameters when fundamental aero-structural variables are altered. The use of reduced-fidelity solvers is prioritised to reduce computational time and cost.

The framework has been structured with a modular architecture, integrating various in-house solvers and existing computational models that interact within a MATLAB environment. The workflow is illustrated in Figure 3. Each

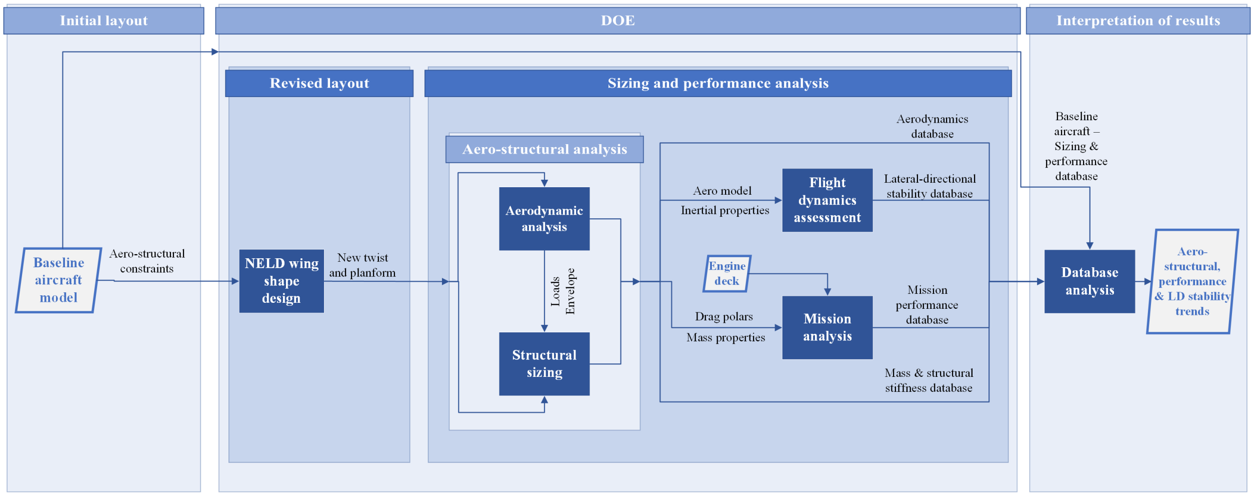

Fig. 3 Flowchart of the design methodology followed.

module is dedicated to a specific discipline, the results of which are then transferred to the subsequent module, either iteratively or sequentially. The analysis prioritises physics-based methods with minimal reliance on empirical data. With this, the necessary aerodynamic, structural and mission performance data is produced to then be evaluated under a comparative approach, facilitating the interpretation of relevant trends and metrics, both interdependent and dissociated. Such a framework provides a comprehensive insight into the fundamental principles governing the conceptual design of wings with structurally constrained spanloads for aerodynamic efficiency.

The following sections provide additional details on the workflow and methods employed. For a comprehensive discussion on the theoretical background, the derivation of the framework, and the historical context of NELDs, the reader is directed to References [53–55].

A. Initial Layout: Baseline Test Case

The initial layout is established using a conventional and well-documented single-aisle airliner as the baseline aircraft, described below. This choice facilitates the verification of results against available data, providing a database from which to extract the necessary aero-structural constraints for the revised NELD wing designs. Thus, an initial sizing via constraint analysis is not required, as the top-level aircraft requirements (TLARs) may be obtained from the baseline configuration, to be fixed and define the minimum requisites that the new designs must satisfy. It is pertinent to note that, rather than emphasising the accuracy of the baseline data, the focus of this study lies in the trends derived from the modification of the baseline model through NELD, thereby revealing the impact of this design approach. Hence, normalisation serves as the foundation for the comparative approach. The baseline configuration is subjected to the same analysis process and methods employed on the wings layouts revised with structurally constrained spanloads, outlined in Section II.B, to compute the necessary benchmark data under equal fidelity and assumptions.

The applicability of NELD theory is under evaluation here as an underlying principle for the design of transonic wings in civil aircraft. The majority of research on the design of wings with NELDs has been conducted on configurations that did not have a specific mission or did not present a realistic context in which to set the case study. Extracting the impact of this design approach from such cases, where performance outcomes cannot be directly compared with existing aircraft, presents challenges.

The proposed configurations maintain a conventional layout, consisting of tube-and-wing, low cantilever wing, single-aisle, and twin-engine aircraft with engines mounted under the wing. This approach diverges from the commonly derived HARW configurations, characterised by a brace-reinforced high-wing, in order to avoid yet further design trade-offs. Hence, the Airbus A320[56] model has been chosen as the basis for constructing the baseline model in this study. This established airliner provides a suitable basis for comparison, for which a vast amount of data is publicly available. It must be noted that the A320 is not exactly replicated here, but it is adopted to create a generic baseline that closely represents a civil transport aircraft in operation today. The configuration and main dimensions of the baseline model are depicted in Figure 4. The baseline aircraft has been equipped with two high-bypass turbofan engines[57] able to produce 150 kN of thrust each at sea-level, which are representative of the propulsive performance given by Pratt & Whitney PW1100G or the LEAP-1A from CFM International. The engine model has been implemented in the form of a look-up table.

The revised layouts modified via NELD wings maintain most of the geometric parameters shown in Figure 4 fixed and unvaried throughout the redesign and analysis. These include the dimensions of the fuselage, the horizontal stabiliser, and the fin, as well as the location of all lifting surfaces. The sizing of the control surfaces and deflections remain constant, along with their normalised position across the span. The aerofoils and their normalised spanwise distribution are also conserved, as well as the engine normalised position. Further geometric properties, TLARs and design flight condition parameters are listed in Table 1, where elements marked with an asterisk remain fixed across all revised configurations. In the present study, the cruise condition is closely examined, as it represents the phase where the aircraft will primarily operate throughout the defined mission.

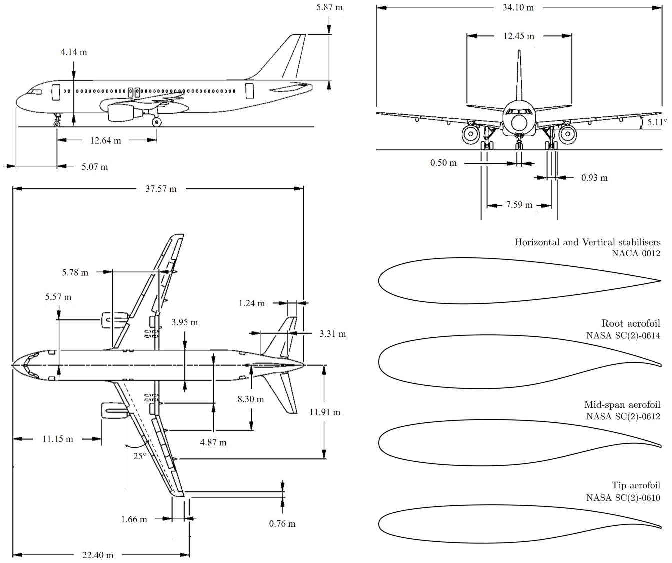

Fig. 4 Baseline A320-like configuration. Adapted from reference [56].

Description	Value
Design lift coefficient	0.5658
Cruise Mach number*	0.78
Cruise altitude*	37,000 ft
Range	3,200 nmi
Maximum Take-Off Weight	73,500 kg
Wing Area*	122.40 m^2

Table 1 Properties of the baseline aircraft model.

B. Revised Layouts

The analysis is initiated with the modification of the wing of the baseline aircraft model, the details of which are exposed in Section II.A. To do so, a wing shape design solver has been developed in MATLAB[58] to enable the design of HARWs under the principles of structurally constrained lift distributions for minimum induced drag. This reduced-order solver is based on the extended lifting line theory[24] and integrates diverse structural design constraints corresponding to selected analytical methods for the derivation NELDs. A summary of the main features defining these theories is provided in Table 2, including the characteristic constraint and the analytical solution for minimum induced drag, for which the reduction in induced drag, D_i, and the associated increase in span, b, are given compared to the elliptic solution.

To start, Prandtl's classic elliptic spanload[59] is taken as a reference point to the analytical ideal solution for minimum induced drag, and denoted by P18. Despite its acknowledged impracticality, this lift distribution serves as an indicator for comparing the deviations of other solutions from the ideal aerodynamic bound. This configuration has been sized to yield the same integrated bending moment as the baseline wing. The elliptic circulation distribution is a function of the circulation at the root, Γ_0, and the spanwise location y over the semi-span s, as presented in Equation 2 within Table 3. Prandtl's alternative approach[27] to aero-structurally efficient wing design is also included in the analysis, labelled P33. As mentioned above, he proposed to prescribe the wing's integrated bending moment as the parameter driving structural weight and allowed the span to increase. By doing so, both aerodynamic and structural efficiency were synthesised into a single theory, for which all solutions would reduce induced drag through span extension whilst maintaining structural weight by shifting the lift towards the root. These solutions would be defined by a family of non-elliptic lift distributions. Here, the optimal solution for minimum induced drag would achieve an 11%

Table 2 Summary of the applied methods for the derivation of structurally-constrained spanloads for minimum induced drag.

Author	Label	Characteristic constraint	Ideal Analytic Solution
Prandtl[59] Elliptic	P18	Span	Reference
Prandtl[27] NELD	P33	Integrated bending moment	$D_i = -11.1\%$; $b = +22.5\%$
Jones[30]	J50	Root bending moment	$D_i = -15.0\%$; $b = +15.0\%$
Klein and Viswanathan[33, 60]	KV75	Integrated bending moment and shear force	$D_i = -7.0\%$; $b = +14.0\%$
Horten[44]	H93	Proverse yaw	$D_i = -5.1\%$; $b = +18.5\%$
Baseline[56]	BA320	-	Benchmark

reduction in induced drag with a 22% span extension as compared to the ideal elliptic spanload, and would be described by a bell-shaped lift distribution. The corresponding circulation distribution, shown in Equation 3, is effectively an expansion of the elliptic spanload that accounts for second-order circulation terms. Jones[30, 31] independently derived an alternative approach to this problem in 1950. Based on his belief in a design philosophy for practical wing design driven by structural requirements, he proposed a solution for minimum induced drag with prescribed wing root bending moment, which yielded an analogous family of curves, referred to as J50. Equation 4 shows that, unlike Prandtl, Jones determines the circulation distribution as a function of the non-dimensional spanwise position of the load centroid, $\overline{y_C}$. This parameter must vary with span extension for the circulation to redistribute the loading. However, what remains fixed and equal to the baseline spanload is the dimensional centroid $y_C = \overline{y_C} s$. Additionally, the formulation is also a function of the flight condition defined by the density ρ, and the airspeed V. Klein and Viswanathan[32, 33, 60] later explored the importance of incorporating structural considerations in the aerodynamic design of wings as a way of coupling both design limitations into a single theory. Their work extended the structural boundary conditions to include a more precise approximation of the wing structural weight, in which the constraints were now determined by the integrated bending moment and shear force distributions. This solution is identified here as KV75 and presented in Equation 5, where the terms denoted by C_1, C_2 and C_3 are a function of the ratio between revised and reference wings. The final spanload investigated originates from the research of the Horten brothers, who directed their efforts towards a different objective, diverging from the optimisation of aero-structural efficiency. Their work with flying wings led them to search for designs that would have increased lateral-directional manoeuvrability through the generation of favourable aerodynamic loads. The solution was given by a bell-shaped spanload, given by Equation 6, tuned to address adverse yaw, named H93. This distribution is effectively equivalent to Prandtl's solution based on fixed integrated bending moment. The equations defining the circulation distribution from each of the approaches presented above can be found in Table 3. Additionally, the baseline circulation distribution, BA320, was derived from the inverse application of the lifting line theory from the available planform parameters, defined as a set of $n = 150$ Fourier coefficients G_n that define the circulation distribution in trigonometric coordinates (θ), given by[24]:

$$\Gamma(\theta) = \sum_{n_{odd}}^{n=150} G_n \sin n\theta \tag{1}$$

The derivations presented in the literature utilise the elliptic spanload as the reference configuration, upon which the aerodynamic and structural constraints are predicted. However, in this study, the formulations have been adjusted to align with the baseline case. Consequently, the initial conditions corresponding to each NELD theory applied are derived from the baseline aircraft, alongside other wing planform and design flight condition parameters, as discussed in Section II.A. With this, the span for a wing with elliptic loading that will have the same integrated bending moment as the baseline model can be derived from References [27] and [32], to yield the relation shown in Equation 7. Similarly, the derivations in References [30] and [60] can be manipulated to compute the span of a wing with elliptic loading that will have the same root bending moment as the baseline model, provided that the non-dimensional centroid corresponding to an elliptic distribution equals $4/(3\pi)$, given by Equations 7 and 8.

$$b_{ibm_e} = \sqrt{\frac{16 I_L}{L}} \tag{7}$$

$$b_{rbm_e} = 3\pi \frac{M_{X_{root}}}{L} \tag{8}$$

Table 3 Circulation distributions investigated.

Author	Label	Circulation distribution
Prandtl[59] Elliptic	P18	$\Gamma(y) = \Gamma_0\sqrt{1-\left(\frac{y}{s}\right)^2}$ (2)
Prandtl[27] NELD	P33	$\Gamma(y) = \left[\Gamma_0 + \Gamma_2\left(\frac{y}{s}\right)^2\right]\sqrt{1-\left(\frac{y}{s}\right)^2}$ (3)
Jones[30]	J50	$\Gamma(y) = \frac{L}{2\rho V s}\left(\frac{12}{\pi} - 6\overline{y_C}\right)\frac{\sqrt{s^2-y^2}}{s} + \left(18\overline{y_C} - \frac{24}{\pi}\right)\frac{y^2}{s^2}\cos^{-1}\frac{s}{\lvert y\rvert}$ (4)
Klein and Viswanathan[33, 60]	KV75	$\Gamma(y) = r_s\left[\sqrt{1-\left(\frac{y}{s}\right)^2}\left(2C_1 + 2\frac{C_2}{\pi}\right) - \frac{C_2}{\pi}\left(\frac{y}{s}\right)^2\log\frac{1-\sqrt{1-\left(\frac{y}{s}\right)^2}}{1+\sqrt{1-\left(\frac{y}{s}\right)^2}}\right]$ (5)
Horten[44]	H93	$\Gamma(y) = \frac{8}{3\pi}\frac{L}{\rho V s}\left[1-\left(\frac{y}{s}\right)^2\right]^{3/2}$ (6)

where I_L is the integrated bending moment, $M_{X_{root}}$ is the root bending moment, and L is the wing lift.

Taking the above factors into consideration, the solver computes the wing planform under the principles of aero-structural equivalence. This involves maintaining the lift, the chosen structural constraint, and the wing area constant, all derived from the baseline aircraft at the design flight condition, shown in Table 1. Additionally, the twist distribution required to generate the sought spanload is also determined. The proposed design and analysis method generates a design space of span-extended configurations, wherein aerodynamic efficiency is improved through span extension, and the associated increase in wing structural weight is minimised as a result of the applied non-elliptic spanloads.

Figure 5 shows a sample of the generated circulation distributions. Specifically, the baseline configuration at the design cruise flight condition is compared against the derived equivalent ideal circulations for each theoretical approach employed, corresponding to Tables 2 and 3. Here, the circulation is presented normalised against the value of the circulation at the root, $\gamma(y)$, while the spanwise axis has been normalised against the corresponding semispan, ξ. Each of the spanloads maintains the structural constraint and the design lift that has been prescribed. The span extension b and resulting induced drag D_i reduction results differ from those in Table 2 because the applied reference point and design parameters are now being taken from the baseline BA320 configuration. Comparing the resulting span b and induced drag D_i values to those listed in Table 2. Figure 6 shows the wing twist distributions of the same design points, now showing the applied ratio of span extension to the baseline wing r_s.

Numerous wing configurations may be computed as a function of span extension and the prescribed aero-structural constraints. The span extensions applied in this study range from the value computed for an equivalent wing with elliptic loading, derived from Equations 7 and 8, up to the span given by reference HARW aircraft concepts being proposed in industry[21, 22]. These boundaries are presented below as the ratio of the revised wing's span to the span of the baseline BA320 model:

$$\begin{aligned}\text{For equivalent integrated bending moment: } & r_s = 0.93\ \ldots\ 1.52\\ \text{For equivalent root bending moment: } & r_s = 0.89\ \ldots\ 1.52\end{aligned} \tag{9}$$

The design space generated comprises $N_{\mathrm{r_s}} = 28$ span extension cases distributed within the specified range for each of the $N_\Gamma = 6$ circulation distributions being evaluated. This results in a total of 168 design points to be analysed. Attention should be kept to the fact that the structurally constrained spanload families will yield different lift distributions at each span extension, for which the load is redistributed and shifted inboard as the span increases. Conversely, the normalised circulation distribution of the baseline, elliptic and Horten configurations remain constant throughout the revised span extension cases.

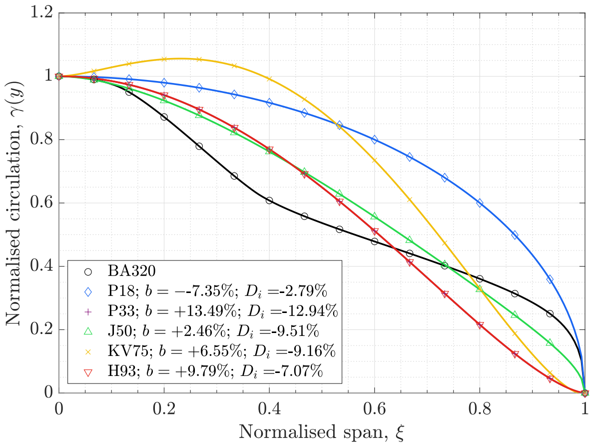

Fig. 5 Comparison of ideal NELD circulation distributions against the baseline wing, its equivalent elliptic spanload.

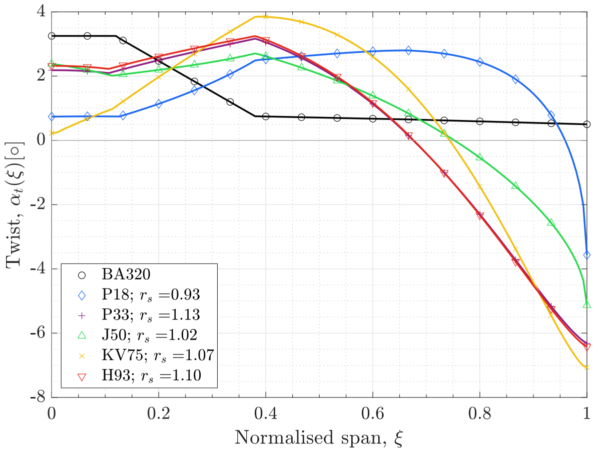

Fig. 6 Comparison of ideal NELD twist distributions.

C. Aero-Structural Analysis

The aero-structural sizing environment employed in this research assumes a well-established approach within the contemporary conceptual design stage. Here, the aerodynamic properties are represented by a vortex lattice model (VLM), and the structural characteristics are determined by a beam model. The aerodynamic and the structural solvers may be coupled to transfer loads and displacements between them and construct the aero-structural model. This enables fast trim calculations for the aircraft under the assumption of small structural displacements for the evaluation of internal and external loads, to determine stiffness and mass properties that will drive the structure through the imposition of stress constraints for structural integrity and minimum mass. This has been achieved through the integration of NeoCASS[61, 62] into the framework's workflow as the aero-structural solver.

NeoCASS is a software for structural sizing and aeroelastic analysis of the whole aircraft. This design tool has been developed in MATLAB, which facilitated its integration into the global framework composed in this study. The methodology adopted here accommodates physics-based theoretical models to enhance the early prediction of structural weight. The loads estimation is performed via a quasi-steady VLM approach with Prandtl-Glauert compressibility correction[63], which is employed to model the complete lifting surfaces layout, consisting of the wing and empennage, to obtain aerodynamic forces and moments of the full configuration. Some of the NeoCASS scripts have been modified to enable the aerodynamic and structural meshes to capture the highly non-linear twist distributions required for the NELD wing designs, for which the number of sections was increased. This approach allows the trimming of the aircraft to yield the aerodynamic loads at the chosen manoeuvre flight conditions. The manoeuvres considered here have been defined according to the relevant airworthiness regulation criteria, in this case, to comply with EASA Certification Specification requirements for large transport aircraft (CS-25[64]). A narrow down-selection of critical loading conditions that demand the highest static strength have been evaluated to ensure that the structural integrity of the aircraft is maintained at all corners of the corresponding operating envelope. These are computed within NeoCASS and include pull-up manoeuvres at maximum load factor, gust encounter, sudden control displacement, high descent velocity landings and take-off with one-engine-inoperative. The flight envelope is shown in Figure 7, where the blue shade represents the range of variation of the flight envelope due to weight and geometry variation caused by the wing modification. With this, the manoeuvres can be now fully parametrised, for which a summary of the flight points assessed is presented in Figure 8. The loads envelope is calculated for the principal structural components of the airframe, these being the wing, empennage and fuselage, and is then used iteratively to size the structure. The initial mass estimation is provided here by a semi-empirical method[65, 66], which proposes an extended approach that includes additional parameters specifically related to geometry and layout, while considering loads and performance as well as constant non-structural mass components.

The structural analysis is based on linearised beam theory for the calculation of load-bearing material and estimation of the main structural components' mass. The method is extended to a finite volume three-node beam model, which is then coupled to the aerodynamic lifting surface method to account for airframe flexibility and compute nodal displacement. Various spatial coupling schemes are available for the construction of the interpolation matrix to transfer

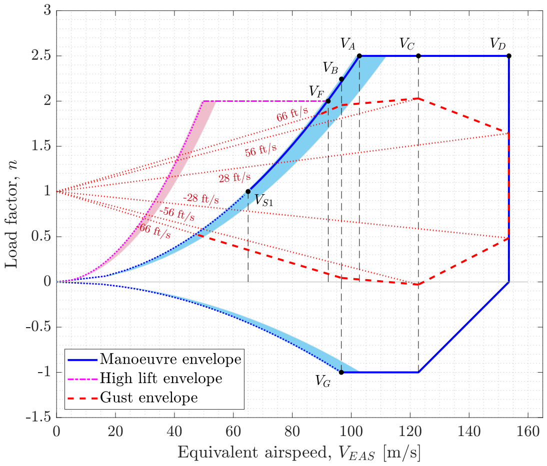

Fig. 7 Design operational envelope.

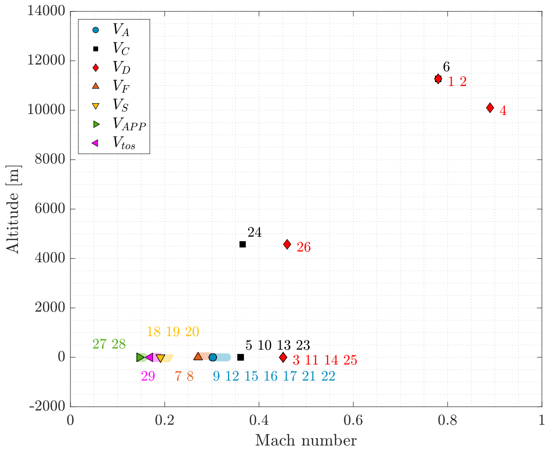

Fig. 8 Flight points assessed and manoeuvre ID.

data from structural to aerodynamic mesh. The beam model is constructed by representing the lifting surfaces as a set of multi-web box beam elements that construct the stick model. The internal cross-section of the wingbox is then defined, which enables the assessment of the local mechanical properties and the derivation of the structural mass and stiffness distributions. Similarly, the internal load-carrying fuselage structure must be defined to construct its associated stick model, along with additional points to transfer and recover the stresses between the airframe components. NeoCASS provides several structural layout solutions for both fuselage and lifting surfaces that are characterised by the definition of the shell and stiffeners type, as well as the main structural design constraint. For this study, the fuselage structure has been defined by a Z-stiffened shell, longitudinal frames, and the minimum amount of structural material is considered as a compromise between critical buckling and pressure conditions. The wing-box of the lifting surfaces has been modelled with a truss-stiffened cover and Z-stiffened webs. This allows for the consideration of further structural constraints such as torsion, aerofoil thickness and minimum skin gauge allowances, to discard infeasible solutions that do not satisfy the chosen structural integrity requirements. The analysis is performed to calculate the minimum amount of material under structural integrity requirements, which have been set to satisfy ultimate static buckling and strength. This enables the estimation of structural weight, as well as the calculation of stresses and displacements, to be directly driven by approximate physics phenomena. However, the design constraints adopted here will not necessarily yield the global optimal solution for minimum structural weight. Figure 9 shows the resulting aero-structural coupled meshes for the baseline BA320 configurations and the Prandtl P33 model with a 22% span extension. For in-depth discussion and derivation of the theoretical foundation of NeoCASS, please refer to the available documentation[61, 62, 67].

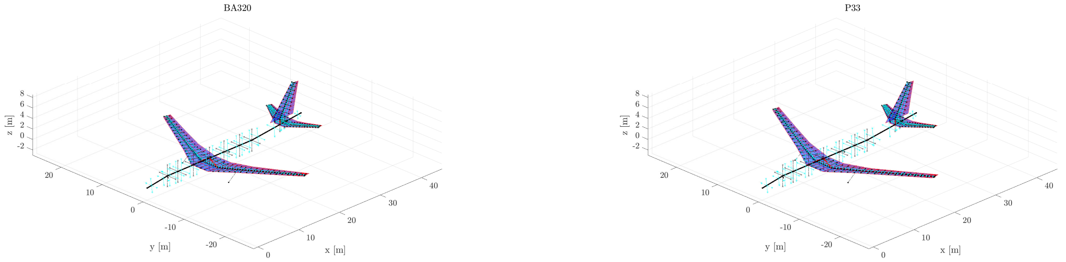

Fig. 9 Coupled structural and aerodynamic models generated with NeoCASS[67].

D. Mission Performance Analysis

The end goal of the study presented here is to examine the cumulative impact of the trade-off between aerodynamic and structural characteristics introduced by NELD wings. This is done through the analysis of mission performance for each of the revised and sized configurations, serving as a convergence point for all involved disciplines. In this analysis, range is the output to be maximised to characterise performance, as it represents the assembly of an aircraft design trade-offs, widely presented in the form of the Breguet range equation:

$$R = \frac{V}{TSFC}\frac{L}{D}\log_e\left(\frac{W_0}{W_F}\right) \tag{10}$$

The above equation depicts the role of each these pivotal parameters to best achieve the mission. Hence, for a maximum range R we want to fly with minimum thrust-specific fuel consumption $TSFC$, at a maximum L/D and airspeed V, with the highest initial to end weight ratio W_0/W_F, which is ideally obtained with the largest fuel weight. To provide a robust estimation of the lift-to-drag ratio L/D, it is necessary to consider a comprehensive buildup of drag components, as drag inflicts a critical contribution to the thrust required and the total energy balance throughout the mission. Up to this point, the aerodynamic analyses carried out have mainly taken into consideration the impact of lift-induced drag through the use of inviscid and incompressible flow assumptions given by the lifting line and the vortex lattice models. consequently, the aerodynamic analysis is extended for the computation of the trimmed drag polars for low and high speed conditions, for which the contribution of profile drag is superimposed and added independently.

For the calculation of the complete set of aerodynamic data required to perform the mission analysis, a suite of legacy codes has been integrated into the framework under the criteria for simplicity of implementation and run-time minimisation. AVL[68] is used to compute the trimmed drag polars in potential flow. Compressibility is also addressed in AVL using the Prandtl-Glauert correction. Furthermore, AVL enables the easy modelling of control surfaces and high-lift devices in order to obtain their contribution to lift and drag. Now, the inviscid data of the lifting surfaces is combined with the profile drag polars obtained from XFOIL[69], which is a tool for the design and analysis of subsonic aerofoils. Here, the profile drag is computed for each aerofoil at the corresponding flight conditions, and then added by linear superposition via interpolation and integration of the two-dimensional local drag distributions on each lifting surface. Finally, additional profile drag contributions for the fuselage and engine derived from historical data are directly added to the total component drag[70, 71]. AVL and XFOIL enable parallel batch processing via straightforward communication with the MATLAB-based framework via input and output formatted files. The polars are computed at a combination of flight speeds and altitudes for various angles-of-attack to create lookup tables that will be then treated as surrogate models for aerodynamics. The drag curves computed for the low-speed segments of the mission will include the flaps deflected and the additional contributions from landing gear and speed brakes[72–74]. The flight points are listed in Table 4. The lifting surfaces have been discretised to provide the same aerodynamic mesh as the one produced in NeoCASS' VLM model and shown in Figure 9, yielding 572 vortices. The relevant control surfaces have been modelled too.

Table 4 Range of flight points variables for the calculation of high and low-speed drag polars.

Mach, M_∞	0.10 to 0.82
Altitude, h	0 ft to 39,000 ft
Angle-of-attack, α	-2° to 14°

The mission performance analysis uses the weight breakdown, resulted from the aero-structural sizing, and the computed drag polars to predict the performance of the revised configurations. This analysis is performed in the Flight Optimization System (FLOPS)[75], a tool for conceptual and preliminary design and evaluation of advanced aircraft concepts. FLOPS utilises the energy-based approach for mission analysis, a rapid low-order method that is fairly established for the evaluation of fixed-wing aircraft. The mission profile is kept constant for all aircraft configurations, and is optimised for maximum range. The engine model has been integrated via a series of lookup tables that provide power and thrust characteristics for the different segments of the mission profile. FLOPS provides an interface that can be easily communicated and run in parallel within the MATLAB environment of the proposed framework. This module returns the effect caused by NELD wing modification on the performance of the aircraft as a whole. Its impact on range and other top-level aircraft requirements (TLARs) is studied to unveil the effect of such parameters on the resulting aero-structural trade-offs.

The mission profile used for this study is simple and has been envisioned as such to emphasise the fundamental performance characteristics for each of the principal segments in a mission. No turns, accelerations or hold segments are modelled in the mission. The climb profile optimisation is performed for minimum fuel-to-climb, in which the climb speed is limited to a maximum of 250 KCAS below 10,000 ft under the CS-25 certification specification requirement. The same constraint is applied for descent, which is flown at optimal lift-to-drag ratio. The trajectory optimisation routine in FLOPS will select the optimum altitude for each energy level. The cruise segment is calculated for a fixed Mach number, constant lift coefficient, obtained through empirical formulation[75]. The block fuel has been fixed in all cases. This includes the reserve fuel, which accounts for a hold time of 30 min, but no reserve mission to an alternate airport is calculated. Figure 10 shows the diagram of such a mission profile. With this, the analysis is set as a direct mission performance calculation for each configuration, in which the ramp weight is fixed and the range is calculated.

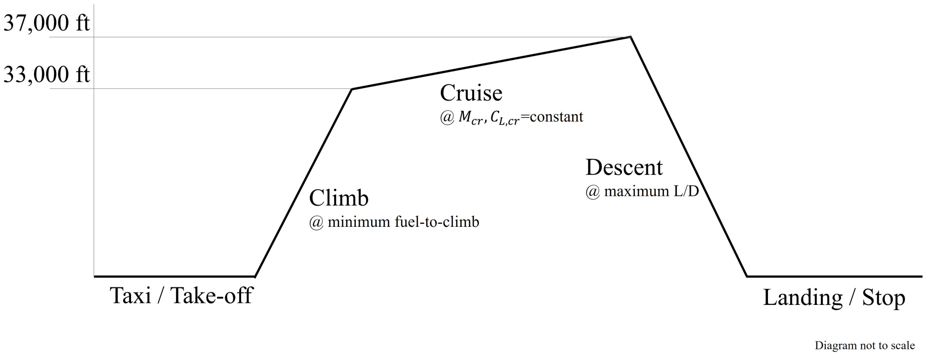

Fig. 10 Representation of a typical cruise-climb mission profile.

E. Additional Limitations

The scope of this research has been confined to a particular context and set of variables in order to give clarity to the study outcomes, better identify trends in a well-known scenario, and be able to increase confidence in the methodology given that further validation is required. It is recognised that the excluded factors outlined below play a vital role in the design of wings for minimum drag and weight. Despite model accuracy reduction, this approach enables rapid analyses, particularly beneficial in the initial design stages when exploring diverse options. Additionally, the comparative nature of the proposed assessment facilitates relative normalization of results, allowing for meaningful comparisons even in the presence of systematic errors from simplified assumptions and methodological limitations.

Given that the interest lies in the specific impact of varying the wing lift distribution and span on the aero-structural interactions, the number of design variables has been limited to reduce the influence of irrelevant design variables on the analysis, while the aircraft configuration being envisioned does not depart from conventional layouts. The proposed aircraft revisions are limited to the wing's geometry. In reality, any such alterations to the wing are likely to have a significant impact on other components and characteristics of the aircraft, including but not limited to the aircraft's static and dynamic stability. Alterations to the aircraft's operational empty weight would require a reevaluation of the engine's power capabilities. Other considerations such as the analysis of engine emissions or noise footprint have not been regarded. Aeroelastic constraints are not considered to drive the structural sizing, which can result in increased weight, reduced performance, increased time and cost of the design, and safety concerns. The structural sizing process does not take into account the impact of weight reduction resulting from fuel consumption. Fatigue and other structural dynamic effects are also excluded, which would further impact the sizing of the wing structure. The selection and impact of airframe material are not explored in the design and analysis process. It is fixed for all configurations and only one material will be used for the complete airframe. The assessment process does not encompass manufacturing considerations, which are subject to potential alterations from the anticipated twisting and extension of the wing. Such modifications could increase the complexity of the manufacturing process, as well as cause detrimental impact on the internal space allowances of the wing. The aerodynamic analysis employs linear models. Therefore, non-linear transonic flow characteristics are approximated, where phenomena such as local shock waves and non-linear effects such as separation, are partially accounted for in the form of local profile drag increase. Consideration of these effects will be a critical factor in the calculation of the actual aerodynamic efficiency across the flight envelope due to the large washout found in NELD wings. Furthermore, wing deformation was not modelled in the computation of drag polars with AVL;

therefore, the mission analysis was conducted solely on the rigid airframe configurations. The proposed research scope introduces several sources of uncertainty from the limited input data, multi-fidelity, and inherent simplifications coming from the system being modelled and the evaluation methods being used. Additional analysis should be conducted to validate the resulting trends and metrics and quantify their associated uncertainty.

III. Current Findings

The proposed design and analysis process yields span-extended configurations for which aerodynamic efficiency is improved through span extension and the consequent growth in wing structural weight is reduced as a result of the applied structurally-constrained spanloads. A systematic design space exploration has been enabled through the use of a design of experiments methodology under a set-based design process, delaying the elimination of poorer design points so as to avoid the use of conventional criteria used to quantify efficiency. The comparative presentation of figures of merit to assess the performance of the designs provides further insight than the use of other traditional metrics such as the lift-to-drag ratio.

A. Model Fidelity Impact on Aero-Structural Trends

The early theories for aero-structural wing design, being explored here and in the literature, are insightful and elegant approximations that can be employed as a prelude to the conceptual design phase. However, analytical consideration of all the potential variables would be an exceptionally challenging task, if ever possible. Consequently, classical formulations must make several restrictive simplifications to derive an analytical solution. The analysis framework proposed in this study extends some of these assumptions through the use of increased fidelity in the analysis methods and models, as discussed in Section II.

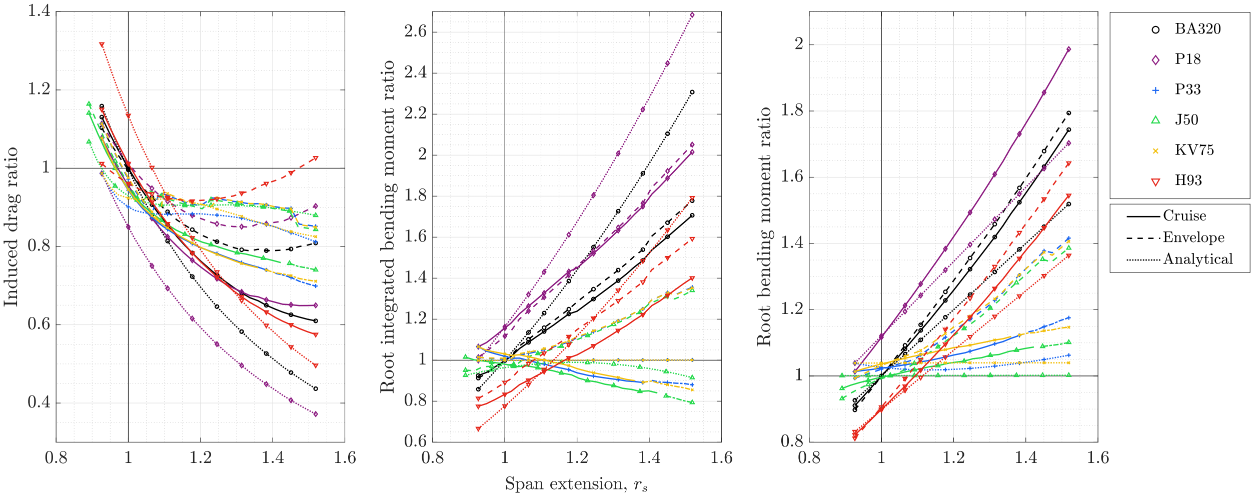

Fig. 11 Aero-structural trends due to aerodynamic loads for span extension against the baseline configuration.

The impact of manipulating model fidelity is presented through the trends of the aero-structural characteristics that the wing undergoes during NELD re-design, as shown in Figure 11. Particularly, the wing induced drag, integrated bending moment, and root bending moment are normalised and compared against the baseline configuration. The dashed line depicts the results obtained from the rigid structural sizing performed on the complete airframe in NeoCASS as described in Section II.C. This sizing was conducted under a set of critical load manoeuvres, constrained for structural integrity under minimum gauge limits and included non-structural masses. The solid line shows the aero-structural behaviour of the structural sizing process resulting from the consideration of only a single flight condition, in this case, the design cruise condition. The dotted line illustrates the analytical results derived from the early theories. Analysing the reductions in induced drag with span extension, the methodology proposed in this study yields more conservative results while still following similar trends to the ones predicted by the analytical theories. Conversely, the configurations that maintain a constant non-dimensional centre of lift show a decline in the growth in aerodynamic efficiency as span is extended. The impact on structural loads shows a notable detriment when compared to the analytical results. While the reduction in aerodynamic efficiency at off-design manoeuvres is only suffered in a small portion of the flight, the penalties on internal loads must be carried at all times, as the structure must be sized accordingly. However, the structure is now also being sized under the combined contribution from aerodynamic, inertial, fuel and engine loads, where the latter components will be providing bending moment relief. For a fixed non-dimensional centroid, the analytical approach generally overestimated the results of the integrated bending moment, while the opposite results for the root bending moment. Still, the structurally constrained spanloads are successful in reducing the structural loads derived from extending wingspan, even when high load factor manoeuvres are included in the sizing. Nevertheless, the aero-structural benefits promised by the theoretical approach are penalised when fidelity is increased. Examining the trends derived from the loads envelope, now only the J50 and the H93 families have design points at which induced drag and integrated or root bending moment are lower than the baseline values.

These results arise from the structural load characteristics obtained for each of the configurations, for which the structurally contained spanloads could maintain the bending, shear and torsion distributions within a 35% of variation against the baseline configuration for the positive load envelope, as opposed to a 66% variation seen in span-extended design with fixed centre of lift. Conversely, the negative load envelope suffers larger changes as span is extended in NELD wings, however the impact on the final sizing remains less significant than that inflicted by the positive loads. Furthermore, the applied NELD modifications of span and spanload yielded variations in the manoeuvres driving the limit loads. In this study, the baseline and elliptic families were defined by a standard $2.5g$ pull-up at the design dive speed and altitude driving structural loads for bending and shear, whereas a $2.5g$ pull-up at cruise will be mostly critical for NELDs. Moreover, a sudden elevator displacement at maximum deflection at the manoeuvre speed with a pitch acceleration for $2.5g$ becomes critical on the outer wing of NELD configurations at low span extensions, and is also driving bending loads of morphing NELD at larger spans. This manoeuvre also drives the critical load condition in spanwise torsion for all wing configurations. However, directional manoeuvres with sudden rudder maximum deflection determine the loads around the wing-engine interface, while a pull-down to $-1g$ is critical at the wing-fuselage intersection. It must be noted that beyond a certain applied span extension, the structurally constrained spanloads begin to generate negative lift at the outboard wing. These solutions are deemed unfeasible for aerodynamically efficient designs and are consequently eliminated from the design space.

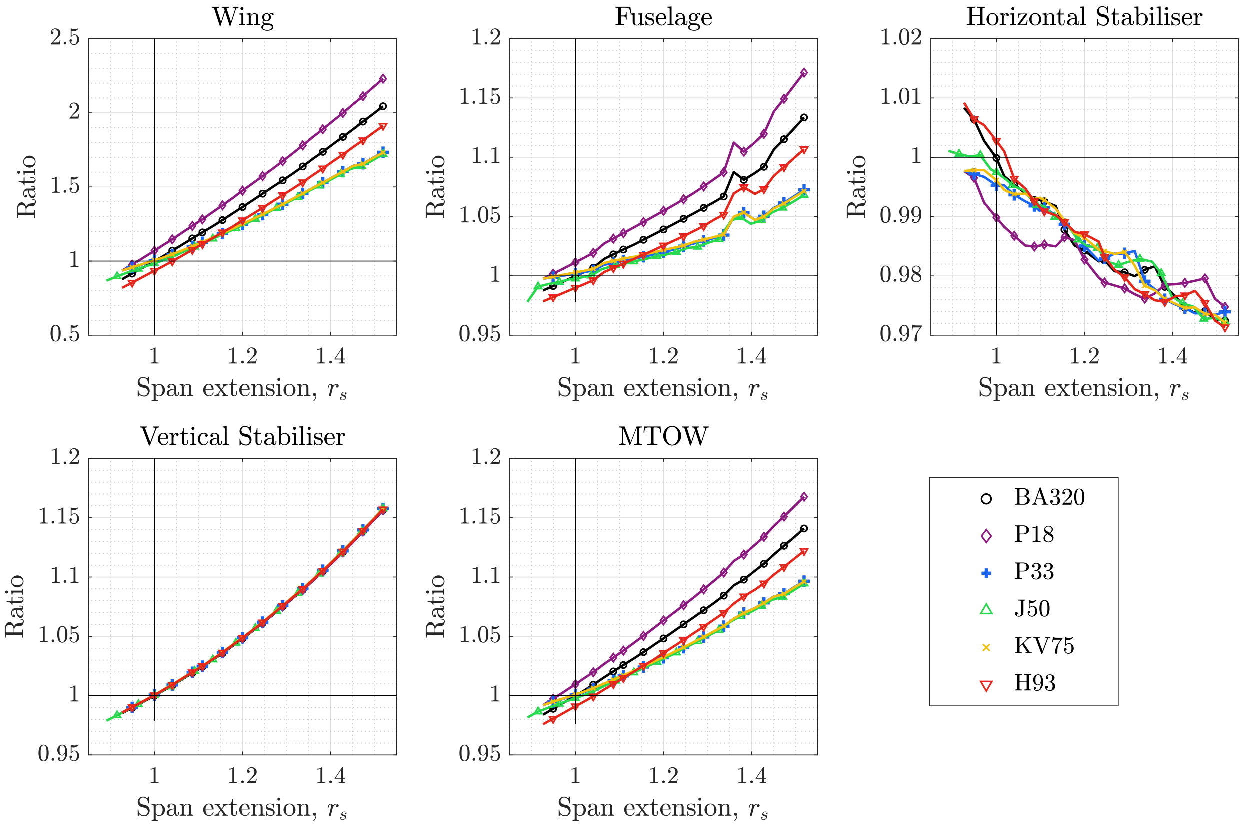

Fig. 12 Weight variation of the structural components with span extension as a ratio to the baseline configuration.

Figure 12 shows the trends for weight increase of all the sized structural components, as well as the overall impact on maximum take-off weight (MTOW), normalised against the baseline configuration. It is shown that while structural weight was not maintained through the use of NELDs, this wing design approach reduces the growth in wing weight increase as the span is extended by approximately 30% in all three cases. On the contrary, this gradient increases as the spanwise position of the centre of lift moves outboard, but this is avoided through the use of NELD. Consequently, a similar result is obtained for the trends in fuselage weight, the variation of which is solely affected in this study by the loads transferred from the wing. The weight of the horizontal and vertical stabilisers was negligibly affected by the spanlaod variation in this study. However, further analysis of the static and dynamic characteristics of the revised layouts could change these conclusions; the impact on the aircraft inertia as the span is extended will contribute to the increase in the weight of the vertical stabiliser, while the horizontal stabiliser is affected by the backward shift in the wing centre of lift.

B. Impact on Mission Performance

The mission performance assessment brings together the findings obtained in each disciplinary analysis and explores the trends and accumulated impact of the trade-offs derived from the design principles adopted. The resulting performance characteristics are shown in Figure 13. The evolution of several TLARs has been plotted against span extension, where the bound of acceptable values has been placed as the improvement from the results given by the baseline configuration. The range cannot be increased with span extension without eventually encountering penalties due to the surpassing of the weight increase over the aerodynamic efficiency improvements achieved. The revised designs with fixed spanload maintain the growth in range up to higher span values due to the increasing lift-to-drag ratio, but the range eventually plateaus for extensions above 40%. The NELD families see an increase in range only up to approximately a 10% of span extension, after which they start yielding a gradual decrease as weight increases with span.

Generally, increasing the wingspan of a given aircraft will provide a detrimental contribution to the top-level aircraft requirements assessed, with the exception of the range. Generally, the use of structurally constrained spanloads shows an analogous impact across most TLARs to that developed on the maximum take-off weight (MTOW) growth, in which the trade-offs between aerodynamic and structural characteristics derived from these designs reduce the weight penalties derived from span extension. This is achieved to such an extent that the trends deflect to provide minor improvements for the NELD configurations found at the lower bounds of span extension in the take-off field length, rate-of-climb and time-to-climb characteristics. Hence, the inwards shift of the centre of lift succeeds in reducing the penalties between the baseline value and revised configurations.

Several metrics for efficiency are evaluated throughout this study, and have been computed and compared in Figure 14, and normalised against the baseline value. To start, the classical lift-to-drag ratio L/D is included, which is found in the Breguet range equation and is sometimes presented as the product of the lift-over-drag with the Mach number to consider aircraft at a wider range of flight conditions. In this case, the design Mach speed is equal for all configurations so the lift-to-drag is simply presented. The effective lift-to-drag[76], $(L/D)^E$, aims to include the impact on mass due to span extension by including the factor of wing mass over total mass in the formulation, where this factor will vary with each wing configuration. Accordingly, the impact of the increasing wing mass is seen with span extension through a decreasing gradient on the trend curve, thus providing a parameter that better integrates the aero-structural trade-offs. The effective span efficiency factor e^E is representative of the wing aerodynamic efficiency with consideration of increase in efficiency due to span extension. Span efficiency is sometimes invoked to compare aircraft performance, but should remain as a comparative factor for the wing, for which it can become an initial prediction metric for the impact on wing weight. Finally, the range-to-weight ratio R/W is proposed as an alternative performance metric, which incorporates the efficiency of the aerodynamics, mass and propulsion altogether, and may be used as a quantifier of the overall performance of the obtained solutions. Metrics such as the fuel efficiency per passenger have not been added to the analysis given that the passenger and fuel capacity of the analysed configurations remains constant. The metrics are presented below:

$$\begin{aligned} \text{Lift-to-drag: } & \frac{L}{D} \\ \text{Effective lift-to-drag: } & \left(\frac{L}{D}\right)^E = \frac{L}{D}\left(1 - \frac{W_{\text{wing}}}{W_{\text{MTOW}}}\right) \\ \text{Effective span efficiency factor: } & e^E = \text{Æ}\!\!R\; e \\ \text{Range-to-weight: } & \frac{R}{W} \end{aligned} \tag{11}$$

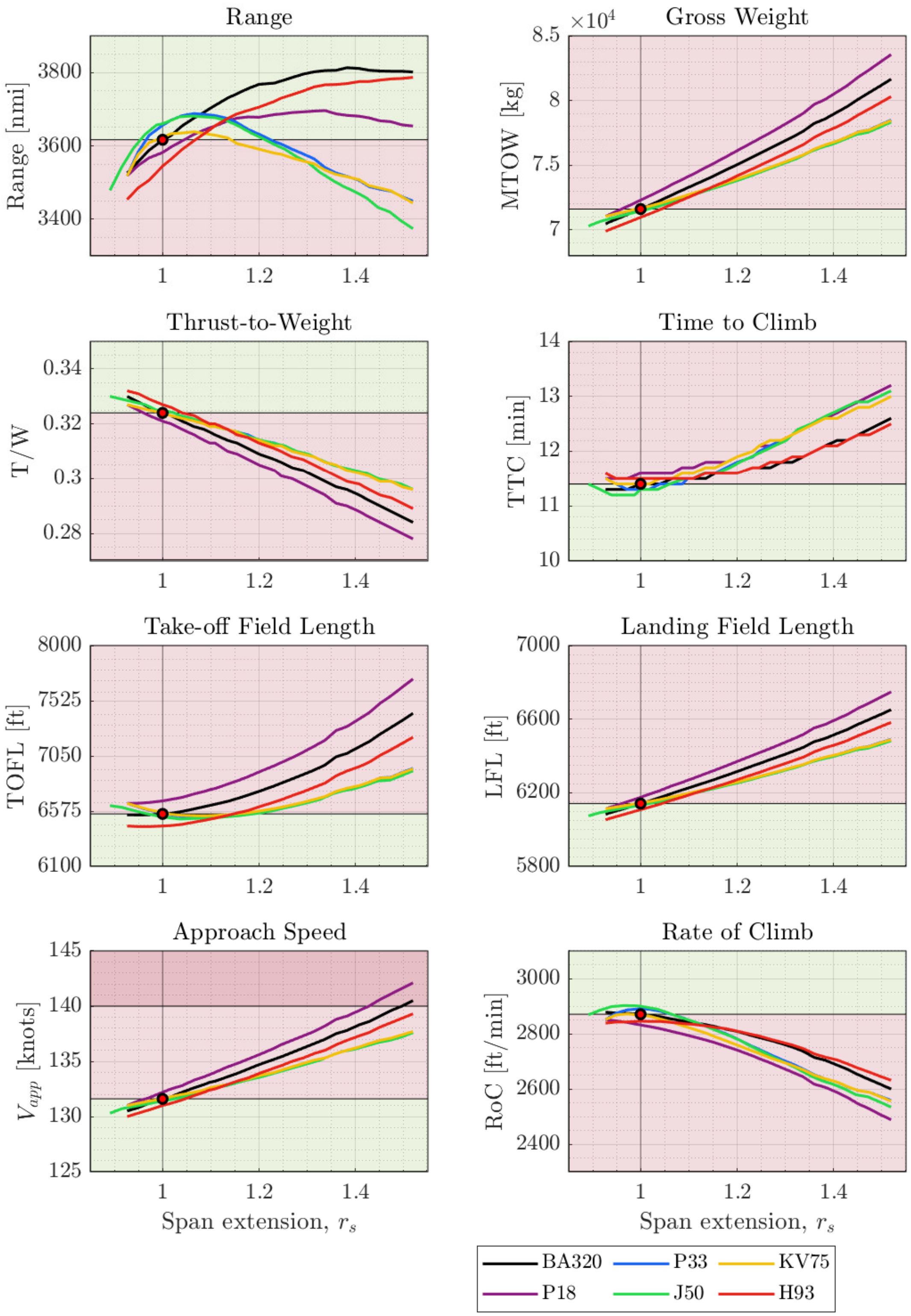

Fig. 13 Trends for top-level aircraft requirements with span extension.

where Æ is the wing aspect ratio, W_{wing} is the weight of the wing and W_{MTOW} is the maximum take-off weight.

Now, the feasibility of the design of wings under the proposed NELD approach is assessed here through the use of

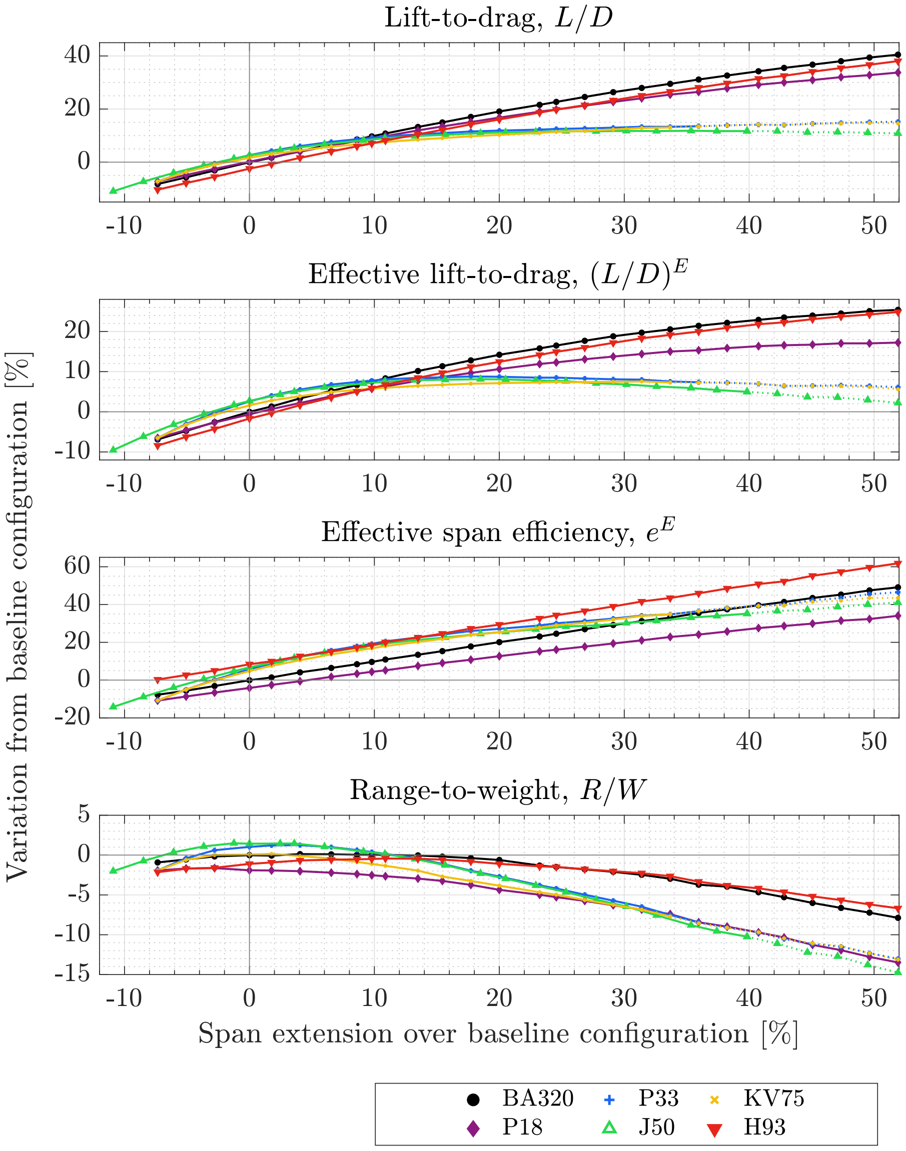

Fig. 14 Comparison of efficiency and performance metrics.

the efficiency metrics presented above. As considered by the author, the most encompassing figure of merit to compare performance improvements of the revised layouts over the baseline configuration is the range-to-weight ratio. This metric more clearly illustrates which spanload solution provides significant improvement in range, while considering the weight penalty due to the increased span. The NELD configurations providing any benefits are the ones derived from Jones and Prandtl's approach, with increases in R/W found for up to 10% span extensions. This equates to a maximum of 2.00% increase in range with a 4.97% span extension causing a weight increase of 0.97% for the P33 family. For the J50 family, the optimum R/W yields a 1.18% increase in range achieved with a span extension of 7.36% and causing a weight increase of 0.73%. The baseline configuration can be extended up to 13.49% in span without penalties in performance, for which the range is increased by 2.10% with the weight becoming 2.04% higher. The design points found at $\frac{R/W}{R/W_{\text{base}}} < 1$ will provide weight increases that will overthrow the gains in range when compared to the baseline configuration.

IV. Conclusions and Further Work

The research presented in this paper addresses some of the challenges being faced by the aviation industry concerning the environmental and socio-economic need to reduce greenhouse emissions. Specifically, this work has centred on approaches that aim at the reduction of induced drag, particularly those utilising the fundamental relation between induced drag and aspect ratio to propose novel concepts with HARWs. However, the multi-disciplinary nature of aircraft design has also been highlighted, along with the associated penalties that derive from these concepts. Among the numerous drawbacks associated with HARWs, this study explores the trade-offs specifically arising between increasing aerodynamic efficiency and reducing structural weight. But alongside the technical obstacles caused by the coupling physical phenomenon, this prospective answer to the aviation revolution accentuates the limitations of today's design methods to adapt to the required innovation, provide a comprehensive inclusion of the multi-disciplinary trade-offs, and enhance design freedom and decision-making, which are imperative traits to be able to satisfy this vision.

To address these challenges, this study provides an assessment of an alternative approach for the conceptual design of high aspect ratio wings under structural constraints. This approach is founded on the trade-off between spanload manipulation and span extension to improve aero-structural efficiency by effectively reducing induced drag while minimising the increase in weight. To do so, a multidisciplinary, multi-fidelity, physics-based design environment has been presented that integrates in-house developed and existing computational models; NeoCASS has been integrated for aero-structural sizing of the airframe components, AVL and XFOIL have been used to expand the aerodynamic analysis, and FLOPS has been incorporated and the tool the assessment of mission performance. Various theoretical approaches proposing structurally constrained spanloads for minimum induced drag have been included in this study to provide a comprehensive juxtaposition of their impact on aero-structural characteristics, which count with the work of Prandtl, Jones, Klein and Viswanathan and the Horten brothers. The set-based design approach allows for the analysis of feasible solutions with regard to overall performance improvement whilst shedding light on the relevant trade-offs derived from the adopted wing design approach. The assessment has been extended to the analysis of mission performance, which has been integrated to provide the grounds in which the aero-structural trade-offs come together, and hence provide synthesised trends and insight on the feasibility of the revised configurations designed under the proposed methodology, as compared to majority of the existing research. The interdisciplinary theoretical foundations adopted in the methodological approach and the framework composition have been outlined, as well as a discussion initiated on alternative efficiency factors metrics, which can provide significant insight into the design space sensitivities of this particular design problem at a conceptual design level. The presentation of additional figures of merit, such as the range-to-weight ratio, to comparatively assess the performance of the designs provides further insight than the use of other traditional metrics such as the lift-to-drag ratio. This yields several span-extended configurations without penalties in performance, following the methodology and metrics employed in the proposed design and analysis process.

Altogether, this can facilitate the identification of the determining contributors and compromises to be made at the early stages of the design, amplifying the designer's control over the design and decision-making processes, while delaying critical decisions and enhancing the optimisation process with more informed drivers. The principles of wing design with structurally constrained spanloads for aerodynamic efficiency align with the future vision for aviation, and it is in this context that the characteristics of NELD presented above can become beneficial. Nevertheless, additional efforts are needed to address the substantial limitations inherent in the proposed research, while further validation through sensitivity and uncertainty analyses will be essential to enhance the robustness of the findings. Additional aircraft concepts that address aero-structural efficiency, such as configuration with winglets or truss-braced HARWs, may be investigated in juxtaposition to further unveil the impact of the proposed designs against other approaches to wingspan extension.

References

[1] Greitzer, E., Bonnefoy, P., la Rosa Blanco, E. D., Dorbian, C., Drela, M., Hall, D., Hansman, R., Hileman, J., Liebeck, R., Lovegren, J., Mody, P., Pertuze, J., Sato, S., Spakovszky, Z., and Tan, C., "N+3 Aircraft Concept Designs and Trade Studies, Final Report. Volume 1," , 2010. https://doi.org/NASA/CRâĂŤ2010-216794/VOL1.

[2] Bruner, S., Baber, S., Harris, C., Caldwell, N., Keding, P., Rahrig, K., Pho, L., and Wlezian, R., "NASA N+3 Subsonic Fixed Wing Silent Efficient Low-Emissions Commercial Transport (SELECT) Vehicle Study. Revision A," , 2010. https://doi.org/NASA/CR-2010-216798/REVA.

[3] DAngelo, M. M., Gallman, J., Johnson, V., Garcia, E., Tai, J., and Young, R., "N+3 Small Commercial Efficient and Quiet Transportation for Year 2030-2035," , 2010.

[4] Wakayama, S., "Lifting Surface Design Using Multidisciplinary Optimization," , 1995. https://doi.org/10.5555/221003.

[5] Sobieszczanski-Sobieski, J., and Haftka, R. T., "Multidisciplinary aerospace design optimization: survey of recent developments," *Structural Optimization*, Vol. 14, 1997, pp. 1–23. https://doi.org/10.1007/BF01197554.

[6] Guenov, M., Fantini, P., Balachandran, L., Maginot, J., Padulo, M., and Nunez, M., "Multidisciplinary Design Optimization Framework for the Pre Design Stage," *Journal of Intelligent & Robotic Systems*, Vol. 59, 2010, pp. 223–240. https://doi.org/10.1007/s10846-010-9397-8.

[7] Defoort, S., Balesdent, M., Klotz, P., Schmollgruber, P., Morio, J., Hermetz, J., Blondeau, C., Carrier, G., and Bérend, N., "Multidisciplinary Aerospace System Design: Principles, Issues and Onera Experience," *Aerospace Lab*, Vol. Multidisci, 2012, p. 15.

[8] Lefebvre, T., Balesdent, M., Bartoli, N., Brevault, L., Defoort, S., Lafage, R., and Schmollgruber, P., "MDO advances for aircraft design in ONERA," Onera, 2014, p. 27.

[9] Clark, D. L., Allison, D. L., Bae, H., and Forster, E., "Metamodeling for Effectiveness Based Aircraft Design Under Uncertainty," American Institute of Aeronautics and Astronautics, 2018. https://doi.org/10.2514/6.2018-3743, URL https://arc.aiaa.org/doi/10.2514/6.2018-3743.

[10] Jungo, A., Zhang, M., Vos, J. B., and Rizzi, A., "Benchmarking New CEASIOM with CPACS adoption for aerodynamic analysis and flight simulation," *Aircraft Engineering and Aerospace Technology*, Vol. 90, 2018, pp. 613–626. https://doi.org/10.1108/AEAT-11-2016-0204.

[11] Du, X., and Leifsson, L., "Optimum aerodynamic shape design under uncertainty by utility theory and metamodeling," *Aerospace Science and Technology*, Vol. 95, 2019. https://doi.org/10.1016/j.ast.2019.105464.

[12] Shi, R., Long, T., Ye, N., Wu, Y., Wei, Z., and Liu, Z., "Metamodel-based multidisciplinary design optimization methods for aerospace system," *Astrodynamics*, Vol. 5, 2021, pp. 185–215. https://doi.org/10.1007/s42064-021-0109-x.

[13] Mura, G. L., Riaz, A., Guenov, M., Molina-Cristobal, A., Chen, X., Sharma, S., Nicolls, K., and Lynas, C., "Early Stage Design of High-Lift Devices with System and Manufacturing Constraints," American Institute of Aeronautics and Astronautics, 2019. https://doi.org/10.2514/6.2019-1035, URL https://arc.aiaa.org/doi/10.2514/6.2019-1035.

[14] Guenov, M. D., Riaz, A., Bile, Y. H., Molina-Cristobal, A., and Heerden, A. S., "Computational framework for interactive architecting of complex systems," *Systems Engineering*, Vol. 23, 2020, pp. 350–365. https://doi.org/10.1002/sys.21531.

[15] Kontogiannis, S. G., Demange, J., Savill, A. M., and Kipouros, T., "A comparison study of two multifidelity methods for aerodynamic optimization," *Aerospace Science and Technology*, Vol. 97, 2020, p. 105592. https://doi.org/10.1016/j.ast.2019.105592.

[16] Kontogiannis, S. G., and Savill, M. A., "A generalized methodology for multidisciplinary design optimization using surrogate modelling and multifidelity analysis," *Optimization and Engineering*, 2020. https://doi.org/10.1007/s11081-020-09504-z.

[17] Mileham, A. R., Currie, G. C., Miles, A. W., and Bradford, D. T., "A Parametric Approach to Cost Estimating at the Conceptual Stage of Design," *Journal of Engineering Design*, Vol. 4, 1993, pp. 117–125. https://doi.org/10.1080/09544829308914776.

[18] Pasquale, D. D., Gore, D., Savill, M., Kipouros, T., and Holden, C., "Cost Modelling for Aircraft in a Multi-Disciplinary Design Context," , 2016. https://doi.org/10.3233/978-1-61499-668-2-471.

[19] Kapania, R. K., Schetz, J. A., Mallik, W., Segee, M. C., and Gupta, R., "Multidisciplinary Design Optimization and Cruise Mach Number Study of Truss-Braced Wing Aircraft," , 2018. https://doi.org/NASA/CR-2018-219836.

[20] Carrier, G., Atinault, O., Dequand, S., Hantrais-Gervois, Liauzun, J.-L., Paluch, B., Rodde, A.-M., and Toussaint, C., "Investigation Of A Strut-Braced Wing Configuration For Future Commercial Transport," Onera, 2012, p. 16.

[21] Bradley, M. K., and Droney, C. K., "Subsonic Ultra Green Aircraft Research," , 2011. https://doi.org/NASA/CR-2011-216847.

[22] Bradley, M. K., Droney, C. K., and Allen, T. J., "Subsonic Ultra Green Aircraft Research. Phase II - Volume I; Truss Braced Wing Design Exploration," , 2015. https://doi.org/NASA/CR-2015-218704/VOL1.

[23] Airbus, "The albatross is inspiring tomorrow's aircraft wings," , 2019. URL https://www.airbus.com/newsroom/stories/the-albatross-is-inspiring-tomorrows-next-generation-of-aircraft-wings.html.

[24] Katz, J., and Plotkin, A., *Low-Speed Aerodynamics*, 2^{nd} ed., Cambridge University Press, 2001. https://doi.org/10.1017/CBO9780511810329.

[25] Su, W., and Cesnik, C. E. S., "Nonlinear Aeroelasticity of a Very Flexible Blended-Wing-Body Aircraft," *Journal of Aircraft*, Vol. 47, 2010, pp. 1539–1553. https://doi.org/10.2514/1.47317, URL https://arc.aiaa.org/doi/10.2514/1.47317.

[26] Calderon, D. E., Cooper, J. E., Lowenberg, M., Neild, S. A., and Coetzee, E. B., "Sizing High-Aspect-Ratio Wings with a Geometrically Nonlinear Beam Model," *Journal of Aircraft*, Vol. 56, 2019, pp. 1455–1470. https://doi.org/10.2514/1.C035296, URL https://arc.aiaa.org/doi/10.2514/1.C035296.

[27] Prandtl, L., "Über tragflügel kleinsten induzierten Widerstandes," *Zeitschrift für Flugtecknik und Motorluftschiffahrt*, Vol. 24, 1933, pp. 556–561.

[28] Hunsaker, D. F., and Phillips, W., "Ludwig Prandtl's 1933 Paper Concerning Wings for Minimum Induced Drag, Translation and Commentary," American Institute of Aeronautics and Astronautics, 2020, p. 12. https://doi.org/10.2514/6.2020-0644.

[29] Bowers, A. H., Murillo, O. J., Eslinger, B., and Gelzer, C., "On Wings of the Minimum Induced Drag: Spanload Implications for Aircraft and Birds," , 2016. https://doi.org/NASA/TP-2016-219072.

[30] Jones, R. T., "NACA-TN-2249: The spanwise distribution of lift for minimum induced drag of wings having a given lift and a given bending moment," , 12 1950.

[31] Jones, R. T., "Minimizing induced drag," *Soaring and Motorgliding*, Vol. 43, 1979, pp. 26–29.

[32] Klein, A., and Viswanathan, S. P., "Minimum induced drag of wings with given lift and root-bending moment," *Zeitschrift für angewandte Mathematik und Physik ZAMP*, Vol. 24, 1973, pp. 886–892. https://doi.org/10.1007/BF01590797.

[33] Klein, A., and Viswanathan, S. P., "Errata: Approximate Solution for Minimum Induced Drag of Wings with Given Structural Weight," *Journal of Aircraft*, Vol. 12, 1975, pp. 756–756. https://doi.org/10.2514/3.59866.

[34] DeYoung, J., "Minimization Theory of Induced Drag Subject to Constraint Condition," , 1979. https://doi.org/NASACR3140.

[35] Pate, D. J., and German, B. J., "Lift Distributions for Minimum Induced Drag with Generalized Bending Moment Constraints," *Journal of Aircraft*, Vol. 50, 2013, pp. 936–946. https://doi.org/10.2514/1.C032074.

[36] Hunsaker, D. F., Phillips, W. F., and Joo, J. J., "Aerodynamic Shape Optimization of Morphing Wings at Multiple Flight Conditions," American Institute of Aeronautics and Astronautics, 2017, p. 14. https://doi.org/10.2514/6.2017-1420.

[37] Phillips, W. F., Hunsaker, D. F., and Joo, J. J., "Minimizing Induced Drag with Lift Distribution and Wingspan," *Journal of Aircraft*, Vol. 56, 2019, pp. 431–441. https://doi.org/10.2514/1.C035027.

[38] Kroo, I., "Trim Drag, Tail Sizing, and Soaring Performance," *Technical Soaring*, Vol. 8, 1984, pp. 127–137.

[39] Lundry, J. L., "Minimum swept-wing induced drag with constraints on lift and pitching moment." *Journal of Aircraft*, Vol. 4, 1967, pp. 73–74. https://doi.org/10.2514/3.43797.

[40] Ning, S. A., and Kroo, I., "Tip Extensions, Winglets, and C-wings: Conceptual Design and Optimization," American Institute of Aeronautics and Astronautics, 2008, p. 28. https://doi.org/10.2514/6.2008-7052.

[41] Eller, D., and Heinze, S., "Approach to Induced Drag Reduction with Experimental Evaluation," *Journal of Aircraft*, Vol. 42, 2005, pp. 1478–1485. https://doi.org/10.2514/1.11713.

[42] Rokhsaz, K., "Effect of viscous drag on optimum spanwise lift distribution," *Journal of Aircraft*, Vol. 30, 1993, pp. 152–154. https://doi.org/10.2514/3.46328, URL http://arc.aiaa.org/doi/10.2514/3.46328.

[43] Abdel-Motaleb, S. A., Taylor, J. D., Hunsaker, D. F., and Coopmans, C., "Comparison of Induced and Parasitic Drag on Wings with Minimum Induced Drag," American Institute of Aeronautics and Astronautics, 2019, p. 20. https://doi.org/10.2514/6.2019-2120.

[44] Horten, R., and Selinger, P. F., *Nurflügel*, Weishaupt, 1987.

[45] Lobert, G., "Spanwise lift distribution of forward-and aft-swept wings in comparison to the optimum distribution form," *Journal of Aircraft*, Vol. 18, 1981, pp. 496–498. https://doi.org/10.2514/3.44717.

[46] Castellani, M., Cooper, J. E., and Lemmens, Y., "Flight Loads Prediction of High Aspect Ratio Wing Aircraft Using Multibody Dynamics," *International Journal of Aerospace Engineering*, Vol. 2016, 2016, pp. 1–13. https://doi.org/10.1155/2016/4805817, URL https://www.hindawi.com/journals/ijae/2016/4805817/.

[47] Sugimoto, T., "Wing design for hanggliders having minimum induced drag," *Journal of Aircraft*, Vol. 29, 1992, pp. 730–731. https://doi.org/10.2514/3.46234, URL http://arc.aiaa.org/doi/10.2514/3.46234.

[48] McGeer, T., "Wing design for minimum drag with practical constraints," *Journal of Aircraft*, Vol. 21, 1984, pp. 879–886. https://doi.org/10.2514/3.45058.

[49] Wakayama, S., and Kroo, I., "Subsonic wing planform design using multidisciplinary optimization," *Journal of Aircraft*, Vol. 32, 1995, pp. 746–753. https://doi.org/10.2514/3.46786.

[50] Ning, S. A., and Kroo, I., "Multidisciplinary Considerations in the Design of Wings and Wing Tip Devices," *Journal of Aircraft*, Vol. 47, 2010, pp. 534–543. https://doi.org/10.2514/1.41833.

[51] Craig, A., and McLean, D., "Spanload optimization for strength designed lifting surfaces," American Institute of Aeronautics and Astronautics, 1988, p. 9. https://doi.org/10.2514/6.1988-2512.

[52] Phillips, W. F., "Lifting-Line Analysis for Twisted Wings and Washout-Optimized Wings," *Journal of Aircraft*, Vol. 41, 2004, pp. 128–136. https://doi.org/10.2514/1.262.

[53] Bragado-Aldana, E., "Assessment of Non-Elliptic Lift Distributions on Span-Extended Wing Design," , 2022.

[54] Bragado-Aldana, E., Lone, M., and Riaz, A., "On wings with non-elliptic lift distributions," 2021.

[55] Aldana, E. B., and Lone, M. M., "Closer look at the flight dynamics of wings with non-elliptic lift distributions," American Institute of Aeronautics and Astronautics, 2020, p. 13. https://doi.org/10.2514/6.2020-0284.

[56] S.A.S., A., "A320 Aircraft Characteristics, Airport and Maintenance Planning," , 2005.

[57] e solutions, T., "Pacelab APD and SysArc," , 2022. URL https://pace.txtgroup.com/products/preliminary-design/pacelab-apd-for-engineers-by-engineers.

[58] Inc., T. M., "MATLAB," , 2021. URL https://uk.mathworks.com/.

[59] Prandtl, L., and Betz, A., "NACA-TR-116: Applications of Modern Hydrodynamics to Aeronautics." , 1923.

[60] Klein, A., and Viswanathan, S. P., "Approximate solution of minimum induced drag of wings with given structural weight," *Journal of Aircraft*, Vol. 12, 1975, pp. 124–126. https://doi.org/10.2514/3.44425.

[61] Cavagna, L., Ricci, S., and Travaglini, L., "NeoCASS: An integrated tool for structural sizing, aeroelastic analysis and MDO at conceptual design level," *Progress in Aerospace Sciences*, Vol. 47, 2011, pp. 621–635. https://doi.org/10.1016/j.paerosci.2011.08.006.

[62] Cavagna, L., "NeoCASS - Next generation Conceptual Aero Structural Sizing," , 2013.

[63] Anderson, J. D., *Fundamentals of aerodynamics*, 5th ed., Mcgraw Hill, 2010.

[64] EASA, "Certification Specifications and Acceptable Means of Compliance for Large Aeroplanes (CS-25 Amendment 27)," , 2021.

[65] Isikveren, A. T., "Methodology for Conceptual Design and Optimisation of Transport Aircraft," 1998.

[66] Isikveren, A. T., "Quasi-Analytical Modelling and Optimisation Techniques for Transport Aircraft Design," , 2002.

[67] Cavagna, L., Ricci, S., and Riccobene, L., "A Fast Tool for Structural Sizing, Aeroelastic Analysis and Optimization in Aircraft Conceptual Design," American Institute of Aeronautics and Astronautics, 2009. https://doi.org/10.2514/6.2009-2571.

[68] Drela, M., and Youngren, H., "AVL," , 2017. URL http://web.mit.edu/drela/Public/web/avl/.

[69] Drela, M., and Youngren, H., "XFOIL," , 2013. URL https://web.mit.edu/drela/Public/web/xfoil/.

[70] Malone, B., and Mason, W. H., "Multidisciplinary optimization in aircraft design using analytic technology models," *Journal of Aircraft*, Vol. 32, 1995, pp. 431–438. https://doi.org/10.2514/3.46734, URL https://arc.aiaa.org/doi/10.2514/3.46734.

[71] Raymer, D., *Aircraft Design: A Conceptual Approach, Sixth Edition*, American Institute of Aeronautics and Astronautics, Inc., 2018. https://doi.org/10.2514/4.104909.

[72] McCormick, B. W., *Aerodynamics, Aeronautics, and Flight Mechanics*, 2nd ed., Wiley, 1995.

[73] Roskam, J., *Methods for Estimating Drag Polars of Subsonic Airplanes*, Roskam Aviation and Engineering Corporation, 1971.

[74] ESDU, I., “ESDU 79015: Undercarriage drag prediction methods,” , 2000. https://doi.org/9780856792601.

[75] McCullers, A., “Flight Optimization System (FLOPS),” , 2011. URL https://software.nasa.gov/software/LAR-18934-1.

[76] Guynn, M. D., “Effective L/D: A Theoretical Approach to the Measurement of Aero-Structural Efficiency in Aircraft Design,” American Institute of Aeronautics and Astronautics, 2015, p. 14.

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