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Didactical Tool for Wing Weight Estimation in a Preliminary Aircraft Design Stage

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Abstract: - Aircraft preliminary design requires a lot of complex evaluations and assumptions related to design variables that are not completely known at a very initial stage. Didactical activity becomes unclear since students ask for precise values in the starting point. A tentative in providing a simple tool for wing weight estimation is presented for overcoming these common difficulties and explaining the following points: a) the intrinsic iterative nature of the preliminary design stage, b) provide useful and realistic calculation for the wing weight with very simple assumption not covered by cumbersome calculations and formulas. The purpose of the paper is to provide a didactic tool to facilitate the understanding of some steps in estimating wing weight at the preliminary design level. The problems of identifying the main variables for the initial estimation is dealt with and specifi aspects that are usually hidden by the complexity of the involved disciplines and by the usual calculation methods applied in structural design are pointed out. The procedure is addressed to highlight main steps in wing weight estimation for straight wing weight to highlight the main steps in estimating the wing weight for a general aviation straight wing aircraft at the preliminary design stage. The effect of the main variables on the wing weight variation is also presented confirming well-known results from literature and design manuals.

Key-Words: - Didactical tool, wing weight estimate, preliminary aircraft design

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1 Introduction

Aeronautical design usually requires the solution of complex and multidisciplinary problems. Several disciplines often not so easily analyzed, are investigated taking into consideration a certain level of coupling in specific phenomena [1,2]. Several aspects have to be taken into consideration in searching a solution to the design problem. Such a solution has to fulfil all the expected performances and regulatory requirements aimed at maintaining safety and structural integrity in the operational field. The introduction of innovative and alternative configurations such as the electric powered case, hydrogen fuel cell powered ones, or electro-solar platform [3,4], requires an in-depth comprehension of aero-structural aspects often not addressable without the necessary numerical support. The presence of behaviors associated with flexibility and low weight such as linear and non-linear flutter phenomena [5,6,7], new method for composite structure design [8] or scaling laws application [9] , potentially with important interest in detailed design, introduce the need to solve and analyze coupled and complex equations that often tend to divert the designer attention from the preliminary aspects of the design. This happens even more during the didactic interaction with students also if these aspects remain essential for correct identification of design configuration. From an educational point of view, it is always of fundamental importance to be able to present the main concepts of design with a progressive and increasing difficulty levels by means of subsequent steps so that the complexity of the procedures and calculation methods does not make it difficult to distinguish which are the dominant points and variables in the selection of the configuration. The same applies in reducing the most significant design phenomena to the main basic terms to initially configure the aircraft. Detailed assessments connected to those phenomena that require deep numerical/analytical investigation and experimental verification are postponed to further design steps. It is therefore very useful from a didactical point of view to indicate the main and basic steps for wing weight estimate at the preliminary design phase. The design activity in general is associated with an ideal and operational path that, starting from the known initial data (project data), tries to reach a system / machine / object that realizes them in the operating conditions respecting the expected boundaries. The process that leads from the initial data to the solution is called "design" and involves a series of assessments and checks on compliance with the initial assumptions that are not always fully defined. Most of the variables remains unknown and requires an iterative procedure for achieving an effective result solved out operating through optimization methods for selecting the best compromise with respect to initial requirements and expected performances. A defined configuration ("SOLUTION") has been made available at the end of the design stage: all aspects and behaviors have been defined as verified. This configuration must then be supplied to the manufacturer who will carry out and build a prototype (Fig. 1). By critically comparing the initial data with the proposed solution ("VERIFY"), it is possible to check whether the expected performances have been really fulfilled. After "MANUFACTURING" the aircraft prototype has been built and it is possible to arrange experimental ("TEST") activities on it under established operating conditions. Verification and testing are therefore closely associated with the design activity.

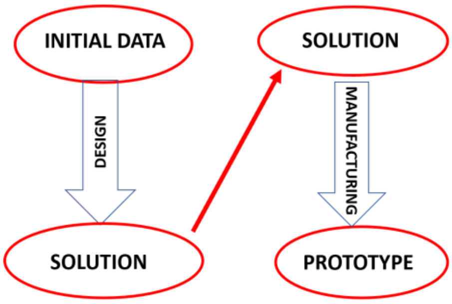


Figure 1: Main steps in design and manufacturing

The design activity is said to be concluded only if tests have given a positive result. The first phase indicated in the Fig.2, is detailed explained in Fig.3 introducing the "conceptual/preliminary" step: starting from the collection of the main committed requirements, a set of values of the main variables involved in the design has been determined to produce a reasonable estimate of expected performances [1,2,10,11]. All useful aspects of the selected or proposed configuration will be made available to the subsequent design phase ("detailed design") which provides drawings useful for fabrication. The flow of the activity included in the first part and shown in the Fig.3 specifies how this flow of operations is intrinsically iterative and useful for comparing proposed solutions with the initial requirements: all the aspects have been verified by the selected configuration with a certain level of effectiveness (optimal) compared to the parameters initially introduced such as minimum weight, minimum cost, maximum specific performance, etc. In the preliminary phase of the aeronautical design several disciplines have to be included, evaluating all those technological aspects that have an impact on the selected configuration (Fig. 4) [12,13,14].

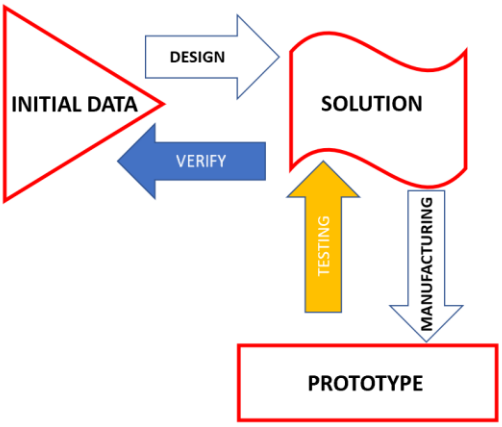


Figure 2: Overall view of the Aircraft Design Phases

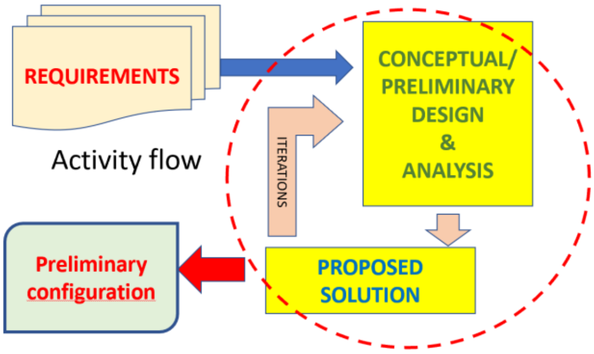


Figure 3: Specific detail of the initial design stage

Some of them can be reported as an example such as: the architecture, the material (with the typical and innovative properties), the technological process, etc. These options orient and define a specific configuration that will present all those initially expected advantages or that will indicate the non-feasibility or sustainability of a certain selection. Very often, at the end of the preliminary phase, contradictory conclusions have been found with respect to cost and weight expectations and a decision has to be assumed for continuing to the subsequent phase. An estimate/evaluation of weights related to several components involved in the aircraft have been introduced with an immediate and reasonable way.

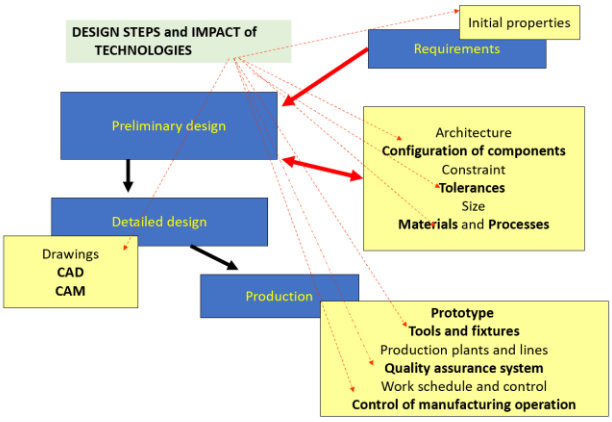


Figure 4: Technological aspects in multidisciplinary Preliminary Aerospace Design phase.

From the didactic point of view, it is always a critical point to go inside the intrinsic iterative nature of the design procedure and to explain the wide uncertainty in the definition of the initial values for those variables involved in preliminary design stage. The way in which the iterative sequence has started can often not be defined and it is usually closed in the mind of experts in related disciplines or consultants. Several authors tried to give a sort of ideal list or “vademecum” for a correct initial decision and fruitful work in design such as statistical database, decision making procedure, performance matrix and so on. In several cases personal experience or know-how, established by previous activity performed on similar configuration, guides the designer into this initial critical decision environment [13]. There are questions that students frequently ask such as:
a) how do I evaluate the initial weight for any aircraft component? b) What is the starting procedure in evaluating the wing weight? c) What load do I consider to be effective for the selected configuration? d) How can I evaluate initial guess for unknown variables to speed up the solution? And so on. Despite having all the information in hand to carry out these calculations, they are in an uncertain position and are not able to continue. In the following sections a simple didactical procedure has been proposed for supporting this critical decision point [13,15]. The procedure is related to the case of wing weight estimate for a typical general aviation aircraft such as those covered in CS-23; CS-25 airworthiness rules. The open literature presents a wide range of research articles about this subject. Geometric parameters and simple structural equations for reinforced shell stress determination are used in [16, 17, 18] while statistical and classical design handbook as in [1,2,13,14,18], are used in [19,20,21]. Formulas related to wing mass estimation were similar or in some cases the same as the well-known handbook in design. Similar procedure supported by CAD and FEM schemes are introduced in [22,23,24,25]. In this case the structure is almost prepare knowing any details or at least most details involved so the weight estimate is more precise and representative, but it is not considered as a preliminary estimate in design procedure. It can be viewed as a detailed evaluation as for detailed design phase. A procedure based on reinforced shell scheme plus FEM is presented in [26]. This case is more flexible in design variation as concerned in preliminary design so it should be preferable in a design loop. According to this short literature review, well-known semiempirical formulas or statistical methods remain the basic methodology for wing weight determination. With this in mind and referring to previously described motivation for didactical approach, a simplified procedure is presented in this paper. The procedure can also be easily transformed into a numerical tool or subroutine or excel sheet useful for students. Basic structural and aerodynamic concepts and formulas related to thin-walled reinforced skin construction and trapezoidal/rectangular-trapezoidal straight wing are considered. Simple reduction as in [23,27,28,29,30] has been reported with specific simple estimate of unknown components.

2 Procedure description and basic assumptions.

According to design manuals, the weight of the wing is commonly separated in two main parts: a) structural weight which includes all those components useful for supporting the applied loads and b) non-structural weight referring to all those added parts which do not give a contribution to the strength and stiffness of the wing but are necessary for a complete wing shape definition (connecting parts and ribs, envelope closure, internal systems and so on). Fuel in wing and other masses eventually distributed inside the wing are considered in a separate term. In general, non-structural weight can be assigned as a fraction of the structural weight or determined according to the evaluation of the remaining parts completing the wing shape beyond the structural one. The wing structure is usually manufactured by means of a thin-walled box configuration positioned on a fraction of the chord length and leaving the remaining one to non-structural contributions. The definition of the structural weight is so referred to the well-known analytical evaluation based on the reinforced-shell scheme. This elementary scheme provides the presence of concentrated areas (stringers) used to support longitudinal stress and two-dimensional thin sections (panels) used to support the shear stresses generated by shear-torsion loads. The material needed to make the structural part must therefore be defined once the applied loads are made available for calculation. However, the load applied to the wing structure remains a function of the aerodynamic contribution developed in operating conditions and of the relieving part due to the inertial reaction according to the selected load factor. At the preliminary design level, when the geometries and airfoils as well as the performance of the aircraft are not yet defined, common questions arise: what aerodynamic load has to be considered? What mass of the wing has to be introduced in the calculation? An answer to these points can be determined with reference to the maximum take-off weight and design load factor established in the initial design data-list connected to wing shape, wing airfoil and flight attitude. It becomes evident how the resulting vertical load on the wing can be expressed by following integral and local resultant equations respectively:

$$Q = L - nW_w \tag{1}$$

$$\frac{dQ}{dx} = \frac{dL}{dx} - n\frac{dW_w}{dx} = q_L - nq_w \tag{2}$$

By didactical point of view two observations arise: 1) the preliminary design phase is intrinsic iterative (wing weight is not determined but it is a function of the resultant load), 2) this iterative nature requires an initial estimate for the involved variables which will be corrected at each interaction as new updates are made available. The internal structural geometries have been changed at specific iteration following more realistic load distribution and compliance to regulatory and performance requirements. From aerodynamic point of view, it is well known that most performing expected load distribution on finite wing is near elliptical while the worst distribution is near a linear one [23]. This gives an answer to previously reported question: in a generic trapezoidal or rectangular-trapezoidal straight wing an average lift distribution can be assumed with a certain confidence. An example is reported in figure 5.

This distribution (Fig.5) is not exactly correspondent to the real one, but it is considered satisfactory while waiting for the real distribution derived by the aerodynamic design group. The real distribution can be introduced into the calculation as soon as it has been made available and the iterative tool is repeated for final definition, Since the maximum take-off weight is initially set as a design data (or assigned from considerations about similar aircraft) and the load factor depends on the category of the aircraft, the total aerodynamic load is established assuming the wing as the only available surface.

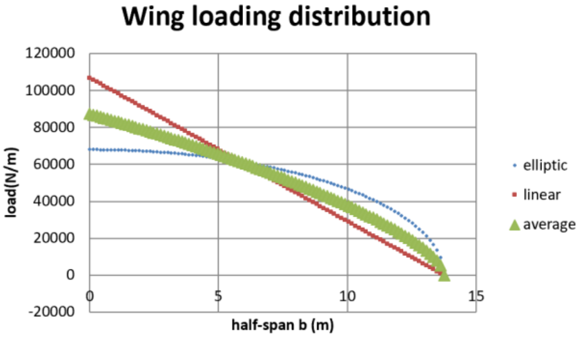


Figure 5: Typical distribution for an optimal and poor aerodynamic configuration

The inertial load associated with the masses distributed on the wing (structural and non-structural) must be also considered in reducing the wing total load. Resultant distributed load can be used for shear load, bending moment and torsion moment determination along the wing half-span according to the following relations:

$$T(z) = -\int_z^b \left[q_L(z) - nq_w(z) \right] dz \tag{3}$$

$$M_b(z) = \int_z^b T(z) dz \tag{4}$$

$$M_t = \int_z^b m_t(z) dz \tag{5}$$

Eqs. 3,4,5 follow well known sign convention and assumptions in simplified beam-wise wing representation from basic structural handbook [29,30]. No engine and no fuel in wing is initially considered, but they can be introduced easily. Based on the load distribution as in Fig.5 and considering the basic relationships for the elementary reinforced shell section, the wing structure is divided in two fundamental parts: bending stress resistant section "Ab" and shear stress resistant section "At+Ators" (due to shear load and torsion) [28,29]. Well-known equations can be proposed based on very simplified assumptions in terms of geometry and structural configuration: 1) the half-wing is assimilated to a straight beam without sweep angle, 2) the radius of inertia of the section must be derivable in a simple manner, 3) the component of area associated with the vertical shear is assigned only to the vertical parts of the section, 4) the torsion moment is applied to a single cell scheme as an approximate representation of the structural box. These points obviously introduce a certain level of simplification in structural behavior, but the general trend in weight calculation is representative of the real situation without shadowing the design concept by means of complex formulas or numerical analyses. As a consequence, the didactical point of view of the procedure is pointed out enabling students to compare ideas and weight trends for design evaluation. Stress level at any section are determined as follows [23]:

$$\sigma(z)=\frac{M_b(z)}{A_b(z)r_b^2(z)}y(z) \qquad (6)$$

$$\tau_s(z)=\frac{T(z)}{A_s(z)} \qquad (7)$$

$$\tau_{tors}(z)=\frac{M_t(z)}{2\Omega(z)s(z)} \qquad (8)$$

Simplified assumptions are evident from the equations 6,7,and 8. Comparing the calculated stress to the reference ones, selected from materials database, the three representative sections are determined. The same wing box must be included in the airfoil shape, therefore there are other constraints:

1) The maximum height of the wing-box does not exceed the maximum assumed thickness of wing airfoil. In the absence of the airfoil, a typical thickness ratio of about 12% to 18% can be used reduced by a certain amount in order to identify a consistent shape; 2) The chord distribution along the wing span is not known at this step but depends on the selected architecture. wing surface, aspect ratio and wing span. Initial estimate is proposed in this case:

a) Consider the radius of inertia of the bending stress section approximated by half the maximum thickness of the profile,

b) Consider the y coordinate for stress evaluation equivalent to the value of the radius of inertia of the section,

c) A rectangular single cell wing-box (a and h as dimensions) with constant thickness and constant shear flow is assumed for torsion moment;

d) The torque is estimated as the resulting transverse load applied at a distance d from the elastic axis (d = 0.25-0.5 c).

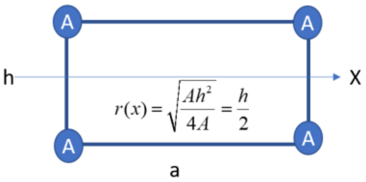
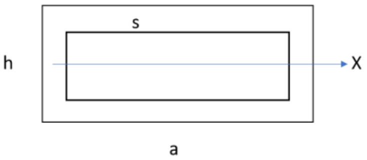


Figure 6a: Simple reinforced shell representation



$$r(x)=\frac{h}{\sqrt{12}}\sqrt{\frac{\left[1-\left(1-\frac{2s}{a}\right)\left(1-\frac{2s}{h}\right)^3\right]}{\left[1-\left(1-\frac{2s}{a}\right)\left(1-\frac{2s}{h}\right)\right]}}$$

Figure 6b: Single rectangular thin-walled box and radius of inertia determination.

The assumption a) is justified by Fig. 6a,6b, both for the simple reinforced shell configuration and for the thin-walled rectangular single cell with a variation less than 10%, at thickness to height ratio not higher then 0.1. This is completely acceptable for a didactical situation. A possible correction can be introduced by changing the coefficient “a-1” in the weight estimation formula Eq. 16. Figure 7 shows that the height of the section at 70% of the maximum profile thickness is a good compromise between simplicity of calculation and representativeness. The same thing can be said for the width which usually does not exceed 1/2 of the local chord providing a representative structural section under torsion load as in the following equations:

$$a=\alpha_1 c \quad 0.3\le\alpha_1\le 0.55 \qquad (9)$$

$$h=\alpha_2 t_{\max} \quad 0.5\le\alpha_2\le 0.8 \qquad (10)$$

$$\Omega=\alpha_1\alpha_2\frac{t_{\max}}{c}c^2\,;\; 2p=2c\left[\alpha_1+\alpha_2\frac{t_{\max}}{c}\right] \qquad (11)$$

$$A_{tors}=s\cdot 2p \qquad (12)$$

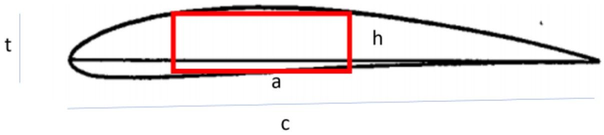


Figure 7: Example of torsional structural section

The areas are then solved out by the introduction of established admissible values for the selected material transforming Eqs 9-12 into the following:

$$A_b(z) = \frac{|M_b(z)|}{\sigma_{ref}\,|r_b(z)|} \quad (13)$$

$$A_s(z) = \frac{|T(z)|}{\tau_{s-ref}} \quad (14)$$

$$A_{tors}(z) = \frac{M_t(z)}{c\cdot\tau_{s-ref}}\left[\frac{\alpha_1+\alpha_2(t/c)}{\alpha_1\alpha_2(t/c)}\right] \quad (15)$$

The overall weight of the wing, including the non-structural part has been determined such as:

$$W_w = 2a_1\int_0^b \left[A_b(z)+A_s(z)+A_{tors}(z)\right]\rho dz + a_2 S_w f_w$$

(16)

The non-structural weight takes into account the weight increase due to overlapping and thickening by means of “a1” coefficient, the weight due to completion of the wing section with a coefficient “a2” (values from 0.2 to 0.35) as a function of the wing surface and with a coefficient “ f” (values within 1 and 2) as a function of the envelope thickness “s”. The estimate of the wing weight should remain between 5% and 15% of the assumed take-off weight (W-mto). The estimated wing weight can be compared with formulas available in the literature ([2,10,11]) and a satisfactory correlation is determined in spite of the very strong simplification introduced for didactical needs.

3 Preliminary Results on a didactical test case and comments

Preliminary results are derived according to the presented simple procedure in order to demonstrate its didactical value. Considering a Regional aircraft configuration and a straight trapezoidal wing shape, the following initial data are introduced as in Table 1. The half-wing geometry and the load distribution are reported in Figure 8a, 8b respectively. According to indicated simplifying hypotheses the deign iteration starts with updating the final weight and wing loading as indicated previously. The last iteration result is reported in Table 2. It is consistent to the expected values as in general aircraft design handbook. A further investigation is performed in order to indicate and explain the effect of specific design variables on wing weight. Main design variables considered here are the following: thickness ratio of the selected airfoil and wing Aspect Ratio with fixed wing surface. Results are reported in table 3 and 4 respectively: the wing weight tends to decrease by increasing the thickness ratio due to high available space inside the airfoil, while the wing weight tends to increase with higher aspect ratio at fixed thickness and wing surface (high slender configuration). It is consistent to well-known result from the literature.

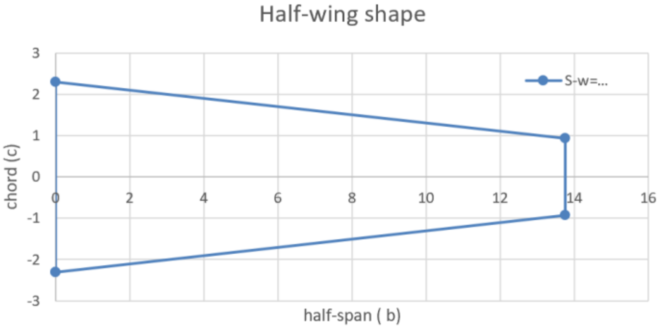


Figure 8a: Half-Wing selected geometry.

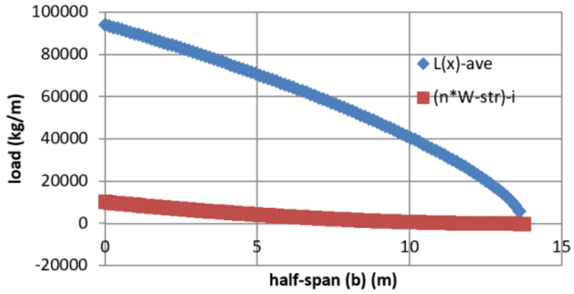


Figure 8b: Wing loading distribution at i-iteration.

W-mto(kg)	Maximum take-off weight	43000
n	Load factor	3.75
b(m)	Half-wing span	13.76
S-w (m2)	Wing area	88.7
c-root(m)	Root wing chord	4.6
c-tip(m)	Tip wing chord	1.85
TR= c-tip/c-root	Taper Ratio	0.403
TC=t/c	Airfoil thickness ratio	0.12
AR =	Aspect ratio	8.54
A1; A2; f =	Eq 16	1.15; 0.25; 1.6
Alfa-1; Alfa-2 =	Eq 9-12	0.35; 0.75
Rho(kg/m3)	Material specific mass	2800
Ref.stress (bending)(Mpa)		280
Ref-stress (shear-tors)(Mpa)		150

Table 1: initial data for preliminary example.

W-mto(kg)	43000
W-w (kg)	2925
W-w/W-mto	0.068

Table 2: Final result on wing weight estimate.

t/c	0.12	0.18
W-w (kg)	2925	2095
W-w/W-mto	0.068	0.048

Table 3: Wing weight variation with thickness ratio

Table 5 presents wing weight variation changing wing surface at fixed AR, chord ratio and thickness ratio. The weight variation is analogous to the one presented in Table 4 where the variation is related to AR but at fixed Sw. It should be noted that the non-structural weight level has remained a function of the indicated coefficients as explained. User can modify numerical values of these coefficients in connection to specific design choice such as non-structural material selected or non-structural thickness. For high aspect ratios different internal geometric configurations are possible if compared to the proposed one: multi-cellular sections, stiffened or sandwich sections, high stiff ribs for specific design needs and so on. This deviates from the introduced approximation and a new evaluation is necessary.

t/c	0.12	0.12	0.12
c-tip/c-root	0.4	0.4	0.4
AR	8.58	11.5	18.03
W-w (kg)	2925	4156	7126
W-w/W-mto	0.068	0.097	0.165

Table 4: Wing weight variation with aspect ratio @Sw=88.7m2.

t/c	0.12	0.12	0.12
c-tip/c-root	0.4	0.4	0.4
Sw (m2)	68.7	88.7	108.7
W-w (kg)	2585	2925	3226
W-w/W-mto	0.060	0.068	0.075

Table 5: Wing weight variation with Wing Surface @AR=8.54.

The simplified model presents typical wing weight characteristics of the expected trends as in [1,2,10,11] also if the tool implements a certain level of simplification. Any other adding aspects or variation in simplifying assumption can be entered into the tool by user-student, according to specific design needs. The tool is however didactically effective in comprehension of the design steps and concepts for students who easily understand them.

4 Conclusion

A simplified preliminary aircraft design procedure for wing weight estimation is presented and discussed. Several simplified assumptions are introduced and considered for a clear representation of typical weight trends in aircraft wings without losing representativeness of the results. A didactical tool has been prepared and some preliminary results are reported. A good and clear understanding of the influence that main design parameters have in wing weight determination is addressed. More representative evaluation and other additional details could be considered inside the tool as a second level of investigation, but the validity of this simple basic version remains demonstrated. Presented results are in line with the ones available by literature or specific handbook showing the right tendency of wing weight in function of aspect ratio and relative airfoil thickness. Didactically speaking this is a big help in demonstrating wing weight estimate trends to aerospace students working on aircraft design. These trends are consistent to expected real design situations.

References:

[1] D.P. Raymer. *Aircraft Design: A Conceptual Approach*. AIAA Education Series. 1992.
[2] Jenkinson, Simpkins, Rhodes. *Civil Jet Aircraft Design* . Arnold. 1999.
[3] Romeo G., Frulla G., Cestino E. Design of high-altitude long-endurance solar-powered unmanned air vehicle for multi-payload and operations. *Proceedings of the Institution of Mechanical Engineers. Part G. Journal of Aerospace Engineering. ISSN0954-4100. 221(2007), pp. 199-216.* 2007
[4] Frulla G., Cestino E. Design, manufacturing and testing of a HALE-UAV structural demonstrator. *Composite Structures. ISSN 0263-8223. - 83(2008), pp. 143-153. 2008*
[5] Cestino E., Frulla G., Piana P., Duella R. Numerical/Experimental Validation of Thin-Walled Composite Box Beam Optimal Design. *AEROSPACE. MDPI. ISSN 2226-4310. 7(8) (2020), p. 111.* [https://doi.org/10.3390 /aerospace7080111]. 2020.
[6] Cestino E., Frulla G. Critical Aeroelastic Behaviour of Slender Composite Wings in an Incompressible Flow. *Composite Materials in Engineering Structures*.ISBN: 978-161728857-9- (2013), pp. 313-339. 2013.
[7] Amato E.M., Polsinelli C. Cestino E., Frulla G., Carrese J.N., Marzocca P. HALE wing experiments and computational models to

predict nonlinear flutter and dynamic response. *THE AERONAUTICAL JOURNAL*.ISSN 0001-9240.pp.1-36.[10.1017/aer.2019.38]. 2019.

[8] Danzi F., Frulla G., Romeo G. An Invariant-based Performance-Oriented Procedure for Preliminary Design of Composite Structures. *Aircraft Engineering and Aerospace Technology. ISSN 1748-8842. 90:3(2018), pp. 532-541.*2018. [10.1108/AEAT-11-2016-0228]

[9] Cestino E., Frulla G., Perotto E., Marzocca P. Experimental Slender Wing Model Design by the Application of Aeroelastic Scaling Laws. *Journal of Aerospace Engineering. ISSN 0893-1321. 27:1(2014), pp. 112-120. 2014.*

[10] E. Torenbeek. *Synthesis of a subsonic airplane design.* Delft University Press. 1976.

[11] E. Torenbeek. *Advanced aircraft design conceptual design analysis and optimization of subsonic civil airplane*. WILEY. 2013.

[12] K. T. Ulrich, S.D. Eppinger. *Product Design and Development*. McGraw-Hill, 1995.

[13] G.E. Dieter. *Engineering Design. A material and processing approach*. McGraw-Hill, 2000.

[14] Ashby, D.R.H. Jones. *Engineering Materials 2 -An Introduction to Microstructures, Processing and Design*. B.H. 1998.

[15] M.H. Sadraey. *Aircraft Design A system Engineering Approach*. WILEY. 2013.

[16] Ardema M.D., Chambers M.C., Patron A.P., Hahn A. S., Miura H. , Moore M.D. Analytical Fuselage and Wing Weight Estimation of Transport Aircraft . *NASA TM 110392*. May 1996.

[17] Elham A., LA Rocca G., Van Tooren M.J.L. Development and implementation of an advanced, design-sensitive method for wing weight estimation. *Aerospace Science and Technology* . 29 (2013) 100–113.

[18] Ajaj R.M., Friswell M.I., Smith D., Isikveren A.T. A conceptual wing-box weight estimation model for transport aircraft. *Aeronautical Journal*. May 2013. Volume 177 No 1191, 533-551. 2013.

[19] Essari A., *Estimation of Component design weights in conceptual design phase for tactical UAVs.* PhD Dissertation . Belgrade 1995.

[20] Kim S., Lee B., Yun J., Ahn J., Hwang H. Derivation of a Wing-Weight Estimation Equation for a Roadable Personal Air Vehicle Using Regression Analyses of Data Obtained from Wing Planform Reference Points. *J. Aerosp. Eng. ASCE,* 34(1): 04020098. DOI: 10.1061/(ASCE)AS.1943-5525.0001220. 2020.

[21] Dababneha O., Kipouros T. A Review of Aircraft Wing Mass Estimation Methods. *Aerosp.Sci.Technol. Vol.72, Jan. 2018, pp.256-266.[https//doi.org/10.1016/j.ast.2017.11.006]*

[22] Anhalt C., Monner H.P., Breitbach E. Interdisciplinar wing design – Structural Aspects. *SAE International .03WAC-29*. 2003.

[23] R.M Spath. Simple wing weight estimation equation. Aircraft Design: A Conceptual Approach. *Conf. S.A.E.E. Inc Baltimore, Maryland US Science and Technology*, 2063-3-J, 10-13 May. 1954.

[24] Spohr A., Schirra J., Hoefling J., Schedl A. Wing Weight Estimation Methodology for highly non-planar Lifting systems During Conceptual Design. *DLR Congress*. Dcoument 301281. 2013.

[25] Bai C., Mingqiang L., Zhong S., Zhe W., Yiming M., Lei F. Wing weight estimation considering constraints of structural strength and stiffness in aircraft conceptual design. *Int'l J. of Aeronautical & Space Sci*. 15(4), 383–395. DOI:10.5139/IJASS.2014.15.4.383. 2014

[26] Benaouali A., Rogolski R., Kachel S. Structural sizing for the weight estimation of a very light aircraft wing. *Proc IMechE Part G: J Aerospace Engineering 2018*, Vol. 232(14) 2681–2687. 2018.

[27] Donaldson, B.K. *Analysis of Aircraft Structures an Introduction*, 2nd ed, Cambridge University Press, New York, USA, 2008.

[28] Niu M. *Airframe Structural Design*, Hong Kong Comilit Press LTD., 1999.

[29] T.H.G. Megson. *Aircraft structures for engineering students*. Butterworth-Heinemann; 3rd edition. 1999.

[30] Li, Z.N. *Aircraft Structure Science. 2nd Edition*. Beihang University Press. 2010.

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