Influence of weight modelling on the outcome of wing design using multidisciplinary design optimisation techniques

J. Mariens, A. Elham and M. J. L. van Tooren
a.elham@tudelft.nl
Faculty of Aerospace Engineering
Delft University of Technology
The Netherlands

ABSTRACT

Weight estimation methods are categorised in different classes based on their level of fidelity. The lower class methods are based on statistical data, while higher class methods use physics based calculations. Statistical weight estimation methods are usually utilised in early design stages when the knowledge of designers about the new aircraft is limited. Higher class methods are applied in later design steps when the design is mature enough. Lower class methods are sometimes preferred in later design stages, even though the designers have enough knowledge about the design to use higher class methods. In high level multidisciplinary design optimisation (MDO) fidelity is often sacrificed to obtain models with shorter computation times. There is always a compromise required to select the proper weight estimation method for an MDO project.

An investigation has been performed to study the effect of using different weight estimation methods, with low and medium levels of fidelity, on the results of a wing design using multidisciplinary design optimisation techniques. An MDO problem was formulated to design the wing planform of a typical turboprop and a turbofan passenger aircraft. The aircraft maximum take-off

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weight was selected as the objective function. A quasi-three-dimensional aerodynamic solver was developed to calculate the wing aerodynamic characteristics. Five various statistical methods and a quasi-analytical method are used to estimate the wing structural weight. These methods are compared to each other by analysing their accuracy and sensitivity to different design variables. The results of the optimisations showed that the optimum wing shape is affected by the method used to estimate the wing weight. Using different weight estimation methods also strongly affects the optimisation convergence history and computational time.

NOMENCLATURE

AR	wing aspect ratio
b	wing span
b_{ref}	reference span (1·905m)
b_s	structural wing span, $b_s = b/\text{Cos}\,\Lambda_{1/2}$
c_r	wing root chord length
g	gravitational acceleration
I_w	wing weight index
n_{ult}	ultimate load factor
PAX	number of passengers
s	range
S	wing reference area
t_{ss}	smeared skin thickness
V_D	design dive speed (EAS)
V_f	fuel volume
w	material specific weight
W_{des}	design all-up weight, $W_{des} = \sqrt{W_{to}\, W_{zf}}$
W_{pay}	payload weight
W_{to}	maximum take-off weight
W_w	wing structural weight
W_{zf}	maximum zero-fuel weight
$(t/c)_{ave}$	wing average thickness-to-chord ratio
$(t/c)_k$	wing thickness-to-chord ratio at kink section
$(t/c)_r$	wing thickness-to-chord ratio at root section
$(t/c)_t$	wing thickness-to-chord ratio at tip section
Λ	wing quarter-chord sweep angle
λ	wing taper ratio
σ	mean stress level at wing root

1.0 INTRODUCTION

Aircraft wing design using multidisciplinary design optimisation is a complex task which involves different disciplines mainly aerodynamic and structure. Different level of analysis are used for wing design and optimisation. Design is started using simple empirical methods and it is proceeded by increasing the level of fidelity of the analysis methods. For instance a variety of methods are available for the aerodynamic analysis of a wing. From a simple lifting line theory or a vortex lattice method[1,2] up to the complex Euler and RANS methods[3-5]. Similarly for weight

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estimation, various methods with different levels of fidelity are available. In an MDO system, selection of a proper method is a challenge. A compromise has to be made for selecting proper tools/methods. The computational time of the methods should be low to make it affordable to call them thousands of times during optimisation. On the other hand, the level of accuracy and design-sensitivity should be high to steer the optimisation to a realistic outcome. Research has been done to study the effect of using different weight estimation methods on the outcome of wing design using MDO techniques.

Weight estimation methods used in the aircraft design processes can be grouped based on their level of fidelity. In general the lower the fidelity, the more the method is based on statistics. Higher class methods rely less on statistical estimations and use more physics based calculations[6]. These calculations require more detailed input parameters. In a wing design task, three class of weight estimation methods are used: statistical, quasi-analytical and analytical methods.

Statistical weight prediction techniques These methods use empirical equations, developed based on existing aircraft, to estimate the wing weight as a function of several significant geometrical parameters. A number of conceptually similar methods, tailored to different classes of aircraft, are presented by Howe[7], Torenbeek[8], Shevell[9] and Raymer[10]. Implementing these methods results in a fast and robust weight estimation with minimum amount of required data. The main problem is the level of accuracy. Another problem is the validity margin, as these method are only valid within the bounds of the original data. Note that such methods are limited when considering new concepts that lie out of the original database.

Quasi-analytical weight estimations Another class of weight prediction techniques are the quasi-analytical methods. These methods are based on elementary strength/stiffness analyses of aircraft structures, augmented by empirical factors and statistical data. This approach enables weight engineers to develop more accurate and also design-sensitive results. Additionally they have a wider validity margin compared to statistical methods. These methods are based on the 'stationary analysis' of a simplified structure. In such a method the primary wing box weight is computed by calculating the amount of material required to resist the applied loads. Contributions of the secondary structures (i.e., flaps, slats, ailerons, etc.) are still estimated based on statistical methods. Examples of wing weight estimations based on this approach are presented by Torenbeek[11], Macci[12] and Elham[13].

Analytical methods

These methods rely on finite element methods (FEM) to size various components of the primary wing structure and compute their weight using the material density. Examples of such methods are demonstrated by Bindolino[14] and Laban[15]. Generally, these methods are more accurate than those mentioned above. However their implementation requires a large amount of detailed geometrical information as well as the structural and material data. This is usually not available in the early design stages. Furthermore, the time required to implement a finite element model and perform the analysis, is significantly longer than computing the simple empirical equations of a statistical method. This makes these methods unsuitable in early design phases and also for weight predictions within a high level MDO processes.

Different combinations of the aerodynamic solver and weight estimation methods have been tested in several recent wing design and optimisation projects. Obayshi[16] examined evolutionary approaches for aircraft design and optimisation using a mid class aerodynamic solver (potential equations) and a statistical weight estimation method presented by Torenbeek[8]. Ursache *et al*[17] presented the first steps of a methodology towards a morphing wing application, by combining a quasi-analytical

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weight estimation method (Torenbeek[11]) and lower fidelity aerodynamic solver (vortex lattice method). Another example is given by Bérard *et al*[18], where they developed and validated a next-generation of the conceptual aero-structural sizing suite using a quasi-analytical wing weight estimation method[19] and both low fidelity (vortex-lattice method and doublet lattice method) and higher fidelity (Edge CFD, Euler code) aerodynamic solvers.

From the examples mentioned above one can conclude that since high fidelity solvers require long computational times, fidelity is sometimes sacrificed in order to obtain faster and less complex models. Therefore it is of great interest to know what the consequences are of selecting a certain solver. The present research was conducted to study the effect of using different weight estimation methods, with different low and medium levels of fidelity, on an MDO assignment for aircraft wing design.

2.0 WING WEIGHT ESTIMATION METHODS

In this section several existing statistical weight estimation methods are explained and compared to each other. This comparison is done by analysing their accuracy and sensitivity to different wing geometry variables. Those methods are also compared to a quasi-analytical method, based on accuracy, design sensitivity and computational time.

2.1 Torenbeek (1) method

Torenbeek has developed several wing weight estimation methods, of which two statistical methods are used in the present research. The first method[8] is a simplified expression, derived based on a typical wing weight estimation method[20]. This method can be used to predict the structural wing weight of civil airplanes with cantilever wings and is presented by the following equation:

$$W_w = W_G \cdot k_w \cdot b_s^{0.75} \left[1 + \sqrt{\frac{b_{ref}}{b_s}} \right] n_{ult}^{0.55} \left(\frac{b_s / (c_r \cdot (t/c)_r)}{W_G / S} \right)^{0.30} \quad \ldots (1)$$

where b_s is the structural wing span defined as $b_s = b/\mathrm{Cos}\Lambda_{1/2}$. The factor of proportionality, k_w, and W_G are as follows (for metric units):

— For light aircraft, $W_{to} \leq 5{,}670$kg: $k_w = 4{\cdot}90 \times 10^{-3}$ and $W_G = W_{to}$ in kg.
— Transport category aircraft, $W_{to} > 5{,}670$kg: $k_w = 6{\cdot}67 \times 10^{-3}$ and $W_G = W_{zf}$ in kg.

The weight given by Equation (1) includes the weight of the high-lift devices and ailerons. If spoilers and speed brakes are incorporated an additional weight equal to 2% of the total wing weight should be added. In the case of wing-mounted engines the wing weight must be reduced by 5% and 10% for two or four engines respectively. Additional reductions can be made for braced wings or in the case that the main undercarriage is not mounted to the wing.

In this method, the primary wing structural weight is determined based on the requirement that in a specified critical flight condition the bending moment due to the wing lift must be resisted by the wingbox structure. The weight of the high-lift devices is estimated based on the critical loading conditions at the flap design speed. The accuracy of this method has been assessed using the actual wing weight of 46 aircraft (dating from about 1940-70s). A standard deviation of 9·64% was achieved[8,20].

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Application of the method to several high-subsonic short-haul airplanes led to the conclusion that the original method underestimates the wing weight. This underestimation can be caused by (a) the extra weight (up to 20%) required to provide adequate stiffness against flutter and (b) the weight penalty due to long service life[20]. Since a simplified expression (Equation (1)) of the original method (the method presented in Ref. 20) is used in this paper, a larger deviation than the indicated standard deviation is expected.

2.2 Torenbeek (2) method

Another statistical method, also developed by Torenbeek, was used for this research. This wing weight estimation method is presented by Torenbeek[21] and it is derived from a quasi-analytical method described by the same author[11]:

$$W_w = 0{\cdot}06\frac{w}{\sigma_r} n_{ult}\sqrt{W_{to}\cdot W_{zf}}\,\frac{b^3}{S}\,\frac{1}{(t/c)_{ave}\cos^2\Lambda}\,\frac{1+2\lambda}{1+\lambda} + wt_{ss}S \qquad \ldots(2)$$

In this expression the term w/σ_r represents the weight of the materials in the upper and lower wing panels. These panels are required to withstand the bending load due to lift, which is represented by $n_{ult}\sqrt{W_{to}\cdot W_{zf}}$. The factor 0·06 is a non-dimensional constant of proportionality. This value accounts for the average values of the bending relief due to e.g. wing and engine masses, structural efficiency, spars locations, etc. The design weight W_{des} and the ultimate load factor n_{ult} refer to the critical combinations of maneuver/gust loads, weight distributions and operating speeds. The meaning of the other values is as follows:

- The term w/σ_r is the ratio of the specific wing material weight (w) to the mean stress level at the wing root σ_r. Torenbeek[21] suggested that a statistical average value based on a Al-alloy structure can be used:

$$\frac{w}{\sigma_r} = 40\left[1+1{\cdot}10\left(W_{to}/10^6\right)^{-1/4}\right]\times 10^{-6} \qquad \ldots(3)$$

- The average thickness-to-chord ratio t/c is found by suitable weighing of the wing thickness to chord ratio distribution in spanwise direction.
- The sweep angle Λ is theoretically related to the elastic axis. However, since its location is usually unknown, Torenbeek suggested to approximate it by the mean quarter-chord line.
- The smeared skin thickness t_{ss} is defined by

$$t_{ss} = 0{\cdot}004\left(1+\sqrt{W_{to}/10^6}\right) \qquad \ldots(4)$$

As it is mentioned before, this method was derived from a more sophisticated method[11]. The original method is characterised as follows:

- The wing structural weight is divided into functional components. The weight of each component is estimated by implementing either a statistical or a semi-analytical equation.
- The wingbox structure is sized in such a way to have minimum amount of material in the upper and lower equivalent panels required to resist the bending moment and the minimum amount of material in the spars webs to resist the shear force. These values are obtained implementing an analytical structural analysis method.

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Table 1
Estimated versus actual wing weight for several transport aircraft[21]

Aircraft	W_{to} [kN]	Wing weight computed [kN]	Wing weight actual [kN]	error [%]
Boeing 747-100	3,158	391·6	384·4	+1·9
Airbus A340	2,486	345·0	340·9	+1·2
Fokker F-28 Mk4000	315·8	32·03	33·28	–3·8
Cessna Citation II	59·16	5·950	5·730	+3·8

- The effect of variation in the thickness-to-chord ratio and the compressive stresses (buckling criteria) have been taken into account.
- A series of semi-empirical equations have been developed to estimate the ribs weight, the non-optimum weight penalties, the weight of the fixed leading and trailing edge structures as well as the weight of the high-lift devices and the control surfaces.
- The mean stress level is computed as a function of the aircraft maximum take-off weight using an empirical equation. This equation is valid for Al-alloy structures. A user-selected design stress levels is also possible for alternative material applications.

The original method was validated using several transport aircraft. The results are shown in Table 1. Although the small number of aircraft considered for validation does not permit to determine the mean prediction error. Nevertheless the table indicates that the original method yields good results for the size effect. The results from the simplified method will most-likely deviate more than the original one.

2.3 Shevell method

Shevell[9] developed a statistical method based on a wing weight index, which is related to the weight of the fully-stressed wing box. This weight index is defined as follows (in imperial units):

$$I_w = \frac{n_{ult} b^3 \sqrt{W_{to} \cdot W_{zf}}}{(t/c)_{ave} S^2 \mathrm{Cos}^2 \Lambda} \frac{(1+2\lambda)}{(1+\lambda)} 10^{-6} \quad \ldots (5)$$

From Equation (5) one can observe that the weight index is proportional to the compressive and tensile loads due to the bending moments at the root of the wing in the skin and the spars caps. Figure 1 shows the variation of the ratio of the wing weight to the wing planform area in square foot with respect to the wing weight index. Based on this figure the total wing weight is estimated as follows[9,22]:

$$\frac{W_w}{S} = 4 \cdot 22 + 1 \cdot 642 I_w \quad \ldots (6)$$

The first term on the right hand side of this equation is a constant and represents the secondary wing weight. The second term varies in proportion to the amount of material required to resist the applied bending loads and represents the primary wing weight.

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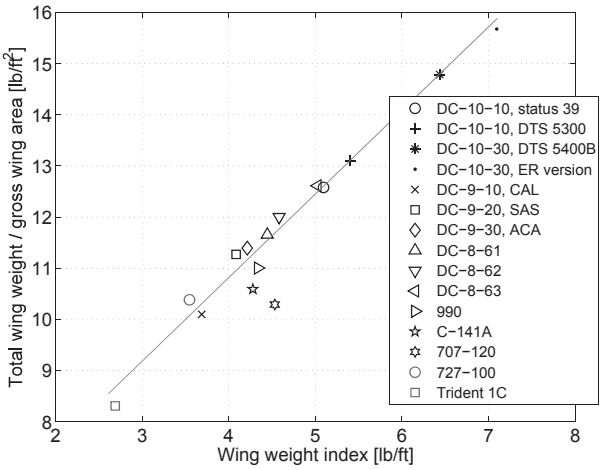


Figure 1. Statistical wing weight correlation (reproduced from Ref. 9).

2.4 Howe method

A statistical weight estimation method was developed by Howe[7], in which the wing weight is derived based on the number of passengers or the payload weight for a particular airplane. In this fundamentally empirical method, the wing weight is calculated as a function of the main geometric and operational parameters. The estimated wing weight is correlated to some actual wing weight values. The equation for wing weight estimation is as follows:

$$W_w = g\frac{C_1}{C_5}\left[AR^{0.5}S^{1.5}sec\Lambda\left(\frac{1+2\lambda}{3+3\lambda}\right)\frac{W_{to}}{gS}n_{ult}\left(\frac{V_D}{(t/c)_r}\right)^{0.5}\right]^{0.9} \quad \ldots(7)$$

Coefficient C_1 in this expression is defined as follows:

(a) Long range, $s > 5{,}000$km

$$C_1 = 0{\cdot}00072 - 0{\cdot}0005(270 + 0{\cdot}05s)PAX \times 10^{-6} \quad \ldots(8)$$

(b) Short/medium range, W_{to} . 46, 000kg

$$C_1 = 0{\cdot}00167\ .\ 0{\cdot}016(370 + 0{\cdot}03\text{s})PAX \times 10^{-6} \quad \ldots(9)$$

(c) Turboprop, $W_{to} \leq 46{,}000$kg

$$C_1 = 0{\cdot}00149 - 5{\cdot}8PAX \times 10^{-6} \quad \ldots(10)$$

(d) Long range jet freight aircraft

$$C_1 = 0{\cdot}00072 - 0{\cdot}0005(2{\cdot}08 + 0{\cdot}00038s)W_{pay} \times 10^{-6} \quad \ldots(11)$$

(e) Turboprop freight aircraft

$$C_1 = 0{\cdot}00077 - 0{\cdot}00053(2{\cdot}08 + 0{\cdot}00038s)W_{pay} \times 10^{-6} \quad \ldots(12)$$

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Table 2
Coefficient C_5 in Equation (7)

Type of aircraft	C_5
Tailless delta	1·10
Long haul jet transports	1·16
Short/medium haul jet transports	1·20
Executive jet aircraft	1·30
All other types	1·24

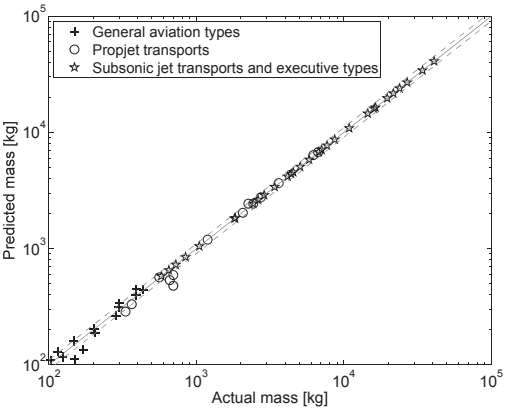


Figure 2. Howe method — actual and predicted wing masses for civil aircraft (reproduced from Ref. 23).

Values of the factor C_5 are presented in Table 2.

This method was tested on 118 aircraft for which sufficient data was available or could be reasonably assumed[23]. These tested aircraft have a take-off weight range from about 700kg (Cessna 150) to more than 377,000kg (Boeing 747-200). Figure 2 shows the results of the civil aircraft that were used as the test cases, together with ±10% boundaries. For 76% of those aircraft, the error of the wing weight prediction is less than 10%.

2.5 LTH method

The last statistical method which is used in this research is the empirical equation developed by Dorbath on behalf of LTH (Luftfahrttechnisches Handbuch) organisation[24]. The equation is presented below:

$$W_w = 2 \cdot 20013 \cdot 10^{-4} g \left[401.146 S^{1.31} + \left(\frac{W_{to}}{g} \right)^{1.1038} \right] \cdot (t/c)_{rep}^{-0.5} AR^{1.5} \frac{1}{\mathrm{Cos}\,\Lambda} \quad \ldots (13)$$

In this equation the representative thickness-to-chord ratio $(t/c)_{rep}$ is defined as $0{\cdot}6(t/c)_r + 0{\cdot}3(t/c)_k + 0{\cdot}1(t/c)_t$. Table 3 shows the range of the values for which this method is valid. The validation results of this method shows a standard deviation of 6·2% (see Fig. 3).

2.6 Elham modified weight estimation technique (EMWET)

In addition to those mentioned statistical methods, a quasi-analytical weight estimation method is also used for this research. The student version of the EMWET (Elham modified weight estimation technique) tool[13] is used as a quasi-analytical weight estimation method. This tool makes use of an analytical approach to size the wingbox primary structure. The structural and material parameters, the applied loads and the geometrical data of the wing planform and relative airfoils are required to implement this method. Several passenger aircraft from different manufacturers (Fokker, Boeing and Airbus) have been used for validation. The validation study done by Elham[13] has demonstrated an average accuracy in the order of 2% as shown in Table 4. This level of accuracy is comparable to the higher class methods such as the FEM based weight prediction methods, while the computational time is in the same order of magnitude as the empirical methods.

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Table 3
Validity margin of the LTH method

Parameter	Range of values	Unit
Wing mass	4,100 – 50,300	[kg]
Reference wing area	75 – 550	[m^2]
Maximum take-off mass	40,000 – 400,000	[kg]
Representative *t*/*c* ratio 0·10 - 0·15	[-]	
Aspect ratio	6·9 – 9·6	[-]
Quarter-chord sweep angle	15·0 – 37·5	[º]

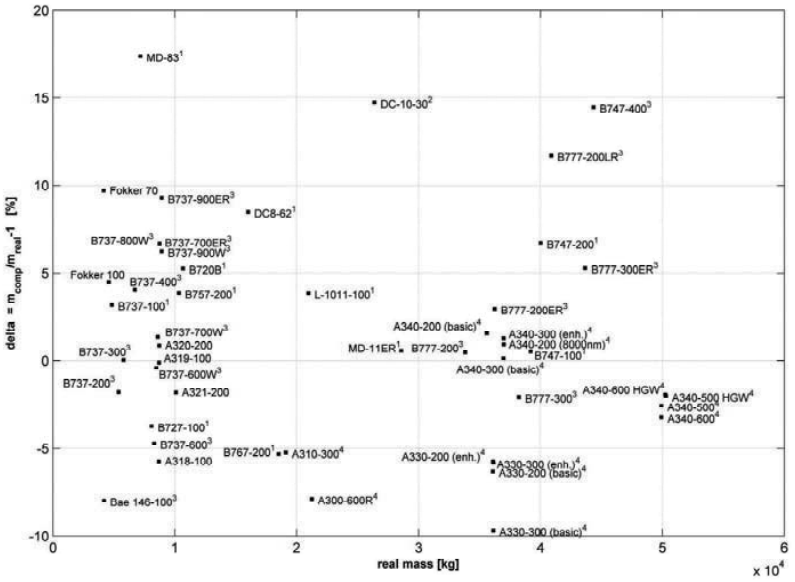


Figure 3. Validation results of the LTH method[24],

Table 4
Validation results of EMWET

Aircraft	W_{to}[kg]	Error [%]
Fokker 50	20,820	–0·72
B737-200	52,390	+0·15
B727-300	95,028	–2·71
A300-600R	170,500	+1·86
A330-300	217,000	–2·18
B777-200	242,670	+2·66

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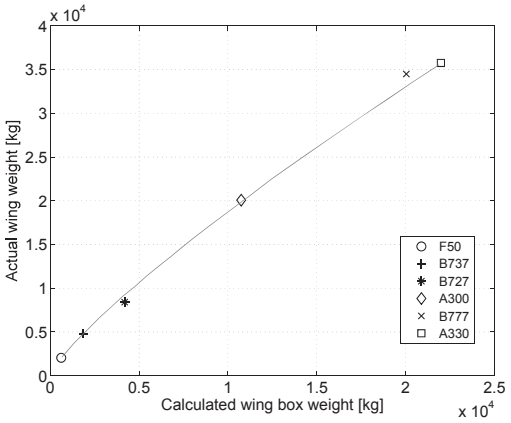


Figure 4. Actual total weight of the wing versus the analytically computed wing box weight (ribs weight and non-optimum weights are excluded)[13].

The EMWET tool calculates the primary and secondary weights separately. However, the student version of EMWET uses a regression to find the total wing weight (W_w) based on the analytically computed wing box weight (W_{calc}), as shown in Fig. 4. Applying a power regression results in the following equation:

$$W_w = 10{\cdot}147 W_{calc}^{0{\cdot}8162} \quad \text{with } R^2 = 0{\cdot}9982 \qquad \ldots (14)$$

Note that by using the student version instead of the full version of EMWET the accuracy of the results might slightly deviate from the average error of 2%, as will be shown later when comparing the accuracy of the treated methods.

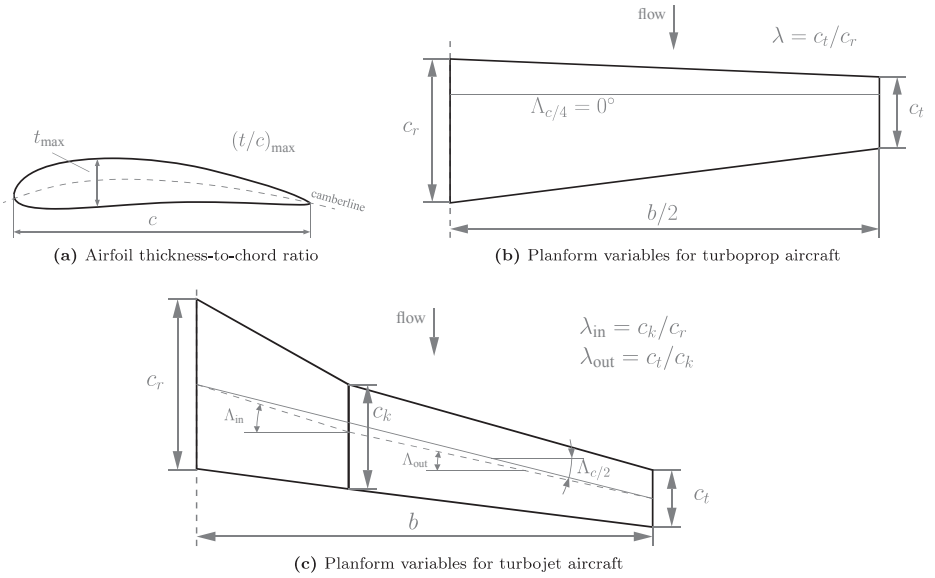
2.7 Method comparison

The above mentioned weight estimation methods are compared by analysing their accuracy and sensitivity to several independent wing geometry variables. A typical turboprop and a turbojet passenger aircraft are used for this study. A distinction can be made among the independent wing parameters for the sensitivity analyses:

- wing span b
- root chord length c_r
- taper ratio λ (tip chord length divided by root chord length)
- thickness-to-chord ratio at root $(t/c)_r$, tip $(t/c)_t$ and kink section $(t/c)_k$ (only for turbojet aircraft)
- twist angle at tip section ε_t (downward negative)
- mid-chord sweep angle $\Lambda_{c/2}$, only for turbojet aircraft

Note that the quarter-chord sweep angle of the turboprop aircraft is near zero and consequently the sensitivity to sweep for the turboprop aircraft is not considered.

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(a) Airfoil thickness-to-chord ratio

(b) Planform variables for turboprop aircraft

(c) Planform variables for turbojet aircraft

Figure 5. Wing geometry variables.

Table 5
Sensitivity of the wing weight estimation methods to various wing variables

Wing weight as a function of ...										
Method	W_{to}	W_{zf}	b	c_r	Λ	λ	$(t/c)_r$	$(t/c)_k$	$(t/c)_t$	ε_t
Torenbeek (1)		✓	✓	✓	✓	✓	✓			
Torenbeek (2)	✓	✓	✓	✓	✓	✓	✓	✓	✓	
Howe	✓		✓		✓	✓	✓			
EMWET	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Shevell	✓		✓	✓	✓	✓	✓	✓	✓	
LTH	✓		✓	✓	✓	✓	✓	✓	✓	

Figure 5 illustrates the wing geometry variables for both the turboprop and turbojet aircraft, that are used for the method comparison. Table 5 gives an overview of the dependency of each method to those mentioned parameters. Each method depends on the wing span, sweep angle, taper ratio and the root thickness-to-chord ratio. Except the Torenbeek[1] method, the other methods are sensitive to maximum take-off weight.Investigating the method presented by Howe (Equation (7)) closely, it can be concluded that the root chord length is canceled out by the reference wing area and the aspect ratio (as they include c_r). Hence, the Howe method is the only method that does not depend on c_r. Torenbeek (2) and EMWET methods require the maximum zero-fuel weight as input. Torenbeek (1) and Howe are the only methods independent of the tip and kink thickness-to-chord ratio.

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Table 6
Error of wing weight estimation

Method	Turboprop aircraft error [%]	Turbojet aircraft error [%]
Torenbeek (1)	8·89	–19·70
Torenbeek (2)	6·45	–19·69
Howe	0·59	–4·46
EMWET	–3·30	2·30
Shevell	12·20	–17·53
LTH*	–	–3·77

* this method is not valid for F50 class aircraft

2.7.1 Accuracy analysis

The accuracy of all methods is analysed using the actual wing weight of a turboprop and a turbojet passenger aircraft. Fokker 50 is selected as the turboprop aircraft and Fokker 100 is selected as the turbojet aircraft. The actual wing weight of those aircraft is available in Ref. 25. Table 6 shows the errors of wing weight prediction using different methods. The error was calculated as follows:

$$\varepsilon = \frac{W_{calc} - W_{actual}}{W_{calc}} \quad \ldots (15)$$

From Table 6 one can observe that the quasi-analytical method under-predicts the wing weight for the turboprop aircraft compared to the other methods. For the turbojet aircraft this is the opposite. In this case the quasi-analytical method over-predicts the wing weight, while all the statistical methods under-predict that.

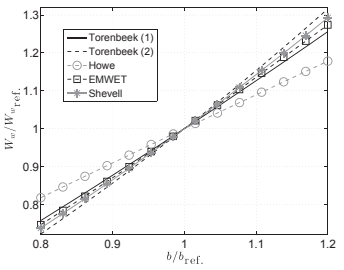
In general, the weight prediction of Fokker 50 is for most methods within 10%. The Shevell method is the only method which has an error more than 10% (12·2%). A possible cause of this slightly larger deviation can be explained by the fact that the relation between the total wing weight and the weight index (Equation (6)) was derived using only turbojet aircraft. The error of Fokker 50 wing weight estimation using EMWET, is slighty higher than the one presented in Table 4 . This difference can be explained by the fact that the student version of EMWET tool uses regression to estimate the total wing weight based on the primary wing weight. In other words, in the student version the secondary wing weight is not estimated seperately but it is estimated as a function of the primary wing weight.

The Howe method shows a good accuracy with an error of 0·59% for the turboprop aircraft. This can be clarified by the fact that this method includes a term that depends on the airplane type. Similarly to the turboprop aircraft, EMWET shows a good accuracy for the turbojet aircraft (2·3% error). For the same reason as explained before, the Howe method also estimates the wing weight accurately for the turbojet aircraft. On the other hand, the Torenbeek (1), Torenbeek (2) and Shevell methods show an under-prediction of about 18-20%. As mentioned by Torenbeek[20], reasons for these underestimations can be caused by the extra weight (up to 20%) required to provide adequate stiffness against flutter and weight penalty due to long service life cost.

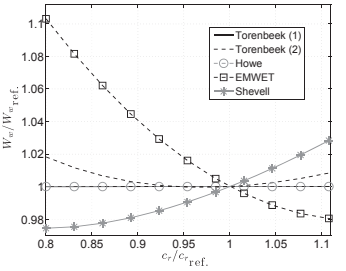
2.7.2 Sensitivity analysis

A study has been performed to investigate the sensitivity of the above mentioned weight estimation methods to the design variables. Consequently, gaining more insight about their behaviour can

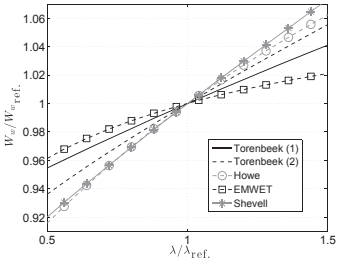
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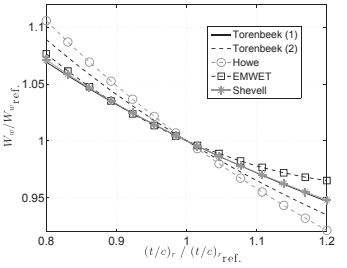
(a) Sensitivity of the wing weight with respect to the wing span.



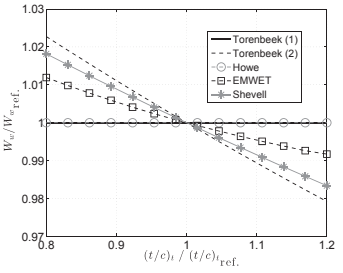
(b) Sensitivity of the wing weight with respect to the root chord length.



(c) Sensitivity of the wing weight with respect to the wing taper ratio.



(d) Sensitivity of the wing weight with respect to the root thickness-to-chord ratio.



(e) Sensitivity of the wing weight with respect to the tip thickness-to-chord ratio.

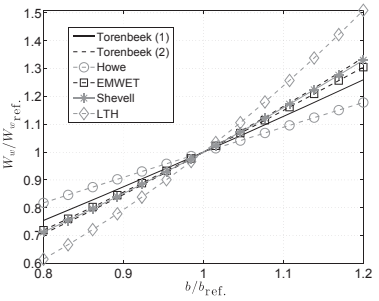
Figure 6. Wing weight sensitivity with respect to the wing geometry variables for turboprop aircraft.

also serve as a foundation to explain their impact on optimisations. Both the turboprop and the turbojet aircraft are used for sensitivity analysis.

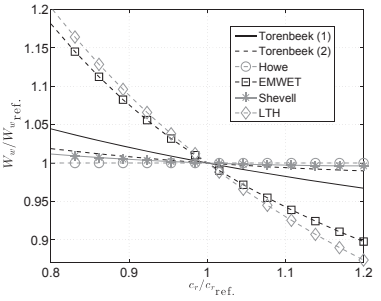
The sensitivity study is performed for the independent wing geometry variables for which the wing weight shows the greatest changes. The independent parameters are: wing span, root chord length, taper ratio and sweep angle. Wing sweepback is (mainly) applied to increase the drag divergence Mach number of a wing at transonic condition[9]. By increasing the drag divergence Mach number, the airplane can reach higher speeds. The considered turbojet aircraft flies at transonic speeds. However, this is not the case for the turboprop aircraft. Therefore, there is no sensitivity investigation of the sweep angle applied for the turboprop aircraft.

Figures 6 and 7 illustrate the sensitivity of the wing weight to those mentioned design variables. From Figs 5 and 6 it can be concluded that a 10% decrease in the wing span results in a weight reduction of about 10-15% for the turboprop aircraft and about 10-20% for the turbojet aircraft. In Table 5 it is indicated that the Howe method is independent of c_r, which can be clearly seen in Figs 5(b) and 6(b).

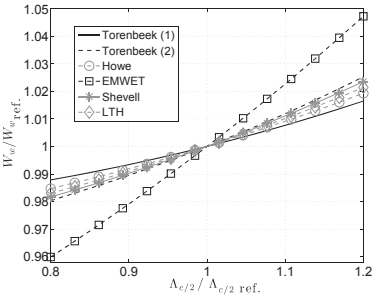
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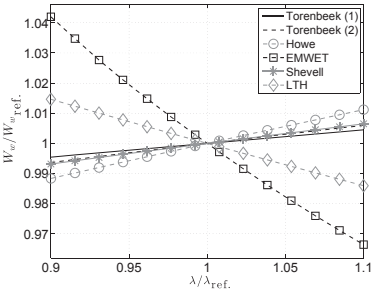
(a) Sensitivity of the wing weight with respect to the wing span.



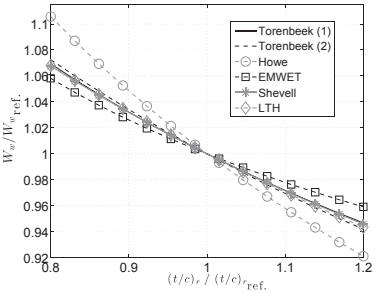
(b) Sensitivity of the wing weight with respect to the root chord length.



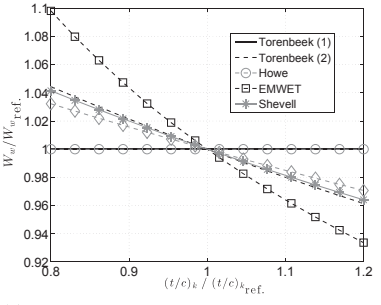
(c) Sensitivity of the wing weight with respect to the mid-chord sweep.



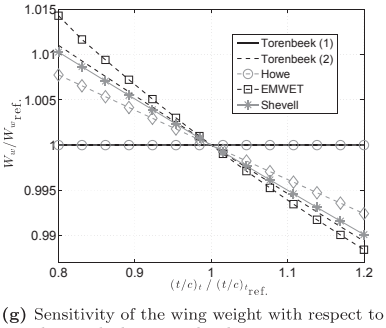
(d) Sensitivity of the wing weight with respect to the wing taper ratio.



(e) Sensitivity of the wing weight with respect to the root thickness-to-chord ratio.



(f) Sensitivity of the wing weight with respect to the kink thickness-to-chord ratio.



(g) Sensitivity of the wing weight with respect to the tip thickness-to-chord ratio.

Figure 7. Wing weight sensitivity with respect to the wing geometry variables for turbojet aircraft.

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For both test cases, the sensitivity of the wing weight to the wing span shows the same trend for all methods. The LTH method for the turbojet case shows the largest change in the wing weight by varying the wing span, see Fig. 6 . For the turboprop case, the Howe method is insensitive to the root chord length, as can be derived from Equation (7) . This is illustrated in Fig. 5. Analysis of the sensitivity of the wing weight to the wing taper ratio for the turboprop aircraft shows the same trend as the wing span (see Fig. 5), in which the wing weight increases by increasing the taper ratio. The sensitivity of the wing weight with respect to the wing taper ratio for the turbojet aircraft indicates a different trends compared to the turboprop case. To be more specific, the EMWET and LTH method show opposite behavior than the other methods and to what was observed from the turboprop aircraft. The sensitivity to the quarter-chord sweep shows a similar trend for all methods, except the EMWET method is more prone to varying with the sweep angle. The reason for the different behavior of the quasi-analytical method is that the design variables also affect the aerodynamic loads required by the EMWET method. From Figs 5 and 6 it can be deduced that the Torenbeek[1] and Howe method are insensitive to the tip thickness to chord ratio. For the turbojet aircraft, Fig. 6 shows that the Torenbeek[1] and Howe methods are also insensitive to the wing thickness to chord ratio at kink position.

3.0 MDO OF AN AIRCRAFT WING

A series of wing MDO assignments have been performed to evaluate the effect of using different weight estimation methods on the MDO of an aircraft wing. Those turboprop and turbojet aircraft mentioned in the previous section are used as test cases. The MDO system consists of three disciplines: aerodynamics, performance and weight. The sequential quadratic programming (SQP) algorithm from Matlab software is used as the optimiser.

3.1 Objective function, design vector and constraints

The optimisation problem is described as follows:

$$\begin{gathered} \min_{x} \quad F(x) \\ \text{subject to } g_i(x) \leq 0 \; i = 1, \ldots, m \\ h_j(x) = 0 \; j = 1, \ldots, n \end{gathered}$$

The aircraft maximum take-off weight (MTOW) is considered as the objective function. The design vectors for two different test cases are as follows:

$$\text{turboprop aircraft: } x = [b, c_r, \lambda, (t/c))_r, (t/c)_t, \varepsilon_t] \quad \ldots (16)$$

$$\text{turbojet aircraft: } x = [b, c_r, \lambda_{in}, \lambda_{out}, \Lambda_{in}, \Lambda_{out}, (t/c)_r, (t/c)_k, (t/c)_t, \varepsilon_t] \quad \ldots (17)$$

It is important to note is that the turbojet aircraft has a kinked wing, as illustrated in Fig. 4, and therefore two taper ratios and two mid-chord sweep angles are introduced to size the inner and outer wing. The values of the variables are allowed to change according to engineering expertise, see Tables 7 and 8 , and must be restrained in order to generate a realistic design. The quarter-chord sweep angle is kept constant ($\Lambda = 0°$) for the turboprop case.

The MTOW is considered to be the sum of three terms: the wing weight, the mission fuel weight and the rest weight.

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Table 7
Design variables for the turboprop aircraft

Design variables	b [m]	c_r [m]	λ [-]	$(t/c)_r$ [-]	$(t/c)_t$ [-]	$\cdot_t$ [°]
Initial values	29·00	3·56	0·40	0·21	0·15	–2·0
Lower bounds	20	2·5	0·3	0·25	0·25	–5
Upper bounds	40	5	0·5	0·10	0·10	5

Table 8
Design variables for the turbojet aircraft

Design variables	b [m]	c_r [m]	λ_{in} [-]	λ_{out} [-]	Λ_{in} [°]	Λ_{out} [°]	$(t/c)_r$ [-]	$(t/c)_k$ [-]	$(t/c)_t$ [-]	ε_t [°]
Initial values	28·08	5·60	0·64	0·35	16·24	11·90	0·12	0·12	0·09	–2·00
Lower bounds	20	3·5	0·5	0·3	5	5	0·08	0·08	0·08	–5
Upper bounds	40	6·5	0·8	0·5	22	35	0·15	0·15	0·15	5

Table 9
Flight conditions for turboprop and turbojet aircraft

Parameter	Turboprop aircraft	Turbojet aircraft
Cruise altitude [m]	7,620	10,675
Cruise Mach number	0·55	0·77

$$W_{to} = W_w + W_f + W_{rest} \quad \ldots(18)$$

The rest weight is initialised based on the reference aircraft actual weight and remains constant throughout the optimisation. The wing weight is estimated using different weight estimation methods. The fuel weight is calculated using the aircraft range performance equation (including the aircraft aerodynamic efficiency) and a series of statistical data.

Optimising the aircraft wing for cruise condition may result in an unrealistic value for wing loading because the value of wing loading is affected by some other segments of flight such as take-off and landing (the effect of wing loading on the aircraft stall speed). Hence, a constraint is defined to keep the wing loading smaller or equal to that of the reference aircraft.

$$\left(\frac{W_{to}}{S}\right) \leq \left(\frac{W_{to}}{S}\right)_{ref} \quad \ldots(19)$$

The flight conditions at which the turboprop and turbojet aircraft operate, are given in Table 9. Based on the flight altitude, the remaining state parameters (such as air density and viscosity) are derived.

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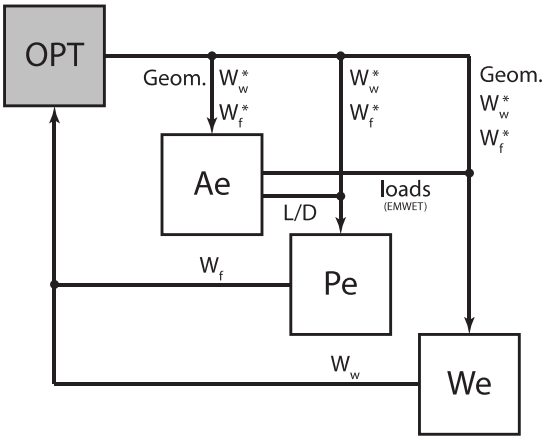


Figure 8. Design structure matrix of MDO system with aerodynamics, performance and weight modules.

3.2 MDO strategy

The individual discipline feasible (IDF) strategy[26] is selected for this MDO assignment. Using this strategy, the feedbacks between different disciplines are removed. Instead, the optimiser is made responsible for the consistency of the coupling variables.

The design structure matrix of the MDO system is illustrated in Fig. 8 including its three modules: aerodynamics (*Ae*), performance (*Pe*) and weight (*We*). In this workflow, W_f^* and W_w^* represent the coupling variables (also referred to as the surrogate values). Using IDF there is no feedback between the disciplines and therefore there is no necessity for an iterative procedure to converge the multidisciplinary system. A drawback of using this strategy is that additional design variables are introduced. The optimisation problem using IDF can be stated as follows:

$$\begin{aligned} &\min W_{to}(X) \\ &\text{w.r.t } X = (x, W_f^*, W_w^*) \\ \text{subject to} \quad &\left(\frac{W_{to}}{S}\right) \leq \left(\frac{W_{to}}{S}\right)_{ref} \\ &W_f^* = W_f \\ &W_w^* = W_w \end{aligned}$$

As mentioned before, quasi-analytical weight prediction methods require the aerodynamic loads in order to calculate the forces and moments applied to the structure. The aerodynamic loads are calculated by the aerodynamics module. They are then passed to the weight module when the EMWET is used for wing weight estimation.

3.2.1 Aerodynamics module

Strip theory[27] was used to develop an aerodynamic solver. The developed solver combines the results of a three-dimensional vortex lattice method with the results of a two-dimensional airfoil analyser to accurately calculate the total wing drag. The wing lift distribution is calculated by

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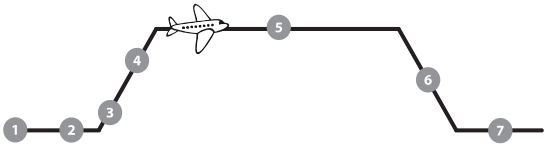


Figure 9. Typical flight mission definition with flight segments.

Table 10
Fuel fraction for each segment in a typical flight mission, suggested values from Roskam[32]

Fuel weight fraction, M_{ff_i}	Turboprop aircraft	Turbojet aircraft
1. Start & warm-up	0·990	0·990
2. Taxi	0·995	0·990
3. Take-off	0·995	0·995
4. Climb	0· 985	0·980
5. Cruise	Calculated	Calculated
6. Descent	0·985	0·990
7. Landing, taxi & shutdown	0·995	0·992

means of a freely available vortex lattice method code, AVL[28]. The aerodynamic characteristics of the wing sections in several spanwise locations are computed using viscous airfoil analysis tools Xfoil[29], MSES[30] and VGK[31]. Once the total lift coefficient and the total wing drag coefficient are known, the wing lift-to-drag ratio can be calculated. In order to calculate the total lift to drag ratio of the aircraft, the drag of the other parts of the aircraft (e.g. fuselage, tail) should be added to the drag of the wing. The drag of the aircraft without the wing is considered as the 'rest drag'. The rest drag of the reference aircraft is determined and in each function evaluation it is normalised using the wing area and dynamic pressure to obtain the drag coefficient of the aircraft minus the wing. This coefficient is added to the wing drag coefficient calculated by the aerodynamic solver. The aircraft total lift is assumed to be equal to the wing lift.

3.2.2 Performance module

The required fuel for the flight mission is calculated using the method presented by Roskam[32]. In this method, the required fuel for the cruise is calculated using the Bréguet range equation, while some statistical factors are used to estimate the fuel weight of the other segments of the flight mission, see Table 10. Each fuel weight fraction M_{ff_i} indicates the ratio of the total aircraft weight at the end of the flight segment to the total aircraft weight at the beginning of the segment, see Fig. 9 .

The total fuel weight fraction indicated the consumed fuel as a ratio of the total aircraft weight at the end of the flight mission to the total aircraft weight at the beginning.

$$M_{ff} = M_{ff_1} \cdot M_{ff_2} \cdot \ldots \cdot M_{ff_n} \quad \ldots (20)$$

Hence, the fuel weight can be determined including a 5% allowance of the total fuel weight as reserve fuel by using the following equation:

$$W_f = 1{\cdot}05\,(1 - M_{ff})W_{to} \quad \ldots (21)$$

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Table 11
Results of wing optimisation for turboprop aircraft

Method	Reduction in W_{to} [%]	b [m]	c_r [m]	λ [-]	$(t/c)_r$ [-]	$(t/c)_t$ [-]	ε_t [°]
Reference wing	-	29·00	3·46	0·40	0·21	0·15	–2·00
Torenbeek (1)	3·45	20·00	5·00	0·37	0·25	0·19	–1·70
Torenbeek (2)	2·83	20·00	4·91	0·40	0·25	0·25	–0·70
Howe	2·76	20·97	5·00	0·31	0·25	0·15	–0·64
EMWET	2·51	20·00	4·56	0·50	0·15	0·16	–2·45

Table 12
Results of wing optimisation for turbofan aircraft

Method	Reduction in W_{to} [%]	b [m]	c_r [m]	λ_{in} [-]	λ_{out} [-]	Λ_{in} [°]	Λ_{out} [°]	$(t/c)_r$ [-]	$(t/c)_k$ [-]	$(t/c)_t$ [-]	ε_t [°]
Reference wing	-	28·08	5·60	0·64	0·35	16·24	11·90	0·12	0·12	0·09	–2·00
Torenbeek (1)	4·44	21·62	6·50	0·67	0·38	21·13	13·58	0·14	0·08	0·10	–2·15
Torenbeek (2)	4·41	21·11	6·50	0·70	0·36	21·10	13·78	0·14	0·08	0·10	–2·15
Howe	4·54	24·69	6·50	0·59	0·30	20·09	14·30	0·15	0·08	0·08	–2·51
EMWET	4·84	20·01	6·49	0·80	0·32	19·75	11·58	0·13	0·08	0·08	–2·01
Shevell	4·03	20·71	6·50	0·74	0·31	17·64	15·92	0·12	0·09	0·12	–2·45
LTH	8·08	20·00	6·50	0·80	0·42	19·78	12·33	0·15	0·08	0·08	–1·82

3.2.3 Weight module

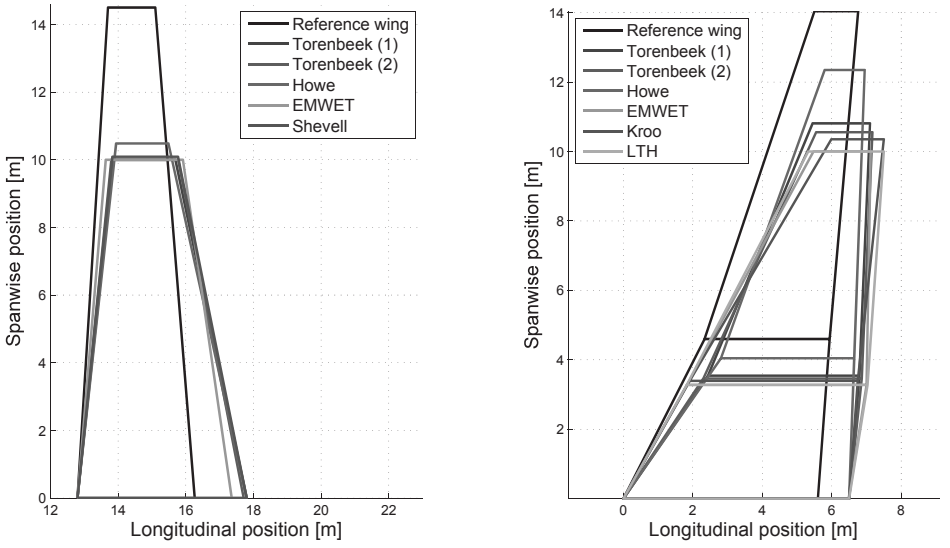
In the weight module, the weight of the wing is predicted using one of the proposed wing weight estimation methods.

3.3 MDO results

Tables 11 and 12 present the results of the wing shape optimisation for the turboprop and turbojet aircraft. Each table also contains the achieved reduction in MTOW compared to the MTOW of the reference aircraft. The achieved reduction in MTOW is up to 3·45% for the turboprop aircraft and up to 8·08% for the turbojet aircraft. The planforms of the optimised wings are shown in Fig. 10 .

A noteworthy aspect of the optimisation results, is that the wing span has been decreased towards its lower bound value. Sensitivity analyses of the weight estimation methods demonstrated that the wing span has a large impact on the wing weight. The objective function is affected by both the wing weight and the fuel weight, where the fuel weight is a function of the aerodynamic efficiency and the aircraft total weight. Increasing the wing span increases the wing aspect ratio (for a constant chord length), which results in a lower induced drag but higher friction drag. Figure 11 shows the variation of the wing weight and the fuel weight of the turbojet aircraft with the wing span. The figure indicates that the wing weight shows a greater impact on the objective function than the aerodynamic efficiency. This explains the fact that the optimiser drives the wing span towards its lower bound. Other design variables (i.e. wing taper, root chord length, kink thickness-to-chord ratio) are also driven towards lower/upper bounds by the optimiser. In contrast to the statistical

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(a) Turboprop aircraft (b) Turbojet aircraft

Figure 10. Planform geometry of the optimised wings.

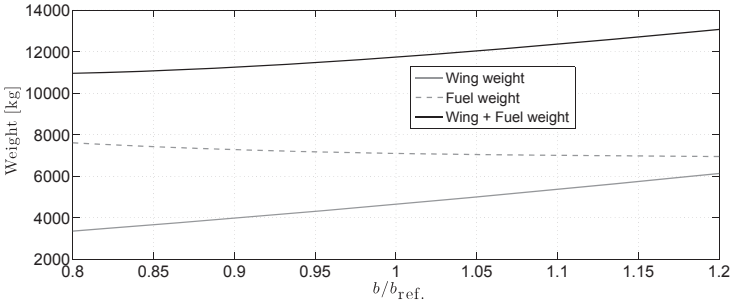


Figure 11. Sensitivity of the wing weight and the fuel weight with respect to the wing span.

weight methods, the quasi-analytical method (EMWET) does not drive the root thickness-to-chord ratio towards its upper bound. Note that the EMWET method, is the only tool used that is sensitive to the wing twist. Hence, the value of the tip twist is purely driven by the aerodynamic analyses in the case of using one of the statistical weight estimation methods.

As the optimisation results show unrealistic configurations, additional constraints are required to model a more realistic situation.

3.4 Additional constraints

In order to obtain a more realistic wing geometry, two additional constraints are applied. A fuel volume constraint is used to ensure that the required fuel for the flight mission can be stored in the wing fuel tanks (available fuel volume). The fuel volume is calculated using the mission fuel weight and the Jet-A fuel density (according to Air BP[33]).

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Table 13
Results of wing optimisation for turboprop aircraft using new set of constraints

Method	Reduction W_{to} [%]	b [m]	c_r [m]	λ [-]	$(t/c)_r$ [-]	$(t/c)_t$ [-]	ε_t [ ]
Reference wing	-	29·00	3·46	0·40	0·21	0·15	–2·00
Torenbeek (1)	1·97	26·35	4·05	0·30	0·25	0·10	–2·18
Torenbeek (2)	2·14	26·34	4·05	0·30	0·25	0·25	–1·36
Howe	1·76	26·36	4·01	0·31	0·25	0·17	–2·41
EMWET	1·38	26·33	4·04	0·30	0·22	0·19	–2·07
Shevell	1·61	26·51	3·93	0·35	0·25	0·25	–1·11

$$(V_f)_{req.} \leq (V_f)_{av.} \quad \ldots (22)$$

Another constraint is applied to keep the aspect ratio AR larger than typical values for turboprop and turbojet aircraft categories[34,35]. This constraint is implemented in order to take into account the performance requirement for the second climb segment.

$$AR \geq \begin{cases} 10 & \text{for turboprop aircraft} \\ 8 & \text{for turbojet aircraft} \end{cases}$$

With these additional constraints, the optimisation problem can be rewritten:

$$\begin{gathered} \min W_{to}(X) \\ \text{w.r.t } X = (x, W_f^*, W_w^*) \\ \text{subject to} \quad \left(\frac{W_{to}}{S}\right) \leq \left(\frac{W_{to}}{S}\right)_{ref} \\ AR \geq \begin{cases} 10 & \text{for turboprop} \\ 8 & \text{for turbojet} \end{cases} \\ (V_f)_{req.} \leq (V_f)_{av.} \\ W_f^* = W_f \\ W_w^* = W_w \end{gathered}$$

3.5 MDO results using additional constraints

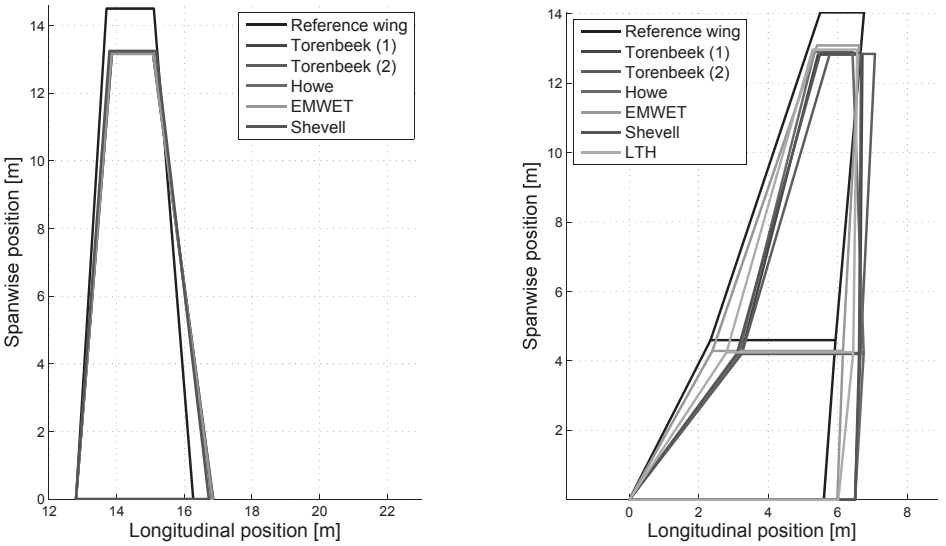
Tables 13 and 14 provide the MDO results for the turboprop and turbojet aircraft. Both cases show smaller reduction in MTOW using three constraints instead of one.

The optimisations convergence history is shown in Figure 13 . Computational time of the MDO processes are shown in Table 15. All optimisations were performed using Matlab R2010b on a computer having an Intel Core2Duo E4400 (2.00Ghz), with 2Gb RAM and Windows 7 (64-bit version). For the turboprop aircraft, the optimiser requires the most iterations for the Torenbeek(1) and Howe methods. Whereas, for the turbojet case, the most iterations are required for EMWET and Howe method.

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Table 14
Results of wing optimisation for turbofan aircraft using new set of constraints

Method	Reduction W_{to} [%]	b [m]	c_r [m]	λ_{in} [-]	λ_{out} [-]	Λ_{in} [°]	Λ_{out} [°]	$(t/c)_r$ [-]	$(t/c)_k$ [-]	$(t/c)_t$ [-]	ε_t [°]
Reference wing	-	28·08	5·60	0·64	0·35	16·24	11·90	0·12	0·12	0·09	–2·00
Torenbeek (1)	4·40	25·65	6·50	0·53	0·38	21·82	13·21	0·14	0·08	0·11	–2·13
Torenbeek (2)	4·17	25·68	6·50	0·53	0·38	22·00	15·39	0·15	0·09	0·10	–2·05
Howe	4·60	25·80	6·50	0·55	0·31	22·00	11·40	0·15	0·08	0·10	–2·07
EMWET	2·53	26·17	5·99	0·63	0·32	16·62	11·52	0·13	0·09	0·11	–2·62
Shevell	3·91	25·73	6·50	0·54	0·34	20·87	12·97	0·15	0·08	0·12	–2·55
LTH	4·43	25·93	6·02	0·61	0·35	20·82	11·39	0·15	0·08	0·10	–1·89



(a) Turboprop aircraft (b) Turbojet aircraft

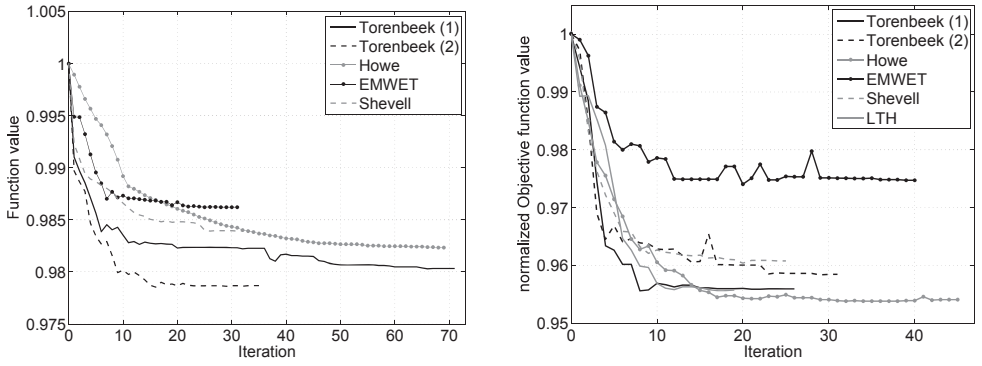
Figure 12. Planform geometry of the optimised wings using the new set of constraints.

Each function evaluation using a statistical method takes about 39 seconds, whereas a function evaluation using EMWET takes 51 seconds.

4.0 CONCLUSION

Several statistical and a quasi-analytical wing weight prediction methods were implemented in an MDO task to optimise an aircraft wing. Two test cases, a turboprop aircraft and a turbojet aircraft, were used. Comparison of the implemented weight estimation methods, based on their accuracy and sensitivity to wing geometric variables, gave better insight into each method. MDO results

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(a) Turboprop aircraft (b) Turbojet aircraft

Figure 13. Optimisation convergency.

Table 15
Computational time of the optimisations using the new set of constraints

Method	Turboprop aircraft [hrs]	Turbojet aircraft [hrs]
Torenbeek (1)	7·61	6·82
Torenbeek (2)	3·88	7·18
Howe	10·32	10·43
EMWET	5·21	14·48
Shevell	8·28	4·85
LTH	-	4·06

for both test cases using one constraint (wing loading), yielding optimised configurations where some design variables were driven towards their lower/upper bounds. A new set of constraints has been added to take into account the requirements related to the other flight segments. Two more constraints concerning the aspect ratio and fuel volume were implemented. Realistic optimisation problems contain more constraints, but the number of constraints used was sufficient for the scope of this research.

The results of the optimisations showed that the output of the optimisation is influenced by the used weight model. When sufficient information about the wing geometry is available, it is of great interest to use weight prediction methods with higher level of design-sensitivity. This allows designers to gain more knowledge about the design and the design-sensitivity. The statistical methods used for wing weight prediction, were insensitive to some design variables (tip twist, tip/kink thickness-to-chord ratios and root chord). EMWET, a quasi-analytical method, is sensitive to all the defined design variables. However, using EMWET (quasi-analytical weight prediction) comes at the cost of increasing the computational time for each iteration by 30%.

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