

Research Article

Conceptual Aircraft Empennage Design Based on Multidisciplinary Design Optimization Approach

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Within a conventional aircraft design process, the horizontal tail and vertical tail are generally sized via volume coefficient methods. In this manuscript, an improved method for conceptual aircraft tail design based on multidisciplinary design optimization (MDO) approach with stability and control constraints has been developed. To develop this method, first, the tail design requirements have been derived from the regulations and the fundamental functionalities of tail plans. Then, the empennage design is formulated as an MDO problem. Eventually the design optimization of horizontal and vertical tail is combined with the design optimization of the aircraft wing. A test case is presented for concurrent wing and tail plane design, which resulted in more than 9% reduction in aircraft block fuel weight and more than 3% reduction in aircraft maximal takeoff weight, which indicates a great potential for fuel burn and carbon reductions with empennage design optimization at conceptual aircraft design phase.

1. Introduction

The need for significant reduction in aircraft fuel burn, carbon and NO_x emissions, noise, and costs moves the aviation industries towards continuous improvements of the transport airplanes by introducing new engines, modifying the aircraft aerodynamics and structures, etc. However, there is still a huge gap between the current development and the ambitious goals set by aviation authorities such as Flightpath 2050 [1]. To address the challenging goals, IATA technology roadmap [2] and the US NASA N+ programs [3, 4] have identified a bunch of potential airframe and propulsion technologies which might be available in 2050 time frame according to technology readiness level. Investigating the effect of these technologies, it has been concluded that the technology development alone cannot reach the desired emission reduction goals. New technologies need to be augmented with new aircraft configurations, as well as new operational scenarios.

Except for the general challenge of aircraft design for new technologies and new configurations, design of tail plans within conceptual/preliminary design is a challenge

by itself. Conceptual aircraft design and optimization, including detailed tail design with stability and control constraints, are more complex compared to the detailed main wing design alone due to the coupling effect to the design of the tail plane and the control surfaces, which is usually done in later and more detailed design stages. Due to the complex and iterative process, most aircraft design tools have neglected the tail design or used simplified tail sizing process, such as tail volume coefficient methods [5, 6].

To design tail plane for new aircraft configurations, it is important to formulate the tail design as a Multidisciplinary Design Optimization (MDO) problem. To do so, all the principle trim, stability, and control requirements need to be defined as design constraints. Galloway [7] has designed aircraft tail plane with stability and control constraints included. Most of the stability derivative calculations and performance estimations in Galloway's work have been taken from the book of Smetana [8], where the empirical methods are focused on small aircraft. Morris [9] has carried out MDO studies with constraints on aircraft dynamic stability for reducing aircraft gross weight and cruise trim drag, where the empennage area

TABLE 1: Tail design requirements from regulations.

Requirements	Subpart	Paragraph	General description
Trim	FAR/CS part 25 Subject group 77	25.161 [14]	Each airplane must meet the trim requirements of this section after being trimmed, and without further pressure upon, or movement of, either the primary controls or their corresponding trim controls by the pilot or the automatic pilot.
Stability	FAR/CS part 25 Subject group 78	25.171-25.181	The airplane must be longitudinally, directionally, and laterally stable in accordance with the provisions of §§ 25.173 through 25.177. In addition, suitable stability and control feel (static stability) are required in any condition normally encountered in service, if flight tests show it is necessary for safe operation.
Controllability and maneuverability	FAR/CS part 25 Subject group 76	25.143-25.149	The airplane must be safely controllable and maneuverable during (1) takeoff, (2) climb, (3) level flight, (4) descent, and (5) landing.
Handling quality	MIL-F-8785C		Control anticipation parameter Flying qualities for aircraft: normal states within the operational flight envelope shall be level 1. Flying qualities for aircraft: normal states within the service flight envelope but outside the operational flight envelope shall be level 2 or better.

TABLE 2: A full list of design variables.

Design variables	Initial value	Lower bound	Upper bound
Area of HTP (m ²)	32.23	18	40
AR of HTP	4.82	3.5	5.5
TR of HTP	0.32	0.28	0.35
Leading edge sweep of HTP (°)	35	10	45
t/c of HTP	0.12	0.09	0.13
Incidence angle of HTP (°)	-1.2	-3.0	1.0
Area of VTP (m ²)	28.21	18	40
AR of VTP	1.67	1.2	1.8
TR of VTP	0.32	0.28	0.35
Leading edge sweep of VTP (°)	40	10	45
t/c of VTP	0.12	0.09	0.13
Area of wing (m ²)	122.41	90	130
AR of wing	9.45	6.5	16
TR of wing	0.24	0.21	0.28
Leading edge sweep of wing (°)	27	15	40
t/c of wing	0.125	0.09	0.13
Longitudinal reference point of wing (m)	11.7	11	13

is sized in the beginning and fixed during the optimization. Fixing the empennage area might narrow down the full design space for optimization as compared to simultaneously optimizing empennage area and other empennage planform parameters. More recently, Cosenza and Vos [10] have studied the handling quality optimization, but only the longitudinal constraints are considered. The work of Garmendia [11] and Denieul [12] represent the tail optimization work with a focus on the design of control devices.

To identify and further study possible aircraft level fuel burn and carbon emission reduction potentials for civil transport aircraft with new airframe technologies, new propulsion systems and new operations, it is very important to extend the aircraft design space via introducing more aircraft components at conceptual aircraft design stage instead

of wing design and optimization alone [13]. In this context, the focus of the current manuscript is to present the improvement of the tail design process based on an MDO approach for large aircraft design space exploration. First, the fundamental requirements on tail design are introduced. Based on the requirements, the total tail design is formulated as an optimization procedure, where the design constraints, design variables, and design objectives are introduced. In the end, case studies with a typical medium range transport aircraft are carried out using the proposed MDO approach.

2. Materials and Methods

2.1. Tail Design Requirements. In order to formulate the tail design for large transport aircraft as an MDO problem, it is

TABLE 3: A full list of design constraints for stability and control.

Requirement	Constraint formulation	Analysis methods	References
Longitudinal static stability	$C_{m\alpha} < 0$	$C_{m\alpha}$ calculated using USAF Datcom	[7, 17, 18]
Longitudinal static stability	Static margin (S.M.) $0.05 < \text{S.M.} < 0.1$	S.M. = $x_{\text{NP}} - x_{\text{CG, aft}}/\text{MAC}$ Neutral point (X_{NP}) is calculated using the AVL tool with cruise flight condition	[19]
Longitudinal dynamic stability	$-40 < C_{m\dot{q}} < -5$	Aft center of gravity $X_{\text{CG, aft}}$ is determined from the loading diagram	[7, 17]
Longitudinal dynamic stability	Short period-natural frequency and damping ratio $0.28 < \omega_{n,sp} < 3.6$; $0.3 < \zeta_{sp} < 2$	$\omega_{sp} = M_\alpha^{1/2}$ $\zeta_{sp} = M_\alpha + M_q/2\omega_{sp}$	[20]
Longitudinal dynamic stability	Phugoid damping ratio $\zeta_p > 0.04$ (level 1) or > 0 (level 2) (level 1 is satisfactory, level 2 is acceptable [21])	$M_\alpha, M_i,$ and M_q are calculated using the methods from [20] $\zeta_p = 1/(\sqrt{2}L/D)$	[21]
Longitudinal control	$S_h > S_{h, \min}$	$S_{h, \min} = (((\Delta x_{cg}/\text{MAC}) + ((x_{np} - x_{cg})/\text{MAC})) - (C_{mac}/C_{L_{max}}))/\{(C_{L\alpha_i}/C_{L\alpha}) (1 - (d\epsilon/d\alpha)) - (C_{LH}/C_{L_{max}})\} \{((V_h/V)^2) (l_h/\text{MAC})\} * S$	[19]
Longitudinal trim	$C_m = 0$ at $C_{L, \text{cruise}}$	$\alpha_{C_m=0}$ calculated using USAF Datcom $\alpha_{C_{L, \text{cruise}}}$ calculated using cruise aircraft mass and flight conditions	[22]
Lateral-directional static stability	$C_{n\dot{\beta}} > 0$	$C_{n\dot{\beta}}$ calculated using USAF Datcom	[23]
Lateral-directional static stability	$C_{l\dot{\beta}} < 0$	$C_{l\dot{\beta}}$ calculated using USAF Datcom	[24]
Lateral-directional static stability	$C_{y\dot{\beta}} < 0$	$C_{y\dot{\beta}}$ calculated using USAF Datcom	[23]
Lateral-directional dynamic stability	$C_{nr} < 0$	C_{nr} calculated using USAF Datcom	[24]
Lateral-directional dynamic stability	Dutch roll damping ratio $\zeta_{dr} > 0.08$	$\zeta_{dr} = -(C_{nr}/8) (2S\rho Vb^3/I_{zz} C_{n\dot{\beta}})^{1/2}$ C_{nr} and $C_{n\dot{\beta}}$ calculated using USAF Datcom	[21]
Lateral-directional dynamic stability	Roll mode time constant $\tau_{roll} < 1.4$	$\tau_{roll} = -4I_{xx}/S\rho Vb^2 C_{lp}$ C_{lp} calculated using USAF Datcom	[21]
One engine inoperative yaw trimming	$S_y > S_{y, \min}$	$S_{y, \min} = (F_{\text{engine}} + q_{\min} C_{D, \text{engine}} A_{\text{engine}}) / y_{\text{engine}} / q_{\min} C_{Lx, \text{yaw}} L_y$	[18]
One engine inoperative yaw trimming	$S_y > S_{y, \min}$	$S_{y, \min} = (F_{\text{engine}} + q_{\min} C_{D, \text{engine}} A_{\text{engine}}) / y_{\text{engine}} / q_{\min} C_{Lx, \text{yaw}} L_y$	[18]

TABLE 4: Calculated component mass as compared to reference [15].

	Calculated (kg)	Reference (kg)	Difference (%)
MTOW	75985.7	77000.0	1.32
OWE	42059.2	42092.0	0.08
Block fuel	14609.2	14733.0	0.84
Wing mass	8165.3	8097.0	-0.84
HTP mass	676.9	682.0	0.75
VTP mass	538.5	522.0	-3.17

reasonable to derive the constraints directly from regulations such as FAR/CS part 25 (as the focus of the manuscript is on large transport aircraft) for trim, stability, and control and MIL-F-8785C for handling quality requirements. Table 1 summarizes these design requirements together with the related sources.

2.2. Tail Design Formulation as an MDO Problem. In this section, the detailed formulation of aircraft tail plane design optimization is presented. First, a general description of the MDO approach is introduced. Then, the derived design constraints are listed. In addition to the optimization process, a brief overview on the analysis modules for the aircraft design and technology assessment tool is given.

2.2.1. General Description of MDO Setup. The whole tail design process is formulated as an optimization problem, which is defined in the following. Since the design of the tail is coupled with the wing geometry, a concurrent optimization of wing, horizontal tail plane (HTP), and vertical tail plane (VTP) is considered. It has to be noted that two scenarios for optimizing (minimizing) are considered: minimizing the aircraft maximum takeoff weight (MTOW) and minimizing aircraft block fuel weight. It has to be noted that in our aircraft design process, the top-level aircraft requirements such as takeoff and landing distance requirements are always satisfied via initial sizing process. That being said, the paper has considered the takeoff and landing requirements during each optimization.

$$\begin{aligned}
 & \text{Min} \quad \{ \text{MTOW or Block fuel weight} \}, \\
 & \text{w.r.t.} \quad x_{\text{wing}}(S, \text{AR}, \text{TR}, \varphi_{\text{LE}}, t/c, x_{\text{ref}}), \\
 & \quad \quad x_{\text{HTP}}(S, \text{AR}, \text{TR}, \varphi_{\text{LE}}, t/c, i_H), \\
 & \quad \quad x_{\text{VTP}}(S, \text{AR}, \text{TR}, \varphi_{\text{LE}}, t/c), \\
 & \text{s.t.} \quad \text{Constraints given in Table 3.}
 \end{aligned} \tag{1}$$

A full list of all design variables used in this paper is listed in Table 2. For wing, HTP, and VTP, the planform parameters, i.e., area, aspect ratio, taper ratio, leading edge sweep, and average thickness to chord ratio are chosen as design variables. In addition, the incidence angle of HTP and the longitudinal reference point of the wing are selected as design variables. Based on the reference data of a medium range transport aircraft [15], the initial values, lower bound and upper bounds, of all the design variables are selected

and shown in Table 2. For better optimization performance (convergence, computation time, tolerance, etc.), scaling strategies [16] have been applied to the design variables, design constraints, and design objectives.

2.2.2. Design Constraints for Stability, Control, and Trim. Based on the functionality requirements of horizontal and vertical tail plans discussed previously, a full list of design constraints for stability, control, and trim has been derived. A detailed mathematical formulation of all the design constraints on stability, control, and trim is summarized in Table 3.

2.3. Analysis Methods for Conceptual Aircraft Design Tool. The aircraft design tool utilized in this study follows a typical aircraft conceptual/preliminary design logic [5–8]. The tool is capable to conceptually design transport aircraft with both conventional (tube and wing) and blended wing body configurations. The effects of new technologies, such as boundary layer ingestion, active load alleviation, and boundary layer suction are included in the analysis. The general descriptions of the aircraft design framework have been introduced in ref. [13]. The analysis disciplines of the design tool explicitly related in the current studies are briefly introduced below.

The geometry file is written in XML format with CPACS [25] compatible methods, which can be read by geometry software such as TiGLViewer and can be further exported to watertight CAD format such as step file for high-fidelity simulations and visualization. Component-based build-up methods are employed for aerodynamic drag polar estimation. The induced drag of the wing and tail plans is calculated using potential flow based solver [26], with fuselage and nacelles corrections; viscous drag is calculated using semiempirical methods with high-fidelity corrections; wave drag is estimated semiempirically based on the method presented in [27]. Analytical methods are used for the primary structure of wing and fuselage, and semiempirical methods are used for secondary structure weight. Datcom-based semiempirical methods [22] are used for calculating both static and dynamic stability derivatives. Engine performance is achieved by GasTurb software [28] with reliable gas turbine cycle analysis capability. The mission is studied by solving the equations of motion with detailed stepwise aerodynamics, mass, and engine performance data. To validate the design and analysis codes, the outputs of the tool for an A320-like medium range aircraft are compared with literature [15] (see Table 4). As can be seen in this table, the calculation deviations from the literature are below 5%.

3. Results and Discussion

In this section, the results of only HTP optimization, HTP-wing optimization, and HTP-VTP-wing optimization are shown to give a better insight into the impacts of different components optimization.

3.1. HTP Optimization. For the first step, we carry out case studies on only HTP optimization. Note that in this case the wing and the VTP planform parameters are fixed to

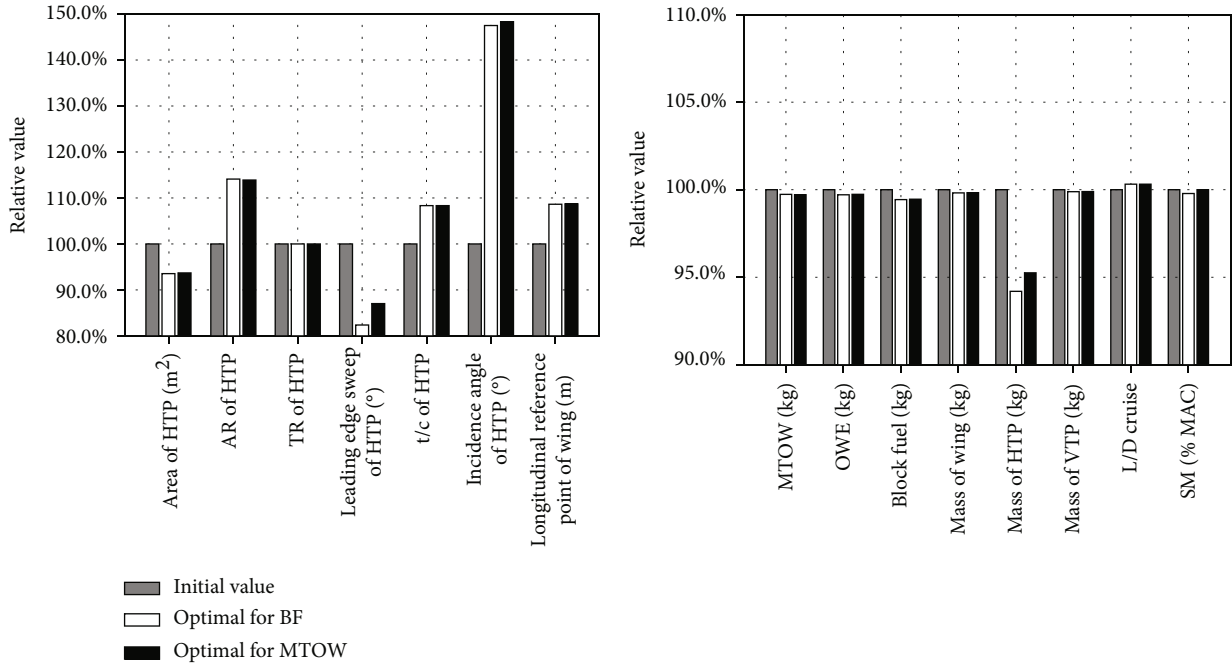


FIGURE 1: Relative changes of design variables, design constraints, and design objectives for HTP optimization.

the initial values. The HTP is optimized for two different cases, i.e., for minimizing block fuel weight and for minimizing the MTOW. The optimization results are presented in Figure 1. As can be seen from the results, the HTP area is slightly reduced for both MTOW and block fuel optimizations. For both scenarios, the reduction for block fuel and for MTOW is within the same order, i.e., around 0.56% for block fuel weight and around 0.27% for MTOW. During the initial optimizations, it has been found out that the constraint on static margin has an important influence on the horizontal tail area. Since only low-fidelity analysis is considered in this work, in order to make sure the tail area is defined properly, the static margin constraint is modified to keep the value of the static margin larger or equal to that of the reference aircraft, 9.2% MAC in this case. The maximum constraint violation of 0.2% for optimizing block fuel scenario is due to a very slight decrease in the static margin value compared to the reference case. However, it is still much larger than the 5% minimum requirement.

3.2. HTP and Wing Optimization. In this optimization case, the wing and HTP geometries are defined as design variables, while the geometry of the VTP is fixed to the initial values. The detailed results for the initial aircraft configuration and the optimized configurations are presented in Figure 2. As compared to the only HTP optimization case, including the wing in the optimization can significantly increase the optimization impacts for both block fuel and MTOW reduction, which was obviously expected. As can be seen, the block fuel can be reduced by 7.3% with an almost unchanged MTOW. When optimizing the MTOW,

the reduction is 1.97% with no benefit of block fuel saving. Note that the maximum constraint violation of 0.2% for the block fuel optimal case is due to a very slight increase in short period damping ratio. Note that the reason why the VTP mass has been slightly changed after optimization with fixed VTP parameters is due to the maximal takeoff weight change for HTP-wing optimization case. The analytic mass calculation method of VTP involves both VTP parameters such as trapezoidal area, span, taper ratio, sweep, but also MTOW [6].

3.3. HTP, VTP, and Wing Optimization. In the third case all the geometrical variables of the wing, HTP, and VTP are included in the optimization. Similar to the previous case studies, the planform parameters of the empennage and the wing are optimized for two different cases, i.e., for block fuel weight and for MTOW reduction. Figure 3 shows the geometric changes of HTP, VTP, and wing optimized for minimal block fuel and MTOW as compared to the original case. A detailed summary of relevant aircraft parameters including design variables for both block fuel optimal and MTOW optimal scenarios are presented in Figure 4. As can be found in this figure, block fuel weight is reduced by 9.42% with 1.68% reduction of the MTOW for the block fuel optimal scenario. The benefit comes from a combination of increasing sweep (wave drag reduction), increasing aspect ratio (induced drag reduction), reducing area of HTP, VTP, and wing (mass and viscous drag reduction), and the snow-ball effects. For the MTOW optimal scenario, the reduction of MTOW is slightly higher, about 3.28%; however, there is almost no reduction in block fuel weight. It has to be noted that for both MTOW and block fuel

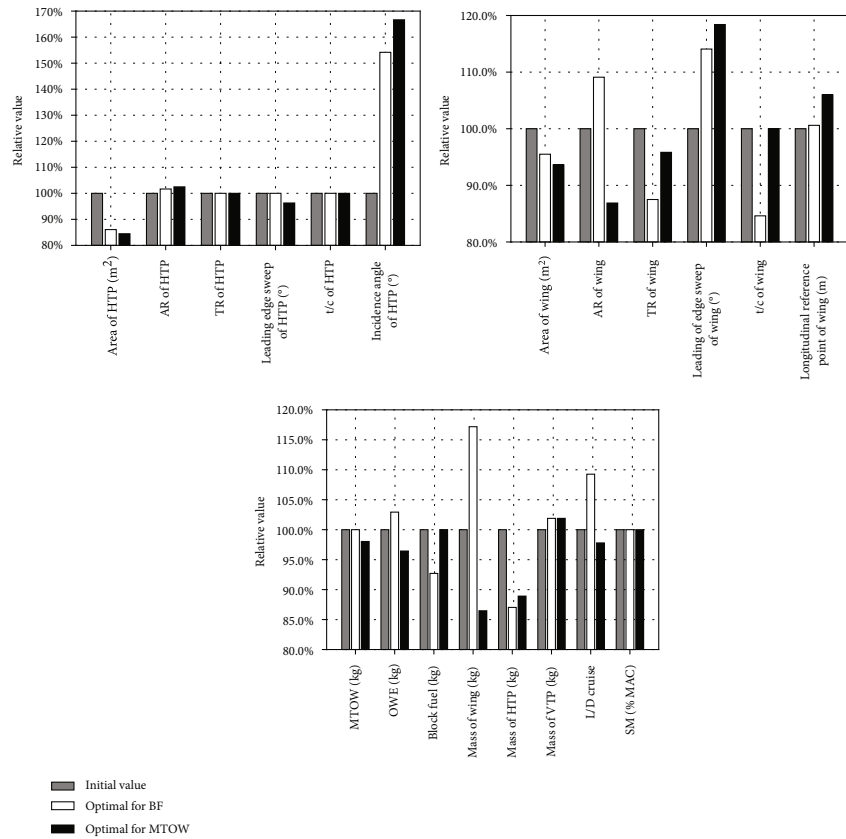


FIGURE 2: Relative changes of design variables, design constraints, and design objectives for HTP-wing optimization.

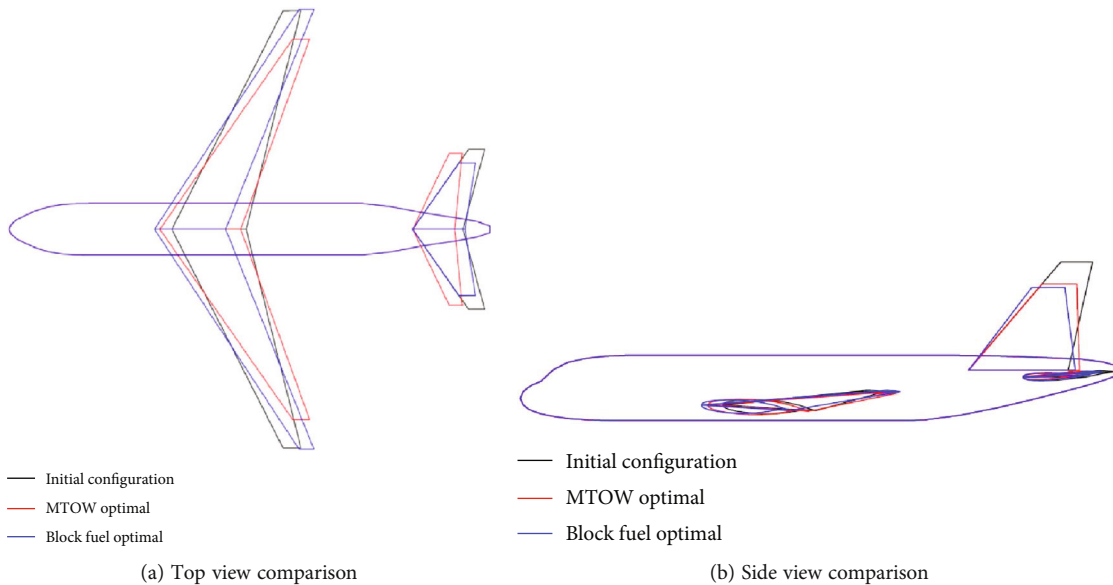


FIGURE 3: Comparison of HTP, VTP, and wing optimized for minimal block fuel and MTOW.

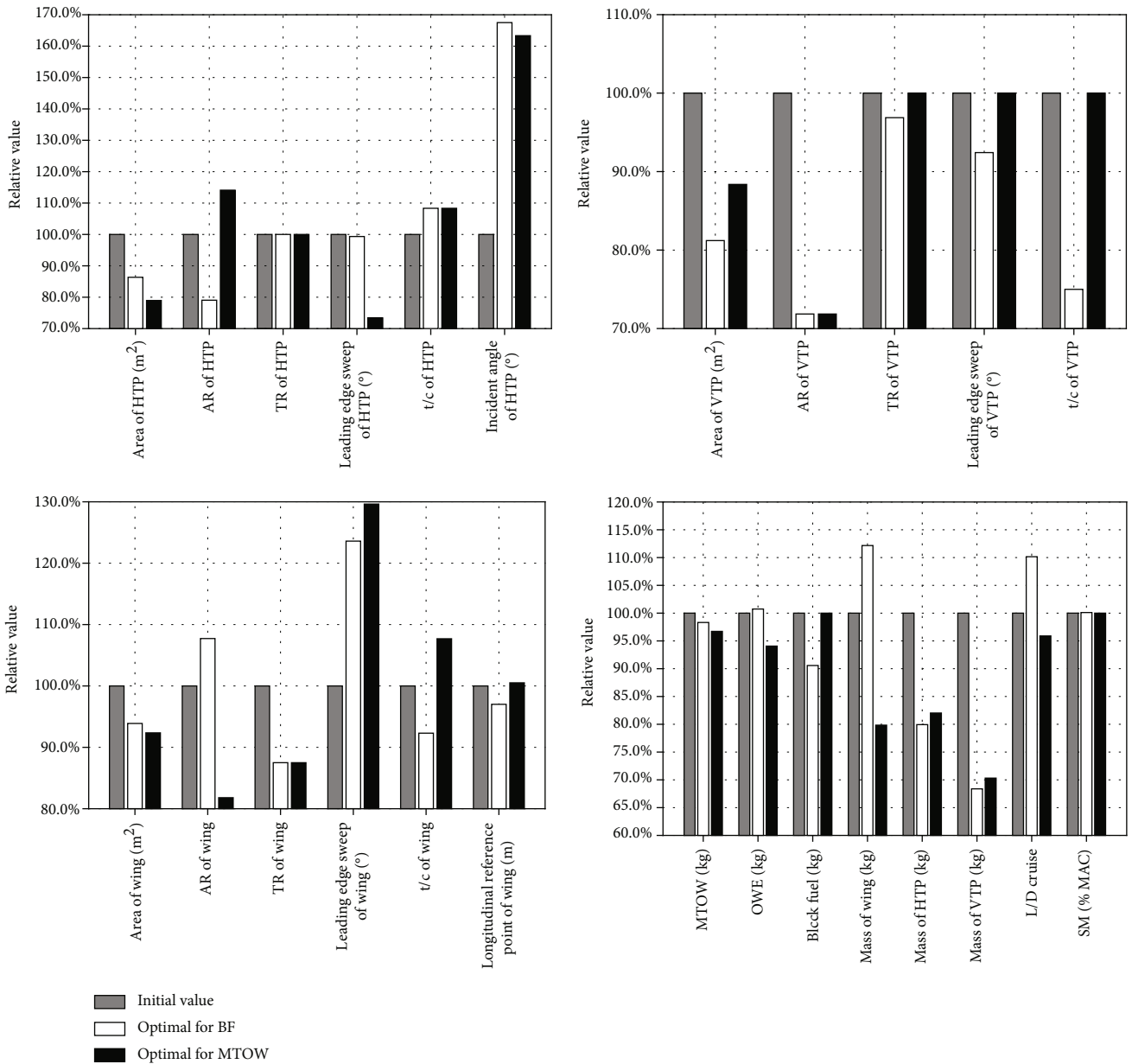


FIGURE 4: Relative changes of design variables, design constraints, and design objectives for HTP-VTP-wing optimization.

optimal scenarios, the area of HTP and VTP has been reduced as compared to the baseline configuration. However, further higher fidelity analyses are required to validate these results.

One important outcome of the optimization is the increased sweep angle of the wing. From higher fidelity wing aerostructural optimization, such as [29], it is expected that the optimizer reduces the sweep angle of the wing. This reduction in sweep angles can be justified by noting that higher sweep angles result in higher structural weight and for the same wing area reduced wing aspect ratio, which increases the induced drag. However lower sweep angle causes higher wave drag. In high fidelity wing optimization, the wing shape (airfoils) is defined as design variables, so the optimizer is able to compensate the increase in wave drag by optimizing the

shape of airfoils. In conceptual design optimization, such as the presented framework, no high fidelity CFD analysis is included, so the airfoil shapes cannot be optimized in details. The effect of airfoil shape on wave drag is considered via a “technology factor,” which is the same for all the airfoils with the same technology class, in this case, supercritical airfoils. Therefore, to reduce the wave drag the optimizer needs to reduce the wing thickness to chord ratio and/or increase the sweep angle. This could be the main reason for getting higher sweep angles for the optimized wing.

4. Conclusions

To deal with the aviation carbon emission reduction goals, it is very important to extend the design space at conceptual

aircraft design phase. In this context, also for better capturing the fundamental stability, control, and trim requirements, the tail design procedure has been formulated as an MDO problem. In particular, detailed constraints have been derived and imposed to the optimization process according to the functionalities of empennage. For case studies, both MTOW and block fuel weight have been optimized with respect to the wing and tail plane geometrical parameters. It has been shown that a block fuel reduction can be achieved by 0.55% via only optimizing the horizontal tail plan with a reduction of MTOW of 0.27%. In comparison, the benefit via concurrent wing and tail plane optimization is quite significant, with 9.42% block fuel reduction and 3.28% MTOW reduction. For the next step, it is meaningful to carry out studies with new technologies, such as active flow control or boundary layer ingestion, integrated for exploring the maximal achievable benefit in block fuel and MTOW reduction, with all constraints especially the stability, control, and trim requirements satisfied.

Data Availability

The data that support the findings of this study are available upon reasonable request.

Conflicts of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References

- [1] "Flightpath 2050-Europe's vision for aviation: advisory Council for Aeronautics Research in Europe," EUROPEAN COMMISSION, 2011, November 2017, <https://ec.europa.eu/transport/sites/transport/files/modes/air/doc/flightpath2050.pdf>.
- [2] IATA, "IATA technology roadmap 2013," 2013, November 2017, <http://www.iata.org/whatwedo/environment/Documents/technology-roadmap-2013.pdf>.
- [3] G. Bezos-O'Connor, M. Mangelsdorf, C. Nickol, H. Maliska, A. Washburn, and R. Wahls, "Fuel efficiencies through airframe improvements," in *3rd AIAA Atmospheric Space Environments Conference*, Honolulu, Hawaii, June 2011.
- [4] W. Kimmel, "Systems analysis approach for the NASA environmentally responsible aviation project," in *3rd AIAA Atmospheric Space Environments Conference*, Honolulu, Hawaii, June 2011.
- [5] S. Gudmundsson, *General Aviation Aircraft Design: Applied Methods and Procedures*, Butterworth-Heinemann, Oxford, Waltham MA, 2014.
- [6] D. Raymer, *Aircraft Design: A Conceptual Approach*, Sixth Edition, American Institute of Aeronautics and Astronautics, Inc, Washington, DC, 2018.
- [7] J. D. Galloway Jr., *Optimization of Conceptual Aircraft Design for Stability/Control and Performance*, Master thesis, 2000.
- [8] F. O. Smetana, *Computer Assisted Analysis of Aircraft Performance Stability and Control*, McGraw-Hill, New York, London, 1984.
- [9] C. C. Morris, *Flight Dynamic Constraints in Conceptual Aircraft Multidisciplinary Analysis and Design Optimization*, PhD thesis, 2013.
- [10] D. Cosenza and R. Vos, "Handling qualities optimization in aircraft conceptual design," in *17th AIAA Aviation Technology, Integration, and Operations Conference*, Denver, Colorado, June 2017.
- [11] D. C. Garmendia, *A multi-disciplinary conceptual design methodology for assessing control authority on a hybrid wing body configuration*, PhD thesis, 2015.
- [12] Y. Denieul, *Preliminary Design of Control Surfaces and Laws for Unconventional Aircraft Configurations*, PhD Thesis, 2016.
- [13] Y. Liu, A. Elham, P. Horst, and M. Hepperle, "Exploring vehicle level benefits of revolutionary technology progress via aircraft design and optimization," *Energies*, vol. 11, no. 1, p. 166, 2018.
- [14] Federal Aviation Regulations, *Part 25 Subpart B Section 25.161, trim*, United States Department of Transportation, 2018.
- [15] K. Risse, K. Schäfer, F. Schültke, and E. Stumpf, "Central reference aircraft data system (CeRAS) for research community," *CEAS Aeronautical Journal*, vol. 7, no. 1, pp. 121–133, 2016.
- [16] A. Messac, *Optimization in Practice with MATLAB® for Engineering Students and Professionals*, Cambridge University Press, Cambridge, 2015.
- [17] M. H. Sadraey, *Propulsion System Design: Aircraft Design: A Systems Engineering Approach, First Edition*, John Wiley & Sons, Inc, 2013.
- [18] P. M. Sforza, *Commercial Airplane Design Principles*, Butterworth-Heinemann, Amsterdam, 2014.
- [19] E. Torenbeek, *Synthesis of Subsonic Airplane Design*, Delft University Press, Delft, 1982.
- [20] R. Brockhaus, W. Alles, and R. Luckner, *Flugregelung*, Springer, Berlin Heidelberg, 2011.
- [21] MIL-HDBK-1797A, *Flying Qualities of Piloted Aircraft*, Department of Defense, 1997.
- [22] J. E. Williams and S. R. Vukelich, *The USAF Stability and Control Digital DATCOM. Volume I. Users Manual*, Air Force Flight Dynamics Laboratory, 1979.
- [23] J. Roskam, *Airplane Design*, DARcorporation, Lawrence Kan, 1985.
- [24] B. Etkin and L. D. Reid, *Dynamics of Flight: Stability and Control/Bernard Etkin, Lloyd Duff Reid*, Wiley, New York, Chichester, 3rd edition, 1996.
- [25] C. M. Liersch and M. Hepperle, "A distributed toolbox for multidisciplinary preliminary aircraft design," *CEAS Aeronautical Journal*, vol. 2, no. 1-4, pp. 57–68, 2011.
- [26] M. Drela and H. Youngren, "AVL," <http://web.mit.edu/drela/Public/web/avl/>.
- [27] O. Gur, W. H. Mason, and J. A. Schetz, "Full-configuration drag estimation," *Journal of Aircraft*, vol. 47, no. 4, pp. 919–939, 2010.

- [28] J. Kurzke and I. Halliwell, "Propulsion and Power: An Exploration of Gas Turbine Performance Modeling," *Springer International Publishing*, 2018.
- [29] J. R. Martins, J. J. Alonso, and J. J. Reuther, "A Coupled-Adjoint Sensitivity Analysis Method for High-Fidelity Aero-Structural Design," *Optimization and Engineering*, vol. 6, no. 4, pp. 33–62, 2005.