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Parametric Analysis for Structural Design and Weight Estimation of Cantilever and Strut-Braced Wing-Boxes

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Computationally cheap and accurate enough weight estimation tools are needed for the multidisciplinary design optimization and the design exploration studies of novel aircraft at the conceptual design stage. In this study, a new wing-box structural design and weight estimation method for conceptual or early preliminary design of novel aircraft configurations is introduced. The wing-box weight estimation is achieved through structural sizing using standard structural theoretical procedures. To achieve this, a new wing geometric description with a new wing-box idealization model is introduced. Realistic symmetric maneuver, rolling, and combined loading cases are generated following CS.25 requirements. The structure is sized considering bending, shear, and buckling constraints, and the total weight is estimated from the sized components. The tool is validated against data from nine cantilever and one strut-braced aircraft with aluminum and composite wing- boxes, and a standard error of 1.7% and an average error of -0.2% are achieved. The effect of the strut addition on the total wing-box weight of high aspect-ratio wings is studied. It was shown that the strut helped reduce the wing-box weight of aluminum and composite wing-boxes by 11.9% and 16.2%, respectively. The capabilities and sensitivity of the new wing-box weight estimation method are also successfully presented through an in-depth parametric study. The effects of fourteen aircraft design parameters on the total wing-box weight of moderate and high aspect-ratio cantilever and strut-braced wings are investigated. It was shown that some design parameters have a significant effect on the wing-box weight of cantilever and SBW aircraft, and any wing-box weight estimation model not covering these effects is likely to have limited accuracy or sensitivity.

I. Nomenclature

Ψ_{edge}	= Non-dimensional idealized wing-box edge thickness as a fraction of local wing section thickness.
Ψ_u	= Non-dimensional idealized wing-box center thickness as a fraction of local wing section thickness.
t_{wb}	= Wing-box local section thickness different than t_{wing} for wing-box idealization purposes.
t_{wing}	= Local section wing thickness
w_{wb}	= Local section wing-box width
$M_{WBW,Calc}$	= Wing-box calculated mass

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$M_{WBW,Actual}$ = Wing-box actual mass

II. Introduction

For decades, cantilever wing transport aircraft have had similar wing designs and planforms. Hence, empirical methods derived from statistical aircraft data have been sufficient in the conceptual design of this type of aircraft; however, these methods are usually not sensitive enough or accurate when a new configuration with no historical data is designed, such as distributed propulsion, a high aspect ratio wing (HARW), or a strut-braced wing (SBW) [1–3]. From a structural design and weight estimation (WE) perspective, there are two solutions to overcome this problem. The first is low-order, physics-based weight estimation approaches, and the second is high-order, finite element analysis (FEA)-based approaches [4–6]. The former requires less computational power and can provide instinct about the design, whereas the latter usually requires more computational power and labor work [7].

Computers enable the use of more complex methods than empirical approaches for conceptual design. However, there is also a tendency to test high number of aircraft candidates in a short time for design exploration studies in the conceptual design stage. In addition to that, if the multi-disciplinary design optimization (MDO) works are carried out, the total computational time can increase tremendously. Considering this requirement, a WE methodology should be both capable of evaluating new ideas accurately and have a feasible computational time. Physics-based approaches meet these requirements when carefully modelled, taking into account the needs of novel aircraft design [3,4,8].

In this paper, we will first introduce a new physics-based wing-box structural design and weight estimation method with validation studies for the conceptual design of traditional and novel aircraft, and later, the capabilities of the tool will be tested with a parametric study. The parametric study is also aimed at providing an instinct for the designers about the effect of the aircraft design parameters on the wing-box weight of cantilever and strut-braced aircraft.

Some parametric studies previously presented by [9–11] for cantilever and SBWs. The objectives were mainly to test the capabilities and accuracy of the mass estimation tools developed by the researchers. In this study, we extended the scope of the parametric work by investigating the effect of fourteen different aircraft design parameters on the WB mass of four different aircraft configurations, including high aspect ratio (HAR) SBW, HAR cantilever wings, and moderate aspect ratio (MAR) conventional aircraft. The sensitivity of the WB mass to the design parameters is compared using an importance factor. Detailed results of the parametric studies are also presented. The effect of different parameters is discussed considering the effect of four different aircraft configurations.

In Chapter-III. , the new wing-box weight estimation approach and its validation study are briefly presented. In Chapter-IV. , a comparative study of the wing-box weight of cantilever and strut-braced wings is conducted. The effects of aircraft design parameters on cantilevers and SBWs with moderate and high aspect ratios are investigated. Different effects of aircraft design parameters on different configurations are highlighted, and their possible reasons are discussed. Finally, in Chapter-V. a brief conclusion is presented, highlighting the noteworthy observations from the research.

III. Methodology

The parametric study is performed with the new structural design and weight estimation tool developed for novel wing configurations. In this section, the methodology used in the development of the new WE tool will be explained.

A. A New Wing-box Structural Design and Weight Estimation Method

The development process of the wing structural design and weight estimation tool is illustrated in Fig. 1. The details of each step are explained briefly in the following sections.

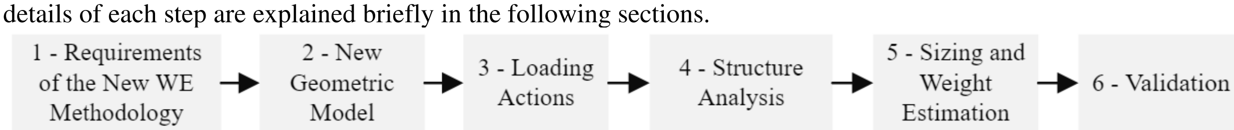


Fig. 1 The development process of a physics-based weight estimation method

1.Tool Requirements and Features

The tool requirements are defined by reviewing previous works in the literature [12–16] and experience gained during the aircraft design projects at Cranfield University. The requirements of a new wing-box weight estimation method for conceptual or early preliminary design of novel aircraft configurations are listed below.

- The new method should accurately estimate the wing-box weight of cantilever wings, HARWs, SBW, wings with distributed propulsion, wings of hydrogen powered aircraft.
- The computational time should be preferably shorter than FE-based WE approach.
- It should be sensitive to the aircraft design parameters and be suitable to be combined with MDO environments.

- The new geometric model should be able to generate any type of wing planform.
- It should be possible to vary wing and wing-box design parameters at each section, and the generation of any number of wing-sections should be possible.
- In 3-D coordinate axes, an infinite number of concentrated loads, such as engines, landing gear, and others, with their inertia, drag, or thrust, should be able to be defined and positioned.
- All geometric models should be coded in a spreadsheet for automation. The physical meaning of the model should be instantly verifiable by the new 2-D front and top aircraft visualisations as shown in Fig. 2.
- Wing-box weight should be calculated automatically using the new WE methodology.

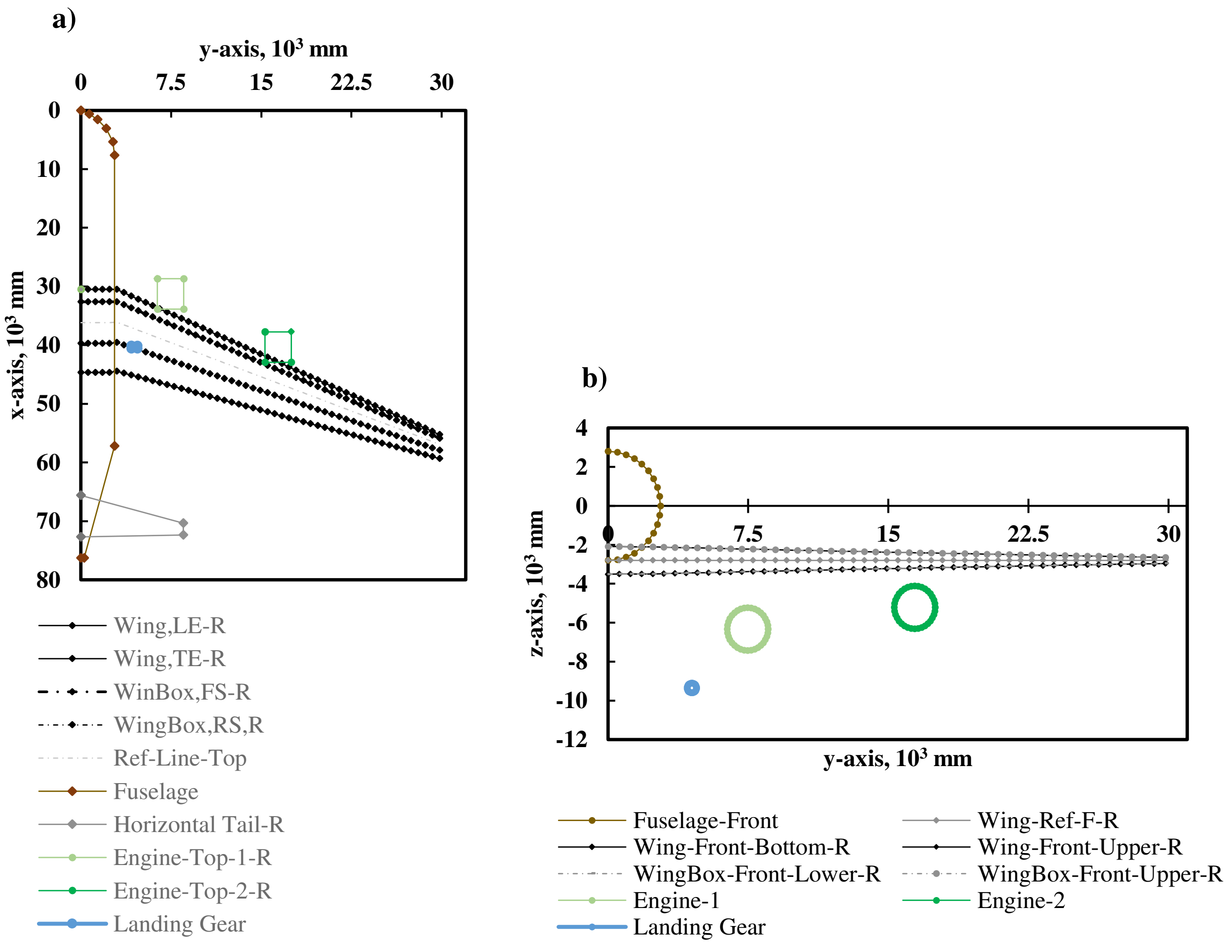


Fig. 2 a) Top-view of the right side of the Boeing 747 aircraft, b) the front view of the same side.

2.New Geometric Model

For the conceptual design of novel aircraft configurations, a new detailed, multi-fidelity 3-D aircraft geometric model is created. The geometric model covers strut, strut-offset, wing-box, wing, tail, fin, canard, and fuselage geometries. Due to the scope of the project, a higher fidelity level is used for the geometric model of the lifting surfaces compared to the fuselage. A sample view of a Boeing 747 aircraft, shown in Fig. 2, is generated in the visualization tool, which is developed using the new geometric model.

Following the findings of previous studies in the field [1,2,14–21] a new, symmetric around two-axes wing-box model is generated for this study. With the change of Ψ_{edge}, the wing-box shape can be transformed from a diamond to a hexagonal and a rectangular shape, as shown in Fig. 3.

Any number of stringer counts can be assigned as an input on the upper and lower surfaces. Due to the symmetric wing-box assumption, stringer counts are equal on the upper and lower surfaces. Stringers are distributed equally, crossing their reference line with the middle surface of the wing skin panel. Spar caps can have a different cross-section than stringers, as illustrated in Fig. 3.

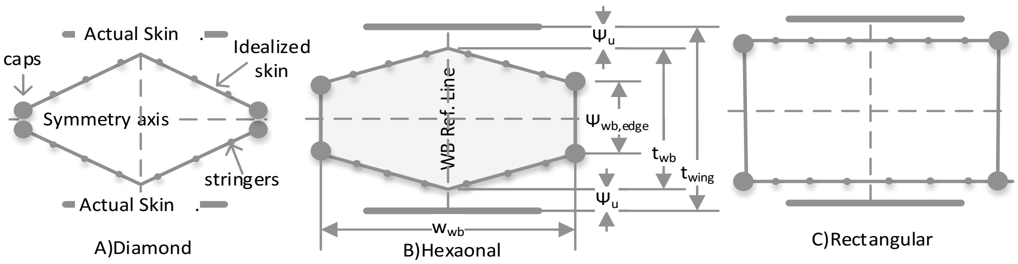


Fig. 3 The geometric model representation of the idealized wing-box.

3.Loading Actions

Aircraft are classified according to their missions and top-level aircraft requirements (TLAR). When the class of the aircraft is defined, for example, as a transport aircraft, airworthiness requirements outline the load analysis requirements. Although novel configurations might require additional caution, airworthiness requirements can still provide an essential guideline to be followed. In this study, the airworthiness requirement of CS.25[25] is followed for the structural design of the turbine powered large airplanes.

CS.25 requires airplanes to be designed under various loading scenarios generated by a combination of altitudes, fuel capacities, payload capacities, speeds, and loading directions. In this study, a total of 195 symmetric loading cases are generated as a default by the tool. A sub-module is coded to create loading cases automatically. The sub-module calculates design speeds, loading factors, and flight envelopes.

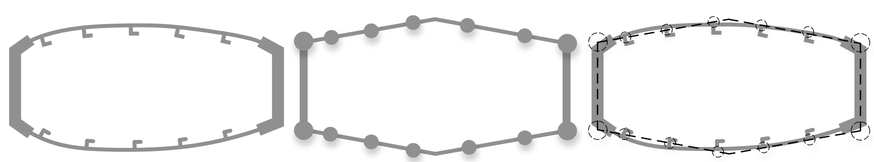
In addition to the 195 symmetric loading cases, more cases arise from rolling conditions and combinations of rolling and symmetric maneuvering. Hence, a total of 483 cases are generated, including gust, maneuver, rolling, and combined cases by default. Rolling cases cover arrest, aerodynamic damping, and steady cases in addition to different speeds, altitudes, fuel loads, and payloads.

After finding all the loads and loading factors of each loading case, shear, bending, and torsion variation along the wing around three axes are calculated to be used in the stress analysis, as explained in the next section.

4.Structure Analysis

Wing-box Stress Analysis

Aircraft components are sized to resist the loads emerging during the different flight cases. Using the load analysis method explained in Section 3 (Loading Actions) together with the geometric model presented in Section 2 (New Geometric Model), stresses on each structural element of any structural component of an aircraft can be automatically calculated. In this study, we size the components of transport aircraft wing-boxes using standard structural design procedures.



A) Actual B) Idealized C) Comparison

Fig. 4 Representation of the wing-box idealization steps.

As shown in Fig. 4., the load-carrying wing structure is assumed to be a single-cell wing-box. Single-cell wing-boxes are commonly used in subsonic or transonic aircraft with wing aspect ratios of moderate to high. Hence, the single-cell wing-box approach provides accurate wing-box WE results, as will be presented in the validation study.

Structural analysis of aircraft components is complicated and requires high computational power and long computation times, neither of which are desirable at the conceptual or preliminary design stage. Hence, a structural idealization approach is used to simplify the geometry of aircraft components to provide a sufficient accuracy level and short computational time in stress analysis, as illustrated in Fig. 4.

Strut Reaction Force

The SBW configuration has a structurally indeterminate problem, and previously simplified solutions are presented to this problem by References.[1,26]. The SBW wing, in this study, is simplified as presented in Fig. 5. The model assumes that the load-carrying structure between the wing-fuselage and the strut-wing attachments is a uniform wing-box. The wing has a fixed end attachment to the fuselage and is simply supported by the strut. If the deflection at the strut joint is assumed to be zero, a solution to the strut reaction force can be derived using Castigliano's theorem as given in Eq.(1). The minor effect of the zero deflection assumption at the strut joint on the calculation of the strut reaction force was previously presented by Ref. [1,26]. When the reaction force (R_{Strut}) is calculated, it can then be added to the load analysis as a concentrated load in 3-D axes.

$$(\Delta_{Strut}) = \int_0^L M\left(\frac{\partial M}{\partial R_{Strut}}\right)\frac{\mathrm{d}x}{EI}$$
$$(\Delta_{Strut}) = \int_0^{l_1} M_1\,(0)\frac{\mathrm{d}x_1}{EI} + \int_0^{l_2} M_2\left(\frac{\partial M_2}{\partial R_{Strut}}\right)\frac{\mathrm{d}x_2}{EI} + \int_0^{l_3} M_3\left(\frac{\partial M_3}{\partial R_{Strut}}\right)\frac{\mathrm{d}x_3}{EI} \qquad (1)$$

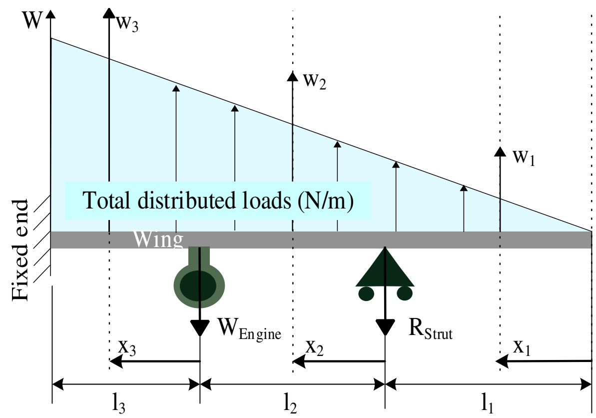


Fig. 5 Simplified SBW problem.

5.Structural Sizing and Weight Estimation

This study presents a physics-based wing-box weight estimation method for novel wing configurations. The wing-box carries the main shear and bending loads, and the shear and bending resisting materials of the wing-box are calculated considering the strength and elastic buckling criteria.

The wing panel thicknesses at each wing section between the mass booms are sized to withstand the worst loading scenarios. The thicknesses of the skin panels of the lower or upper surfaces of the same wing-box section are assumed to be the same. The skin thickness of the wing-box section is equal to the thickest skin panel calculated in this wing-box section.

The mass booms are assumed to have the same cross-section in a wing-section, and their size is equal to the thickest mass boom calculated to resist bending loads in the wing-box section.

In addition to the mass caused by the load-carrying structure as explained above, the rest of the mass sources can be calculated by empirical methods to achieve a total wing-box mass. The mass caused by the non-optimal wing-box mass, wing ribs, and aeroelastic effects can be calculated using empirical equations. In this study, the methods presented in Ref. [4] are utilized.

The total weight of the wing is the sum of the wing-box masses and the secondary structural components, which are the wing leading edge (LE) and trailing edge (TE) devices. The weight of the secondary components can be accurately estimated using existing computationally cheap empirical methods in the literature, and they are not covered in this work.

B. Validation

The developed wing-box mass estimation tools are validated with publicly available actual aircraft data from Refs. [1,27,28]. This section shows the validation results. The computational time of the new tool is recorded less than 10^2 ms for one loading case with an Intel i7-11800H CPU, an octa-core 2.3 GHz computer during the validation studies.

1.Cantilever Wing

The developed weight estimation tool is validated against nine cantilever transport aircraft datasets from the literature [1,27,28]. The result of the validation study is presented in Fig. 6. The aircraft take off gross weight (TOGW) ranges from 18.210 kg to 322.000 kg. Aluminum alloy wing-boxes are used on aircraft C-9A, C-140A, DC-8, 720, 727, 737, 747, and G-159.The aircraft AE-16 is the design of Cranfield University and benefits from the low density of composite materials. A very close estimation of composite wing-box weight is also achieved, as can be seen in Fig. 5.

As a result of the validation study, the accuracy of the new method is measured with a standard error of 1.7% and an average error of -0.2%. The differences, which are indicated in Fig. 5, between the actual wing-box masses and the wing-box mass estimation of the tool might be caused by the limited publicly available aircraft design data and the sensitivity of the new tool to those parameters. The possible source of these differences will be explained with the parametric study in the following sections.

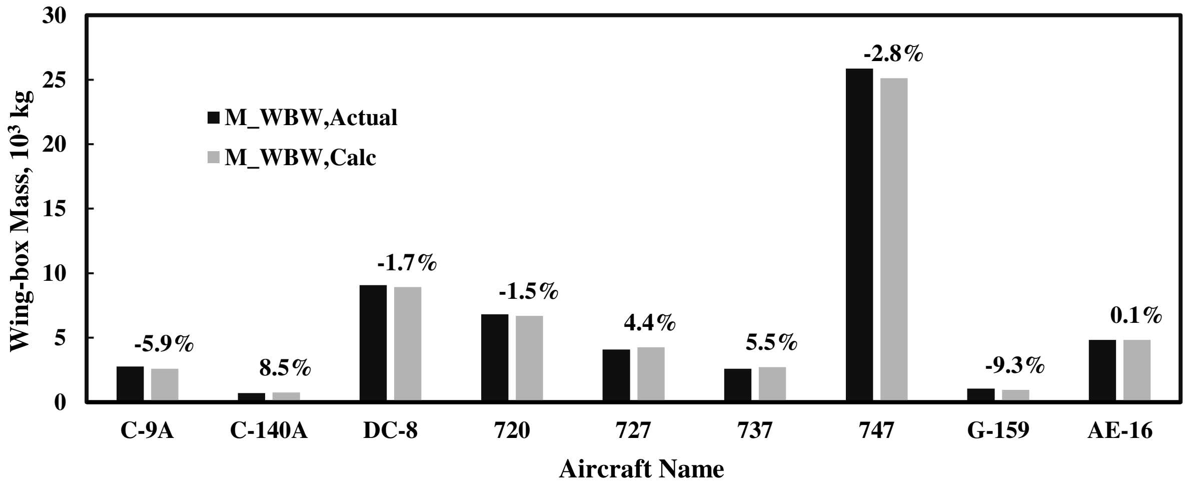


Fig. 6 Validation of wing-box weight estimation tool using actual data from nine aircraft.

2.Strut-Braced Wing

Table 1 Comparison of the SBW wing-box mass estimation of the WE method to data from Ref. [29].

	Shear Resistant Material	Bending Resistant Material	Rib	Aeroelasticity		Total Structural WB Mass, kg
Calculated SBW WB Masses	1124.65	1960.57	125.02	456.69		3666.94
	Skins	**Spars**	**Ribs**	**Spar Caps**	**Rib Caps**	
Actual SBW WB Masses	2735.61	369.22	328.40	104.33	77.11	3614.67
Difference %						**1.4%**

In the SUGAR project [29], higher fidelity level methods compared to the new method are used, including detailed FE analysis, computational fluid dynamics (CFD), and non-linear aeroelastic analysis. Therefore, SBW aircraft data[4] from the Sugar project is chosen to compare with the new physics-based weight estimation method. Quasi-isotropic material from the SUGAR project [29] is chosen to be used in the new method. The wing-box mass estimation from the new method and the SUGAR project are compared in Table 1. The difference between the total wing-box structural mass estimations of the two methods is 1.4%, and it can be considered acceptable for conceptual design level studies of SBW aircraft. Due to the limited publicly available SBW data from detailed design studies, the WE of the new

[4] The wing-box component mass data in Table 1, are taken from Column F of Table 2.26 in Ref. [29]. The data in column F take into account the flutter constraint of 1.15 V_D.

method is only compared with the weight data of one aircraft; however, for a better understanding of the accuracy of the new method, comparison to more aircraft is required.

IV. Results and Discussion

In this section, the results of parametric and comparative studies will be presented and discussed. The total wing-box structural mass variance will be investigated as aircraft design parameters are changed, and the effect of the design parameters will be measured and compared using an importance factor. The study focuses solely on the structural mass of the wing-box (WB); thus, the strut mass is not added to the WB mass of the SUGAR-SBW in the parametric studies, except in Section-B allow for a more accurate comparison of WB mass variations between different configurations.

A. Baseline Aircraft

For the comparative and parametric studies, three aircraft are chosen as baselines: the Boeing 737, the Boeing 747 [1,27,28] and NASA's SUGAR-SBW aircraft [29]. In addition to the three configurations, a high aspect ratio (HAR) cantilever configuration was also created from NASA's SUGAR SBW aircraft, and this configuration is named SUGAR-CANT. SUGAR-CANT is the cantilever version of SUGAR-SBW without a strut, apart from that, the rest of the configurations are the same. Hence, in total, four configurations will be used in the parametric studies, and they are named SUGAR-SBW, SUGAR-CANT, Boeing-737, and Boeing-747. The design parameters of three different baseline models are given in Table 6.

SUGAR-SBW and SUGAR-CANT are chosen to investigate the behavior of HAR cantilever and SBW aircraft and compare them with the moderate aspect ratio (MAR) aircraft of the Boeing 747 and Boeing 737. The main difference between the Boeing 747 and Boeing 737 is their size, and relatedly, their TOGW and OEW. The Boeing 747 is the only configuration to possess four wing-mounted engines, and the rest of the configurations have two wing-mounted engines.

B. Comparison of SBW and Cantilever Wing

A comparative study is conducted to investigate the effect of sturt on wing-box weight reduction. SUGAR-SBW and SUGAR-CANT aircraft are chosen for this study. Aluminum 7075-T6 and quasi-isotropic composite material from Ref.[29] are used to compare the effect of baseline aircraft wing-box material. Aside from the strut addition and wing-box material, all of the baseline design parameters are kept the same as shown in Table 6.

The strut addition provided a 11.9% wing-box weight reduction for aluminium 7075 T6 wing-box aircraft compared to the aluminium cantilever wing-box model. A weight reduction of 16.2% is achieved with the composite SBW wing-box design compared to the composite cantilever wing-box aircraft. The detailed weight breakdown of the wing-box components is given inTable 2.

Table 2 The effect of struts on the weight reduction of composite and aluminum wing boxes.

Aircraft	Shear Resistant Material, kg	Bending Resistant Material, kg	Rib, kg	Aeroelasticity, kg	Strut, kg	Total Structural WB Mass, kg	Mass Reduction, %
Cantilever-Aluminium	1,879.2	2,693.6	221.9	456.7	0.0	5,251.4	
SBW-Aluminium	1,850.8	1,741.7	221.9	456.7	357.0	4,628.0	**-11.9%**
Cantilever-Composite	1,189.5	3,032.1	125.0	456.7	0.0	4,803.3	
SBW-Composite	1,124.6	1,960.6	125.0	456.7	357.0	4,024.0	**-16.2%**

C. Parametric Study

The parametric study is performed to investigate the sensitivity of the total wing-box structural mass to the aircraft design parameters. The effects of fourteen different aircraft design parameters are tested. Another aim is to compare the results of the parametric study generated by the new wing-box WE method to the results of previous studies for a better understanding of the limits and capabilities of the new WE method. The effect of aircraft design parameters on the wing-box weight of moderate and high aspect ratio wings is investigated by comparing SUGAR-SBW and SUGAR-CANT aircraft to Boeing 747 and Boeing 737. The effect of the presence of struts on the sensitivity of the design parameters is also investigated by comparing SUGAR-CANT and SUGAR-SBW aircraft.

The one-factor-at-a-time (OAT) method is used for the parametric study. While one input parameter is changing, the other input parameters are kept at their baseline values. This approach is repeated for each input parameter tested. Using the OAT approach, the effects of the parameters can be compared, and their importance can be evaluated. The OAT approach also makes it possible to observe any probable model failure while testing the parameters, and if there is a failure, the new method can be corrected by focusing on the input parameter causing the failure.

Although the advantages of the OAT approach are presented above, this approach cannot explore the full input space, as it does not cover the simultaneous change of the input parameters. Hence, in this study, to be able to compare the simultaneous change of input parameters, four different aircraft with different TOGW, aspect ratio, and configuration are tested and presented.

In the following sub-section, the studied design parameters are first compared all together using an importance factor. The effect of the strut position on the wing-box mass of SBW configurations is also studied. The design parameters are then grouped into three sub-titles, such as wing-box design parameters, parameters related to inertia, and wing planform design parameters.

1. Comparison of All Input Parameters

To compare the effects of all the input parameters and observe their behaviour on different configurations, an importance factor is employed from Reference[10] to measure the sensitivity of wing-box weight to each input parameter. The formulation of the importance factor is given in Eq.(2) In the calculation of the importance factor of each input parameter, the recorded maximum and minimum WB masses with the change of an individual parameter are used in Eq.(2). The change in the parameters and their upper and lower bound ranges can be found in the graphs in the following sections. The importance of each parameter is calculated for all configurations, and they are presented in Table 1.

$$\%Importance = \frac{Maximum\ WB\ Mass - Minimum\ WB\ Mass}{Average\ of\ WB\ Masses} x100 \tag{2}$$

It can be seen from Table 3 that the wing-box masses of all configurations are sensitive to the aspect ratio the most among the fourteen parameters presented, and the sensitivities of WB masses of different configurations to the same input parameter are not the same. In the following sections, a deeper discussion on the effect of the design parameters will be provided, interpreting Table 3 together with more detailed graphs.

Table 3 The importance of aircraft design parameters or the sensitivity of the wing-box mass to those parameters.

Studied Design Parameter	SUGAR-SBW, %	SUGAR-CANT, %	Boeing-737, %	Boeing-747, %
Stringer Count	21.6	19.2	30.9	27.6
WB Shape Change	41.3	90.2	30.5	43.5
ND Distance Between the Spars	124.3	38.0	90.0	87.8
Centre Wing-box Length	39.9	0.7	20.2	3.8
TOGW	59.5	80.1	39.5	45.8
OEW	28.2	39.7	39.0	21.7
Fuel Stored in the Wing	18.1	28.9	7.8	12.8
Wing Group Mass	22.7	31.0	5.0	5.5
ND spanwise engine position	18.0	37.9	9.1	5.7
Root Thickness to Chord Ratio	38.0	107.1	44.8	242.4
Tip Thickness to Chord Ratio	60.3	64.7	38.5	38.8
Aspect Ratio	348.8	325.3	392.6	274.5
ND Spanwise position of the Sturt	34.2			
ND Chordwise Position of the Strut	3.2			

2.Strut Attachment Position

The position of the strut attachment is an important design parameter for SBW aircraft, and it has been studied previously in Refs. [1,30]. The sensitivity of the new wing-box WE method to the strut attachment point is presented in Fig. 7-b. For the SUGAR-SBW baseline, the minimum WB mass is observed at an ND spanwise position of 0.65. The optimum position of the strut is located marginally outboard compared to previous studies, as the current work only presents the structural mass of WB. When the strut mass is added to the WB mass, the optimum point is likely to move slightly inboard. It can also be observed that WB mass is less sensitive to the ND chordwise position of the strut compared to the ND spanwise position. The optimum attachment point for the minimum WB mass tends to be towards the wing leading edge.

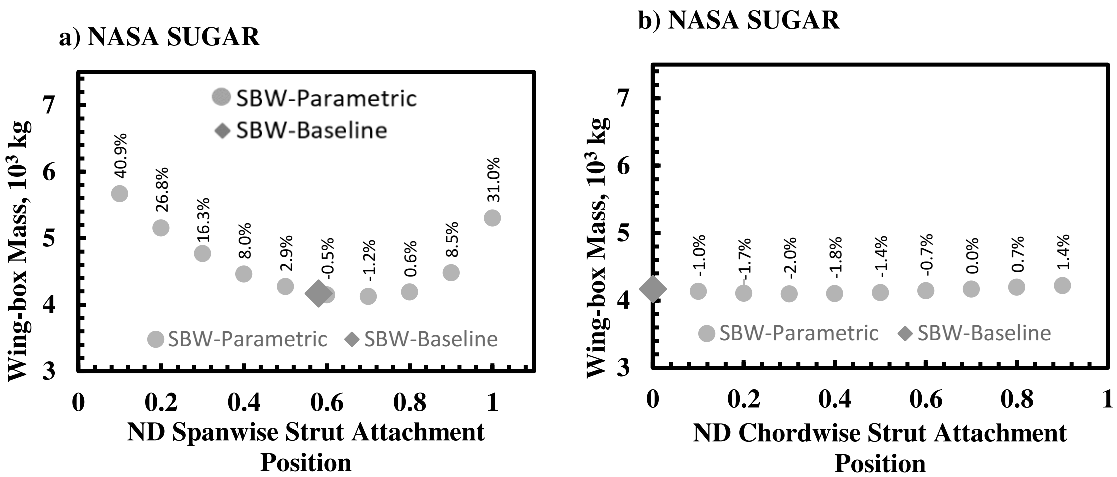


Fig. 7 NASA SUGAR baseline aircraft wing-box mass variation with a) spanwise ND strut attachment point change as a fraction of wing half span and b) chordwise ND strut attachment point change as a fraction of wing section chord.

3.Wing-Box Parameters

Stringer Counts

The stringer count in Fig. 8 shows half of the total stringer counts in a wing-box section. The importance of the stringer count is almost equal for all configurations, as shown in Table 3, but its trend is different for moderate and high aspect ratio wings, as illustrated in Fig. 8. This can be explained by the effect of the different dominant loads for different configurations. With increasing aspect ratio, the bending loads are becoming more dominant in structural sizing, and the major portion of the wing-box mass is caused by the bending-resistant materials, as can also be seen from the example in Table 1.

In moderate aspect ratio wings, however, the effect of shear loads is more dominant, and shear resisting materials account for a significant portion of the WB mass. Hence, if the number of stringer counts are increased in a moderate aspect ratio wing, the distance between the stringers is reduced, which prevents the occurrence of plate buckling and reduces the amount of shear resistant material used.

Apart from that, in high aspect ratio wings, the bending loads are more dominant, and increasing the number of stringers does not provide the same benefit for weight reduction. Due to the assumption of the same mass boom cross-section in a wing-box section in the new model, increasing the number of stringers increases the total bending material mass, as all the mass booms are sized with the same cross-sectional area as the thickest mass boom cross-section calculated in that section. This causes oversized mass-boom components in the model. In summary, it can be said that a higher number of stringers provides more benefits for wings with a moderate aspect ratio.

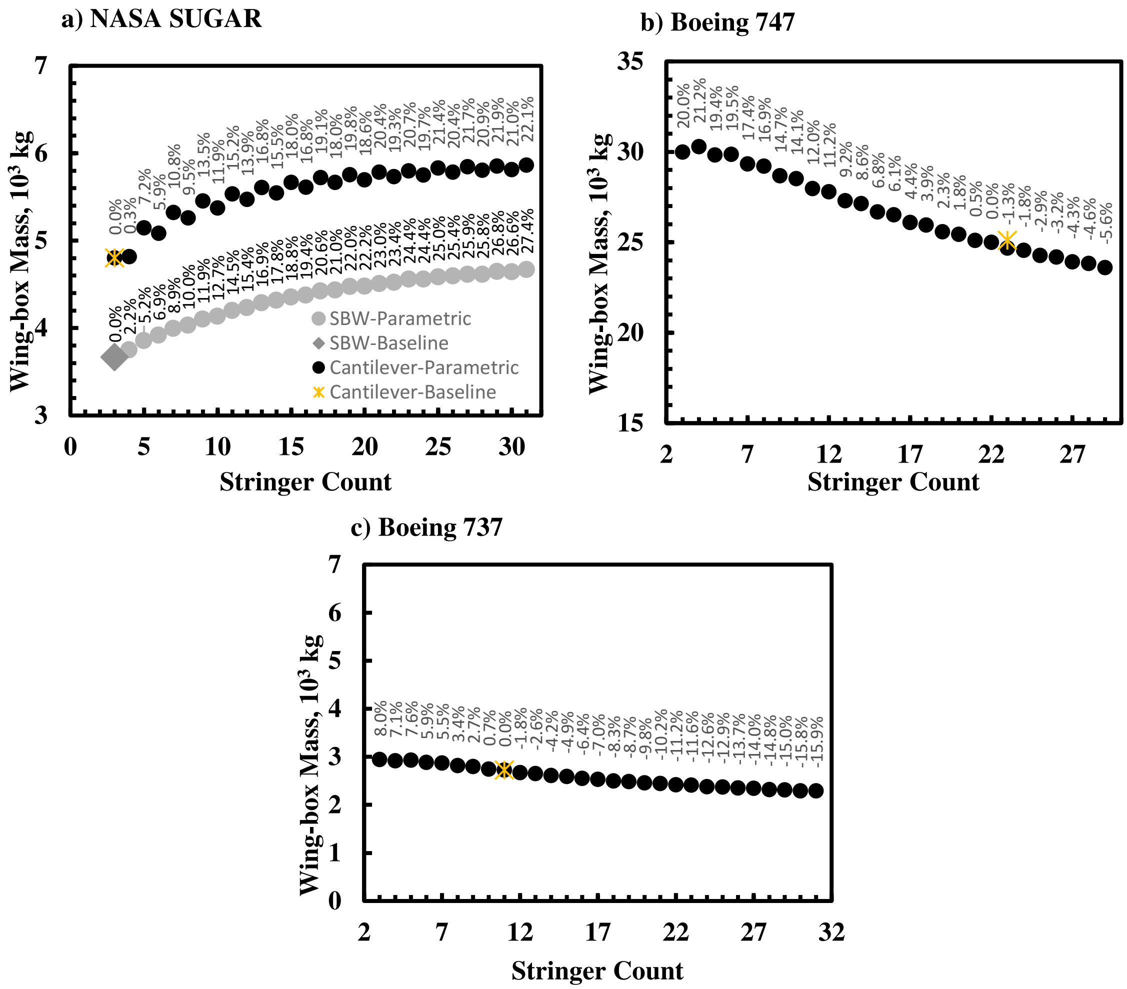


Fig. 8 a) a) NASA SUGAR-SBW, SUGAR-CANT; b) Boeing 747; c) Boeing 737: baseline aircraft wing-box mass variation with total stringer counts.

Idealized Wing-Box Shape

The idealized wing-box shape variation is previously illustrated in Fig. 3. All configurations are very sensitive to the shape of the wing-box model as presented in Table 3. With a rate of importance of 90%, the SUGAR-CANT aircraft wing is the most sensitive configuration to this parameter. When the non-dimensional wing-box edge thickness parameter is changed, the wing-box weight of all configurations changes step by step from a diamond to a hexagonal, and finally to a rectangular shape.

A rectangular wing-box shape is not feasible for most design cases due to the airfoil shape. As a result, a hexagonal model, as shown in Fig. 4. is more representative of the actual wing-box cross section. Apart from that, the WB shape can approach a rectangular or square shape when the distance between the spars is reduced. The combined effect of the reduced distance between the spars and the rectangular WB shape can provide further WB mass reduction; this will be studied in more detail in future studies. This design approach may be promising for future hydrogen-powered aircraft wings because fuel will probably not be stored in the wing-box and the distance between the spars can be adjusted without the need for fuel tanks.

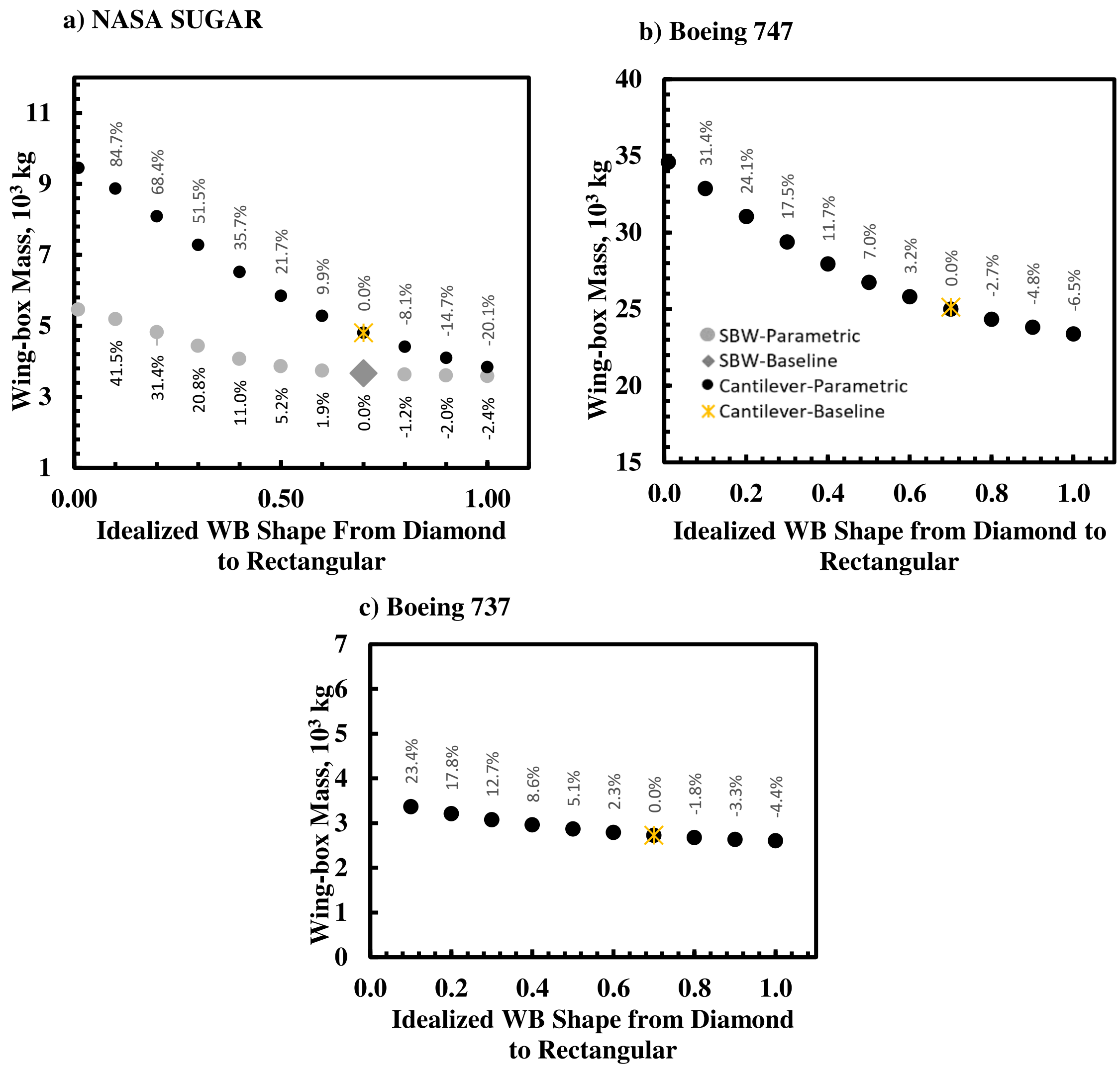


Fig. 9 a) NASA SUGAR-SBW, SUGAR-CANT, b) Boeing 747, c) Boeing 737: the baseline aircraft wing-box mass varies as the ND wing-box edge thickness value (Ψ_{edge}) changes.

ND Distance Between the Spars

The ND distance between the spars is a fraction wing section chord. The WB masses of the SUGAR-CANT, Boeing 737, and Boeing 747 increase with increasing values of the ND distance between the spars, as shown in Fig. 10. However, the SUGAR-SBW had an optimum value around the ND value of 0.4. The increase in WB mass as the distance between the spars increases can be explained by the buckling constraint. When the ND value reaches one, the distance between the spars increases with the fixed stringer count, which causes wider skin panels and requires thicker skins to resist the buckling.

The trend of the reactions of all configurations to ND spar distances is similar; however, their sensitivity levels are different, as can be observed from Table 3. With an importance factor of 124.3, SUGAR-SBW has the highest sensitivity to this parameter. Hence, it can be said that for the conceptual design studies of novel configurations, this parameter should be studied as a design variable. Moreover, the optimum point for the spar positions of the SUGAR-SBW aircraft is more distinguishable compared to the other configurations.

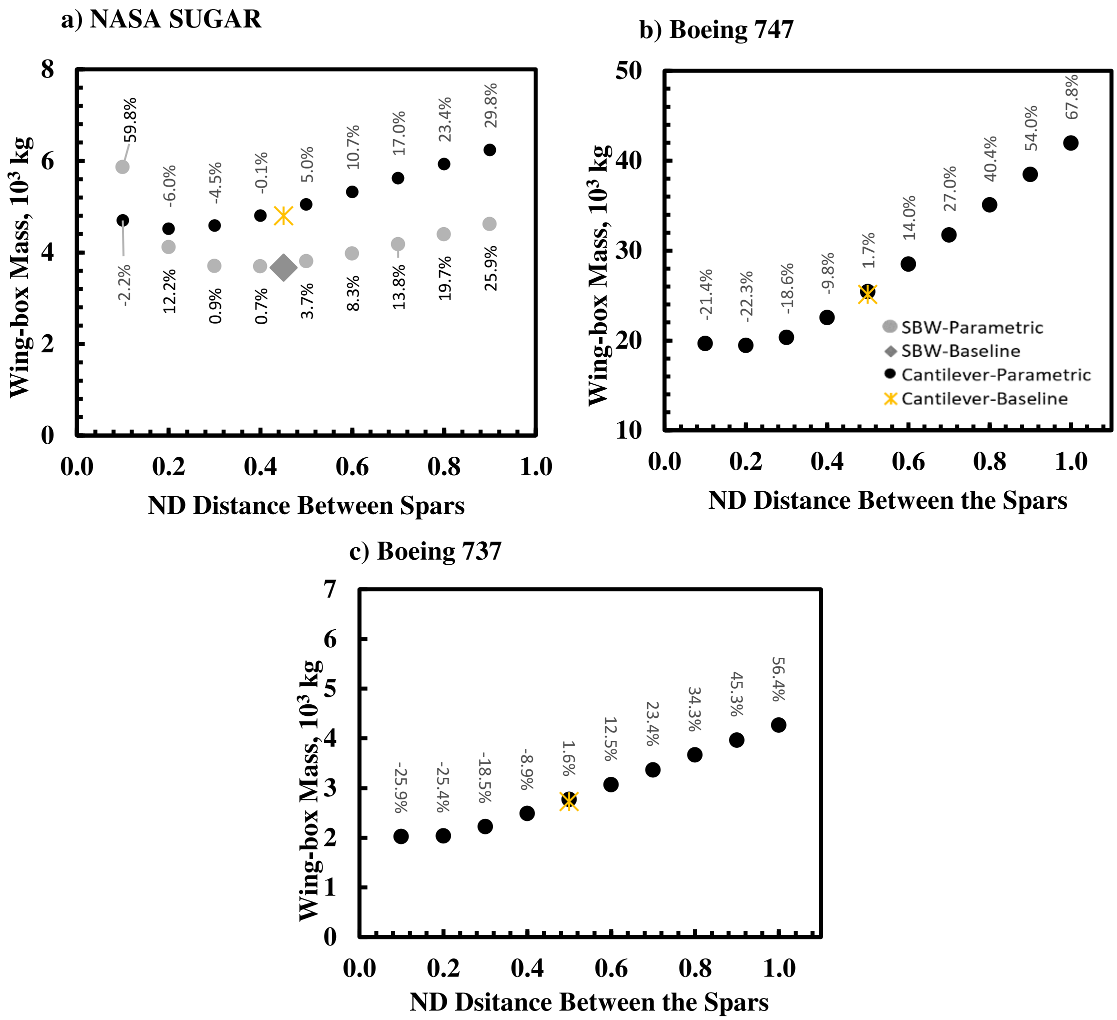


Fig. 10 a) NASA SUGAR-SBW and SUGAR-CANT, b) Boeing 747, c) Boeing 737, baseline aircraft wing-box mass changes as ND distance between forward and rear spars as a fraction of wing section chord changes.

Centre Wing-Box Length

The effect of the length of the center wing-box on the WB is independent of the aspect ratio, as can be seen from Fig. 11 and Table 3. While the SUGAR-SBW aircraft and Boeing 737 are the most sensitive configurations to this parameter, with an importance factor of 39.9% and 20.2%, respectively, the SUGAR-CANT aircraft and Boeing 747 have minimal sensitivity to this parameter.

Although both the SUGAR-SBW and the Boeing 737 are sensitive to the length of the center wing box, they have a different tendency. While the increased length of the center wing-box reduced the WB weight of the Sugar SBW by 9.96%, it increased the WB weight of the Boeing 737 by 17.8% when compared to the baseline values. The weight reduction in SUGAR-SBW is likely to be due to the torsional relief caused by the strut reaction; however, the increase in the WB weight of the Boeing 737 can be due to the increased torsion on the center wing box of this configuration. To better understand the effect of this parameter, further studies are required.

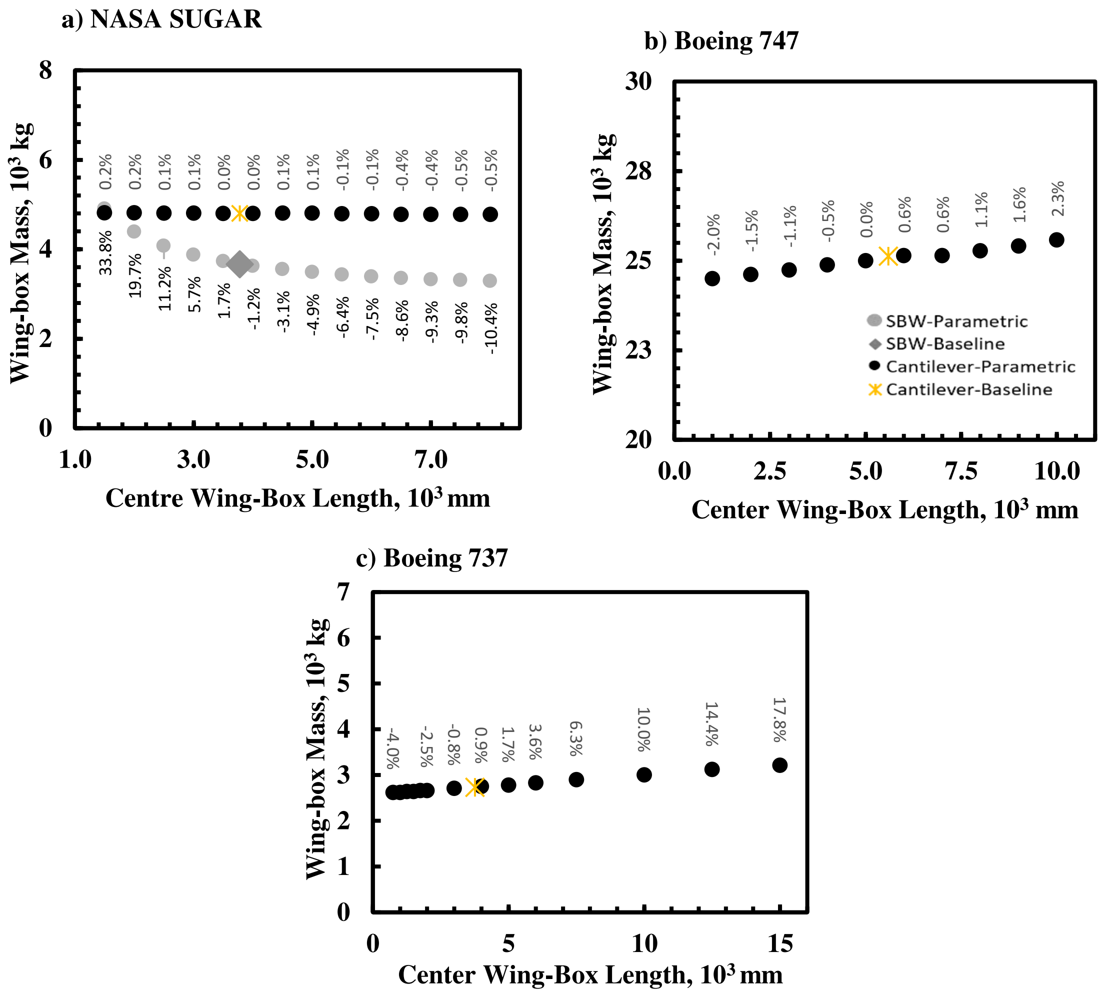


Fig. 11 a) NASA SUGAR-SBW, SUGAR-CANT, b) Boeing 747, c) Boeing 737: baseline aircraft wing-box mass changes with the change of the center wing-box length.

4.Inertia

Take-off Gross Weight and Operating Empty Weight

The TOGW and OEW are important parameters for all configurations, as can be observed from Table 3. The WB masses of all the configurations have more sensitivity to TOGW than OEW. The sensitivity of the WB weight to TOGW and OEW has the same trend for all the configurations. TOGW and OEW have an optimal value for all the configurations to have a minimum WB weight, as can be observed from Fig. 12. The reason behind the increase in WB weight with the increases in TOGW and OEW in Fig. 12. might simply be explained by the increased loads and lift acting on the wing structure. It is also worth noting that the WB masses diverge after reaching the minimum TOGW and OEW values, and this can highlight the significance of these two parameters for an optimum wing-box design.

While the importance values of OEW of all the configurations are closer, the effect of TOGW is considerably higher for high aspect ratio SUGAR-SBW and SUGAR-CANT configurations compared to other configurations with importance factors of 59.5% and 80.1%, respectively.

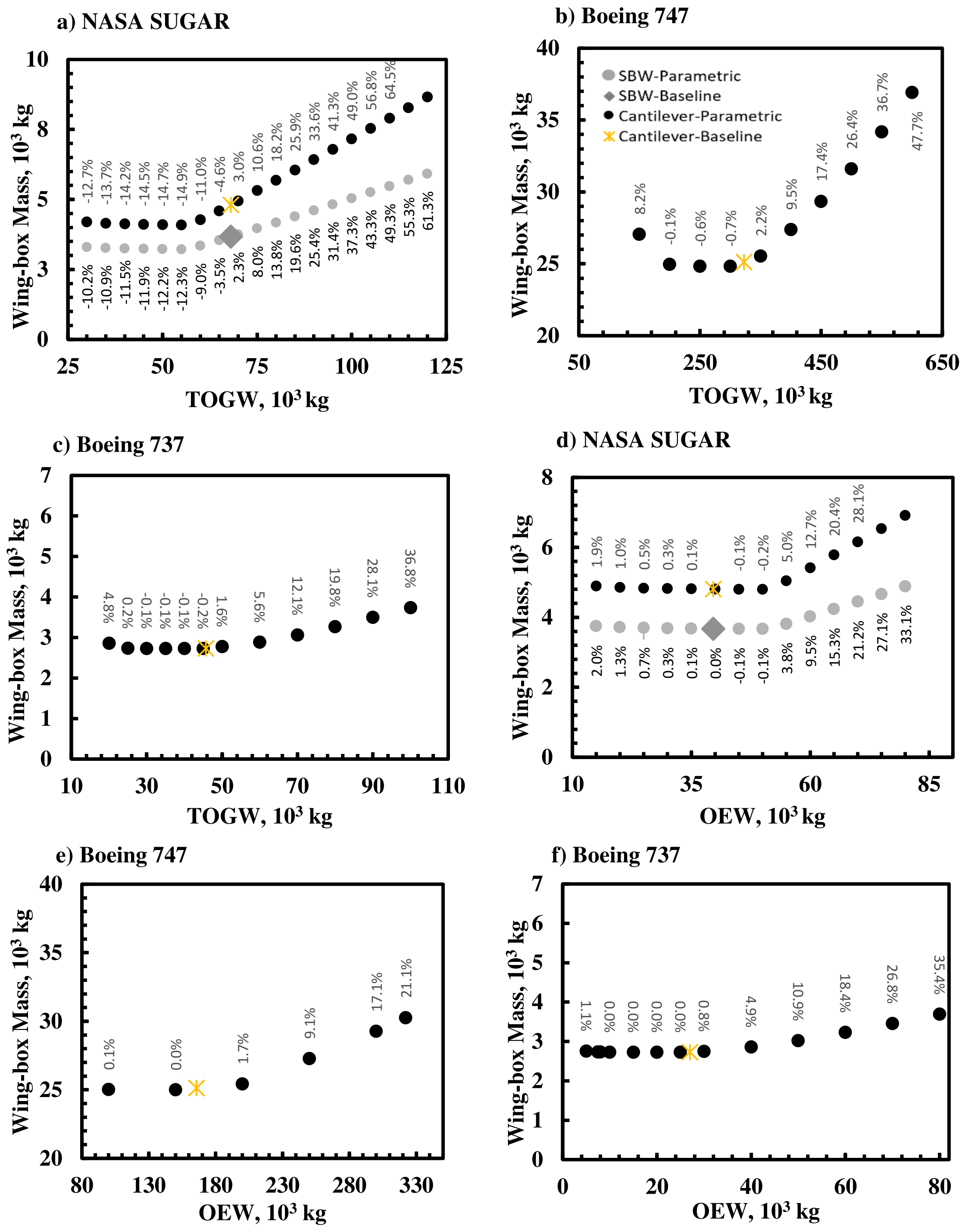


Fig. 12 a) NASA SUGAR-SBW, SUGAR-CANT; b) Boeing 747, c) Boeing 737: baseline aircraft wing-box mass changes with the change in the aircraft take-off gross weight (TOGW). d) NASA SUGAR-SBW, SUGAR-CANT, e) Boeing 747, f) Boeing 737: As the aircraft take-off gross weight (OEW) changes with changes in the baseline aircraft wing-box mass.

Fuel Stored in the Wing

It can be seen from all the graphs in Fig. 13 that the fuel stored in the wing provides inertia relief for the WB and results in a mass reduction of the WB structure. HAR SUGAR-CANT is the most sensitive configuration to the fuel stored in the wing, with an importance factor of 28.9%, and the second most sensitive configuration is also HAR SUGAR-SBW, with an importance factor of 18.1%. This can clarify the importance of this parameter for the WB mass of HAR wings.

This study on the fuel mass stored in the wing might also provide an instinct for future hydrogen powered aircraft configurations that either store the fuel in the wing-mounted drop tanks or fuselage and are likely not to have distributed fuel mass stored in the WB. This disadvantage may be offset by the shorter distance between wing spars, as demonstrated by the results in Fig. 10. The trade-off between the distributed fuel stored in the wing, the distance between the spars, and the positions of the concentrated loads caused by the drop tanks is likely to raise a new design question and should be explored in future studies.

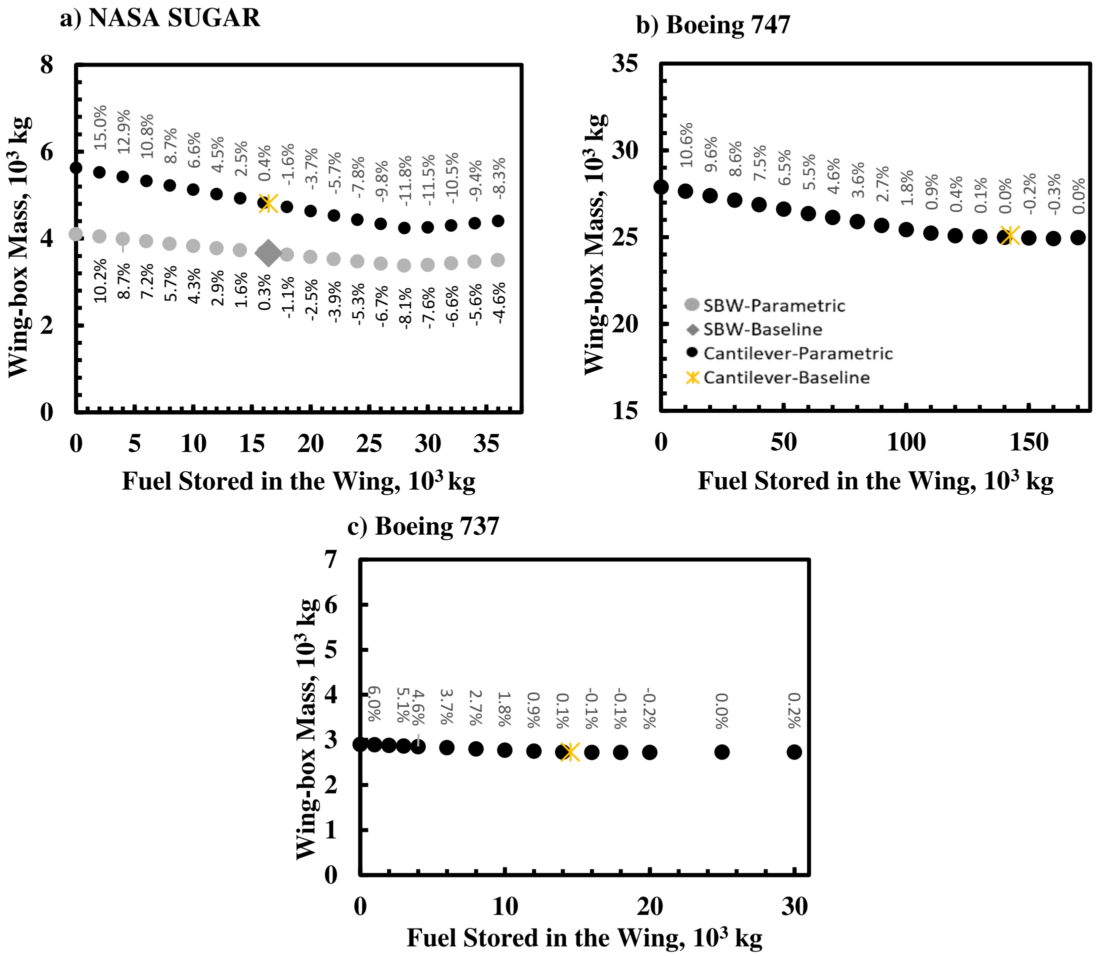


Fig. 13 a) NASA SUGAR-SBW, SUGAR-CANT, b) Boeing 747, c) Boeing 737: baseline aircraft wing-box mass change with the change of the fuel mass stored in the wing.

Wing Group Mass

The wing group mass is the total wing mass of an aircraft. As discussed in the previous sections, short computational times are intended in the conceptual design level studies. Non-iterative direct solutions from the model solvers can reduce the computational time drastically compared to the iterative solutions.

As the wing group mass is a dependent variable on the WB mass, an iterative solution can be required in the WB mass calculations to converge on a final solution. In the physics-based WB mass estimation approach, the inertia load caused by the wing group mass is required in the load analysis. The first estimation of wing group mass can be achieved with the lower-fidelity level empirical WE methods to initialize the higher-fidelity level physics-based WB WE tool. In this parametric study, it was aimed to observe the effect of initial wing group weight estimation on the accuracy of the new physics-based method when a direct WB mass calculation is chosen. Apart from that, this parametric study also shows the effect of wing-group mass on the wing-box mass.

The WB mass of all the configurations has the same trend against increasing wing group mass, as can be observed from Fig. 14. The higher sensitivity of the WB masses of HAR wings to wing group mass compared to MAR wings can be seen from Table 3 and from Fig. 14. While the importance factors of SUGAR-SBW and SUGAR-CANT are 22.7% and 31%, respectively, Boeing-737 and Boeing-747 have importance factors of 5% and 5.5%, respectively.

Although the effect of wing group weight on MAR Boeing 747 and Boeing 737 is minimal and the direct solver approach of the WB weight estimation tool can be used, it has a significant effect on HAR SUGAR-SBW and SUGAR-CANT configurations, and an iterative solver approach is likely to provide higher accuracy. The outcome of the parametric study of the wing group mass; therefore, outlines the importance of an accurate initial wing group weight estimation method for a direct solution approach and also the sensitivity level of the WB mass to wing group mass.

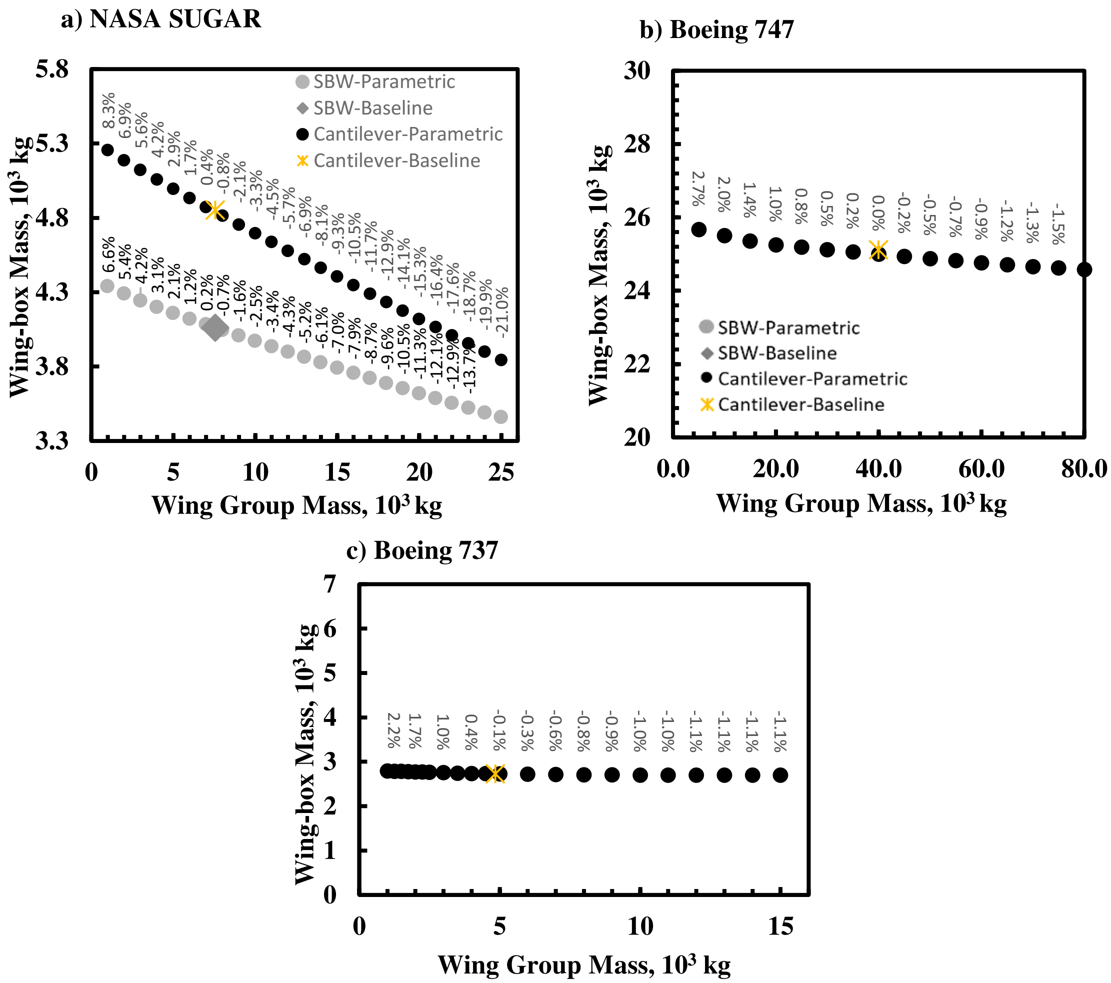


Fig. 14 a) NASA SUGAR-SBW, SUGAR-CANT, b) Boeing 747, c) Boeing 737: baseline aircraft wing-box mass changes with the change in the total wing group mass.

ND Spanwise Position of the Engine

ND spanwise position of the engine is a fraction of wing half span length. As it can be detected from Table 3 and Fig. 15, the spanwise position of the engine has a greater impact on the WB weight of HAR wing configurations compared to the MAR wing of the Boeing 737 and 747. SUGAR-CANT has the highest importance factor of 37.9%, while the second most sensitive configuration is SUGAR-SBW with an importance factor of 18.%. The importance factors for the Boeing 737 and Boeing 747 are 9.1% and 5.7%, respectively. The WB mass of HAR wings tends to reduce with more outboard engine positions; however, the MAR wings do not show an obvious tendency compared to the HAR wing.

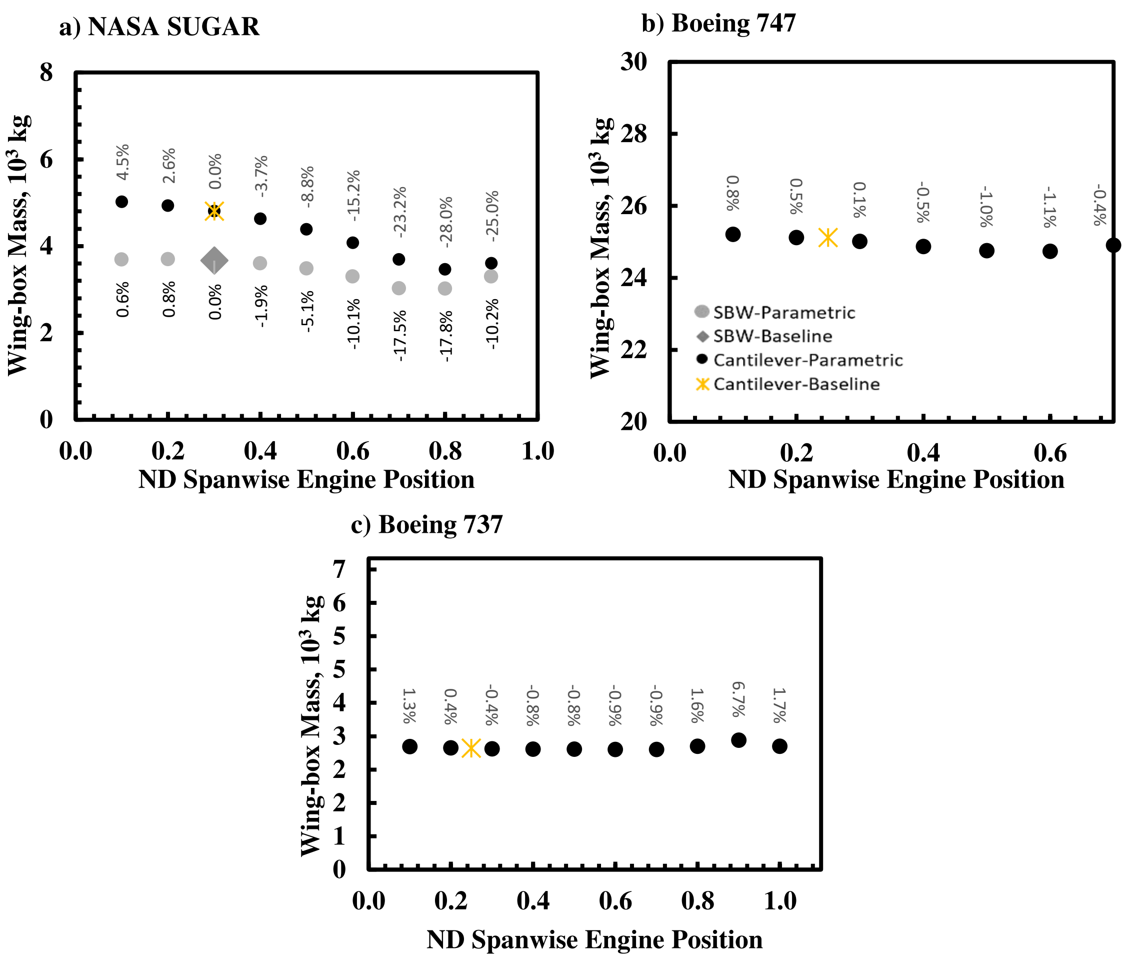


Fig. 15 a) NASA SUGAR-SBW, SUGAR-CANT, b) Boeing 747, c) Boeing 737 baseline aircraft wing-box mass change with the change of the ND spanwise position of the engine.

5.Wing Planform

Thickness to Chord Ratios of the Wing Root and Wing Tip

Both the thickness-to-chord ratios at the tip and at the root are important parameters for all baselines; however, some configurations are more sensitive to those parameters compared to the others. In general, as can be seen from Fig. 16, the WB masses of all the configurations tend to reduce with increasing thickness to chord ratios at the root and at the tip. The trend of WB mass variation with the thickness to chord ratio value in this parametric study matches the result of previous studies from References [9–11].

The reduced WB mass with the increasing thickness to chord ratio can be explained by the increased second moment of inertia of the wing-box cross-section, which reduces the amount of bending resisting material. With increased thickness to chord ratio, the distance between the stringers is also reduced, as the total stringer count is a fixed parameter for this study. The reduced distance between stringers also reduces the thickness of the skin panels to resist buckling; hence, this reduces the required shear-resistant material too.

The sensitivity of the Boeing 747 and SUGAR-CANT to the thickness-to-chord ratio at root is significantly higher compared to the others, with importance factors of 242.4% and 107.1%, respectively. The sensitivities of SUGAR-SBW and Boeing-737 are measured with importance factors of 38.05 and 44.8%, respectively. It appears from Table 3 that, HAR wings of SUGAR-SBW and SUGAR-CANT have more sensitivity to thickness to chord ratio at the tip, with importance ratios of 60.35% and 64.7%, respectively, compared to the importance factors of the Boeing 747 and Boeing 737, with 38.5% and 38.8%, respectively.

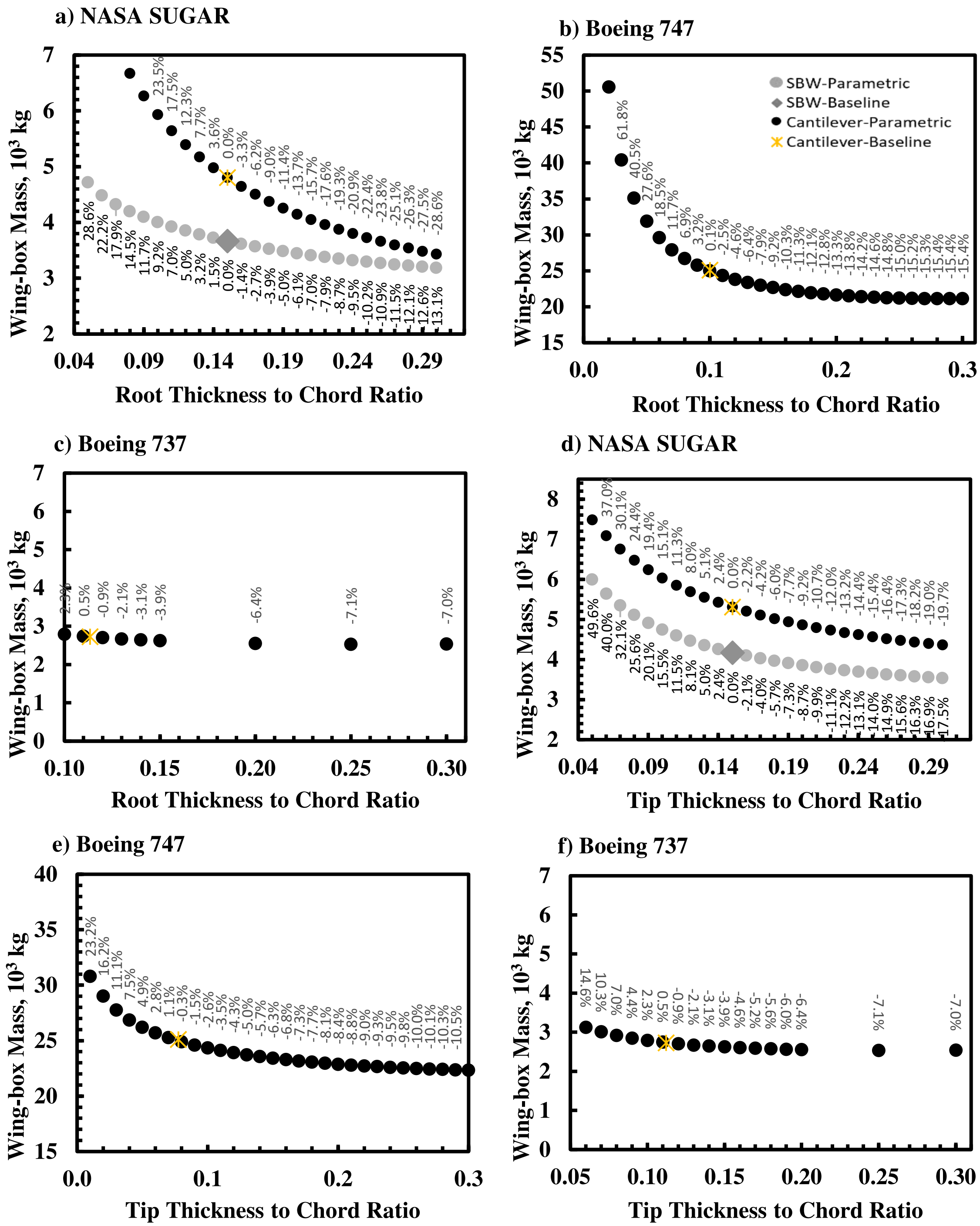


Fig. 16 a) NASA SUGAR-SBW, SUGAR-CANT, b) Boeing 747, c) Boeing 737, baseline aircraft wing-box mass changes as the thickness to chord ratio at the wing root changes. And d) NASA SUGAR-SBW, SUGAR-CANT, e) Boeing 747, f) Boeing 737 baseline aircraft wing-box mass varies as the thickness to chord ratio at the wing tip changes.

Aspect Ratio

In this study, in order to change the aspect ratio, the wing taper ratio and wing surface area are kept fixed when the wing root and tip chords and the wingspan length are changed.

The developed method seems sensitive enough to aspect ratio increases, and the trend of the WB mass variation in graphs correlates with the results of the previous studies from References [9–11].

Among the fourteen different design parameters presented in Table 3, the wing-box mass is the most sensitive to the wing aspect ratio for all the studied aircraft configurations. The wing-box mass increases exponentially with the increasing aspect ratio for all the configurations as presented in Fig. 17.

The WB mass increase with increasing aspect ratio can be explained by drastically increasing bending stresses on the load carrying structures. As previously discussed in Section-Stringer Counts and other sections, bending resistant material becomes dominant for HAR wings, and this also affects the importance factor of some design parameters compared to MAR wings. The WB mass sensitivity to aspect ratio variation of SUGAR-SBW, SUGAR-CANT, Boeing 737, and Boeing 747 are measured with importance factors of 348.8%, 325.3%, 392.6%, 274.5%, respectively.

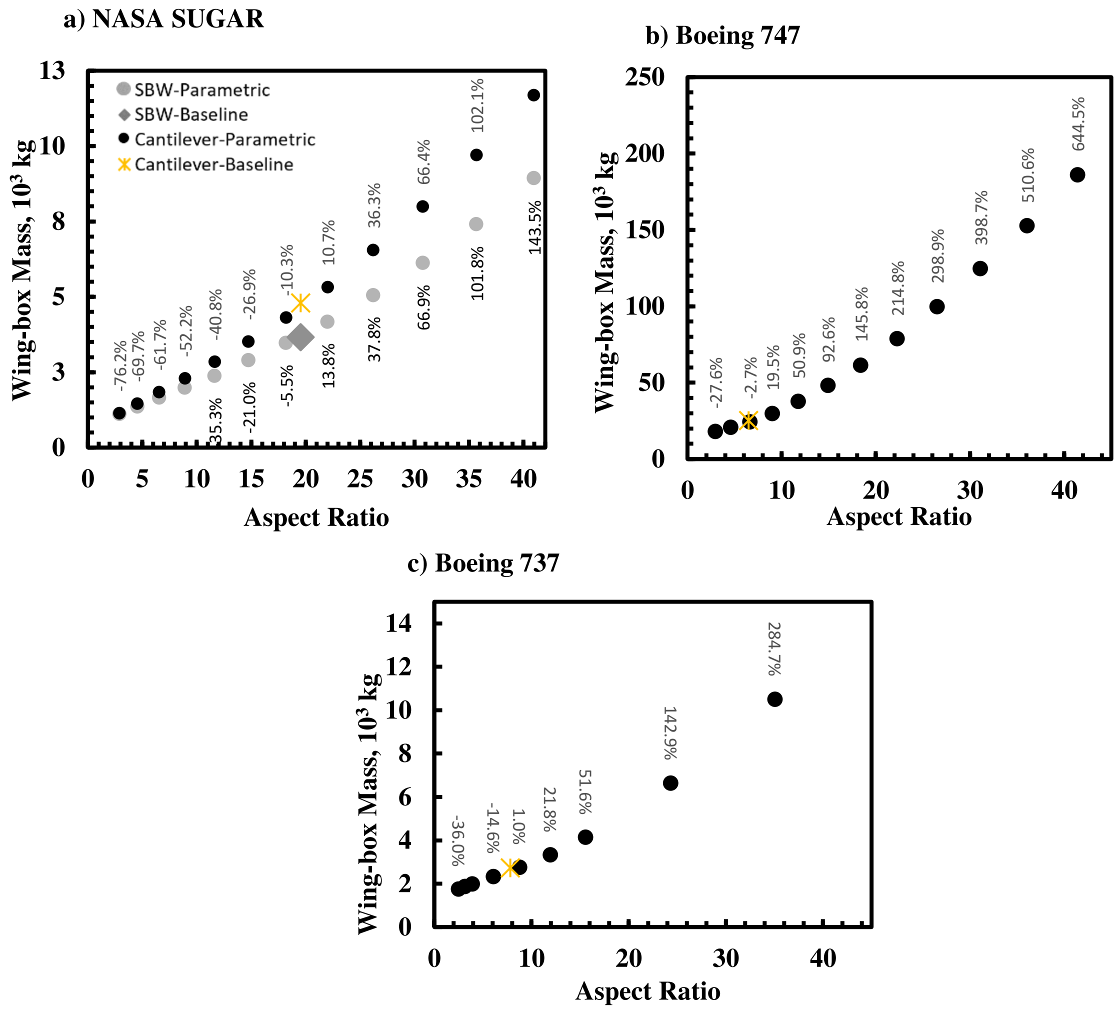


Fig. 17 a) NASA SUGAR-SBW and SUGAR-CANT, b) Boeing 747 and c) Boeing 737, baseline aircraft wing-box mass variation with wing aspect ratio change.

V. Conclusion

For conceptual design studies of novel aircraft, a new, high - sensitivity, computationally cheap, physics-based wing-box (WB) mass estimation approach as well as its implementation in a spreadsheet tool are introduced briefly. To achieve this, new geometric models are developed, and detailed loading cases are considered, including symmetric, rolling, and combined cases following CS.25 requirements. A total of 483 loading cases are covered by default with the new weight estimation tool. The wing-box components are sized against bending, shear stresses, and buckling constraints, and the structural masses of the WB components are calculated from the sizing results. In addition to the calculated mass of load-carrying structures, other sources of wing-box masses are covered with the existing empirical equations from the literature, including aeroelastic mass penalties, rib masses, and other masses caused by the non-optimum design. The new WB WE method achieved a standard error of 1.7% and a median error of -0.2% when validated against data from nine cantilever and one strut-braced aircraft with aluminum and composite wing boxes. In addition to that, fast computational time is achieved in the calculations with less than 10^2 ms for one loading case using an Intel i7-11800H CPU, an octa-core 2.3 GHz computer.

After the validation studies, the effect of the strut on the WB weight reduction is investigated using quasi-isotropic composite and aluminum materials. It was demonstrated that the strut reduced the weight of the wing boxes by 11.9% and 16.2%, respectively, for the aluminum and composite wing boxes.

In the final section of this work, a comprehensive parametric study is conducted to investigate the effects of fourteen different aircraft design parameters on the WB mass of a high aspect ratio (HAR) cantilever baseline of SUGAR-CANT, a high aspect ratio (HAR) strut-braced wing baseline of SUGAR-SBW and moderate aspect ratio (MAR) cantilever wing baselines of Boeing 747 and Boeing 737 using a one-factor-at-a-time sensitivity analysis approach. To be able to compare the effects of fourteen aircraft design parameters on the WB mass, a simple importance factor from the literature is used. The sensitivity of the WB mass to the studied parameters is also presented with detailed graphs generated from the variation of the WB mass value against the studied design parameters.

The optimum strut attachment point that achieves a minimum WB mass excluding the structural mass of the strut is found at a ND span length of 0.65.

The significance of stringer count for four configurations is presented with importance factors and graphs; however, its trend was different for HAR and MAR wings. The increasing stringer counts increased the WB masses for HAR wings but decreased those for MAR wings. The mass increase in HAR wings is explained by the increasing dominance of bending resisting material in WB mass.

The effect of an idealized wing-box shape on WB mass is also investigated. By changing the design parameter of the WB's shape, the idealized shape of the WB is gradually changed from a diamond shape to a hexagonal shape and a rectangular shape. The significant effect of an idealized WB shape is observed. For the HAR SUGAR-CANT configuration, the importance ratio of this parameter reached 90%. All the configurations have decreasing WB mass when the idealized WB shape approaches a rectangular shape.

The effect of the center wing-box length on the WB mass of SUGAR-SBW and Being-737 configurations was significant, with importance factors of 39.9% and 20.2%, respectively, compared to the other configurations. While increasing the center wing-box length caused a reduction in the WB mass of the SBW configuration, it increased the WB mass of the Boeing 737 baseline.

The effect of TOGW is higher for high aspect ratio SUGAR-SBW and SUGAR-CANT configurations compared to other configurations, with importance factors of 59.5% and 80.1%, respectively, despite the fact that the OEW importance values of all configurations have closer values. It's also observed that the WB masses diverge after they approach the minimum TOGW and OEW values, which might emphasize the importance of these two factors for an optimal wing-box design. It was also demonstrated that increasing the mass of fuel stored in the wing-box decreased the WB mass of all configurations due to the inertia relief provided. The significance of wing group weight on the WB mass is also shown for HAR wings. Because the wing-group mass is a dependent variable of the calculated WB mass, iterative WB mass calculations for HAR wings are advised in order to converge to a final WB mass result.

It was shown that the WB mass is significantly sensitive to the thickness-to-chord ratio of the wing tip and root in all configurations. Increasing the thickness-to-chord ratio reduced the WB mass of all configurations, and this outcome correlates with the findings of previous research in the literature. The extreme effects of the wing aspect ratio on the WB mass of all configurations were also shown. An increase in the wing aspect ratio, increased the WB mass of all configurations extremely due to the increased bending stresses, and this trend also relates to the results of the previous studies in the literature.

In summary, the new WB mass estimation approach is validated for HAR and MAR cantilever wings and HAR SBWs. In addition to its high accuracy, the method's sensitivity to aircraft design parameters has been successfully demonstrated. Important points from the parametric and comparative studies are highlighted to provide an instinct for conceptual design studies of novel and traditional aircraft configurations. The importance of covering the effects of fourteen aircraft design parameters to achieve the development of an accurate and sensitive enough conceptual or early preliminary design WB mass estimation method is stated.

The results presented in this paper are suggested to be studied with higher-order WB mass estimation tools to increase confidence in the outlined observations. In future works, the effects of other aircraft design parameters will be investigated using the same research method as in this paper.

Appendix

Table 4 Some of the Boeing 747 design parameters used in the design tool to generate the baseline aircraft for the parametric study.

No	Parameter	Value	Units	No	Parameter	Value	Units
1	Aircraft Name	747		**22**	Wing total mass	39,916.13	kg
2	Root chord	14,137.64	mm	**23**	Wing-box actual mass	25,854.77	kg
3	Tip chord	4,084.32	mm	**24**	Total engine count	4.00	
4	ND front spar location at the wing root as a fraction of wing section chord.	0.15		**25**	Engine mounting type. 1 for wing mounted, 2 for fuselage mounted.	1.00	
5	ND front spar location at the wing tip as a fraction of wing section chord.	0.15		**26**	Engine mass	8,293.12	kg
6	ND rear spar location at the wing root as a fraction of wing section chord.	0.65		**27**	ND spanwise Engine-1 position as a fraction of half wingspan	0.25	
7	ND rear spar location at the wing tip as a fraction of wing section chord.	0.65		**28**	ND chordwise Engine-1 position as a fraction of local wing section chord	-0.25	
8	Wing thickness to chord ratio at the root.	0.10		**29**	ND, z-axis, Engine-1 position as a fraction of local wing section thickness	-3.00	
9	Wing thickness to chord ratio at the tip.	0.08		**30**	ND spanwise Engine-2 position as a fraction of half wingspan	0.55	
10	Wing sweep angle	35.47		**31**	ND chordwise Engine-2 position as a fraction of local wing section chord	-0.25	
11	Wing dihedral	0.00		**32**	ND, z-axis, Engine-2 position as a fraction of local wing section thickness	-3.00	
12	Stringer count	23.00		**33**	Fuselage length	76,300.00	mm
13	Wingspan	59,649.36	mm	**34**	Fuselage diameter	5,600.00	mm
14	TOGW	322,957.77	kg	**35**	Landing gear mounting type. 1 for wing mounted, 2 for fuselage mounted.	1.00	
15	OEW	165,646.04	kg	**36**	ND spanwise LG position as a fraction of half wingspan	0.15	
16	Design diving speed	228.93	m/s	**37**	Main LG Weight	5,522.58	kg
17	Design diving Mach	0.92		**38**			
18	Design cruise speed	213.93	m/s	**39**	Wing maximum lift coefficient	1.50	
19	Design cruise Mach	0.87		**40**	Service Ceiling	13,715.00	m
20	Wing stored fuel mass	142,428.00	kg	**41**	Aspect Ratio Actual	6.55	
21	Total fuel volume	183.00	m^3				

Table 5 Some of the Boeing 747 design parameters used in the design tool to generate the baseline aircraft for the parametric study.

No	Parameter	Value	Units	No	Parameter	Value	Units
1	Aircraft Name	737		**22**	Wing total mass	4,853.44	kg
2	Root chord	5,641.34	mm	**23**	Wing-box actual mass	2,585.48	kg
3	Tip chord	1,607.82	mm	**24**	Total engine count	2	
4	ND front spar location at the wing root as a fraction of wing section chord.	0.15		**25**	Engine mounting type. 1 for wing mounted, 2 for fuselage mounted.	1.00	

5	ND front spar location at the wing tip as a fraction of wing section chord.	0.15		**26**	Engine mass	4,483.33	kg
6	ND rear spar location at the wing root as a fraction of wing section chord.	0.65		**27**	ND spanwise Engine-1 position as a fraction of half wingspan	-3.00	
7	ND rear spar location at the wing tip as a fraction of wing section chord.	0.65		**28**	ND chordwise Engine-1 position as a fraction of local wing section chord	0.25	
8	Wing thickness to chord ratio at the root.	0.11		**29**	ND, z-axis, Engine-1 position as a fraction of local wing section thickness	0.40	
9	Wing thickness to chord ratio at the tip.	0.11		**30**	Fuselage length	31,200.00	mm
10	Wing sweep angle	31.18		**31**	Fuselage diameter	3,760.00	mm
11	Wing dihedral	0.00		**32**	Landing gear mounting type. 1 for wing mounted, 2 for fuselage mounted.	1.00	
12	Stringer count	11		**33**	ND spanwise LG position as a fraction of half wingspan	0.18	
13	Wingspan	28,346.40	mm	**34**	Main LG Weight	781.85	kg
14	TOGW	45,722.11	kg	**35**	Wing maximum lift coefficient	1.60	
15	OEW	27,026.39	kg	**36**	Service Ceiling	11,300.00	m
16	Design diving speed	216.07	m/s	**37**	Aspect Ratio Actual	7.82	
17	Design diving Mach	0.84		**38**			
18	Design cruise speed	201.07	m/s	**39**			
19	Design cruise Mach	0.73		**40**			
20	Wing stored fuel mass	14,514.96	kg	**41**			
21	Total fuel volume	22.60	m^3				

Table 6 Some of the NASA SUGAR Aircraft design parameters used in the design tool to generate the baseline SBW aircraft for the parametric study.

No	Parameter	Value	Units	No	Parameter	Value	Units
1	Aircraft Name	NASA SUGAR		**22**	Wing total mass	7,561.38	kg
2	Root chord	3,309.94	mm	**23**	Wing-box actual mass	3,615.00	kg
3	Tip chord	1,146.40	mm	**24**	Total engine count	2.00	
4	ND front spar location at the wing root as a fraction of wing section chord.	0.15		**25**	Engine mounting type. 1 for wing mounted, 2 for fuselage mounted.	1.00	
5	ND front spar location at the wing tip as a fraction of wing section chord.	0.25		**26**	Engine total mass	5,996.5	kg
6	ND rear spar location at the wing root as a fraction of wing section chord.	0.60		**27**	ND spanwise Engine-1 position as a fraction of half wingspan	0.3	
7	ND rear spar location at the wing tip as a fraction of wing section chord.	0.60		**28**	ND chordwise Engine-1 position as a fraction of local wing section chord	-0.25	
8	Wing thickness to chord ratio at the root.	0.15		**29**	ND, z-axis, Engine-1 position as a fraction of local wing section thickness	-3.00	

9	Wing thickness to chord ratio at the tip.	0.15		**30**	Fuselage length	42,587.67	mm
10	Wing sweep angle	13.47		**31**	Fuselage diameter	3,776.98	mm
11	Wing dihedral	-1.50		**32**	Landing gear mounting type. 1 for wing mounted, 2 for fuselage mounted.	2.00	
12	Stringer count	3.00		**33**	Main LG Weight	1,163.46	kg
13	Wingspan	51,798.25	mm	**34**	Wing maximum lift coefficient	1.50	
14	TOGW	68,038.86	kg	**35**	Service Ceiling	12,435.84	m
15	OEW	39,598.61	kg	**36**	Aspect Ratio Actual	19.54	
16	Design diving speed	165.00	m/s	**37**			
17	Design diving Mach	0.76		**38**			
18	Design cruise speed	150.00	m/s	**39**			
19	Design cruise Mach	0.71		**40**			
20	Wing stored fuel mass	12,485.63	kg	**41**			
21	Total fuel volume	20.50	m^3				

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